1 ST 2023/2024



Thermo I

DR:

Ahmed Abuyaghi

Introduction and Basic Concepts

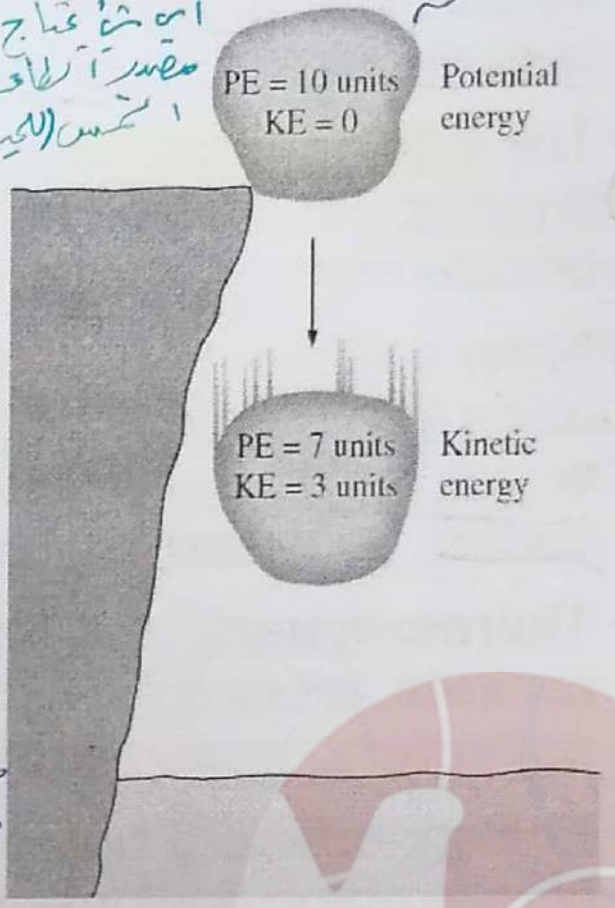
- One of the most fundamental laws of nature is the conservation of energy principle. It simply states that during an interaction, energy can change from one form to another, but the **total amount of energy** remains constant. That is, energy cannot be created or destroyed.
- A rock falling off a cliff, for example, picks up speed as a result of its potential energy being converted to kinetic energy.
- A person who has a greater energy input (food) than energy output (exercise) will gain weight (store energy in the form of fat), and a person who has a smaller energy input than output will lose weight.
- The change in the energy content of a body or any other system is equal to the difference between the energy input and the energy output, and the energy balance is expressed as:

$$E_{in} - E_{out} = \Delta E.$$

CamScanner الممسوحة ضوئيا بـ

THERMODYNAMICS AND ENERGY-1

- **Thermodynamics**: The science of *energy*.
- **Energy**: The ability to cause changes.
- The name *thermodynamics* stems from the Greek words *therme* (heat) and *dynamis* (power).
- **Conservation of energy principle**: During an interaction, *energy can change from one form to another*, but the total amount of energy remains constant.
- Energy cannot be created or destroyed.
- **The first law of thermodynamics**: An expression of the conservation of energy principle.
- The first law asserts that *energy* is a thermodynamic property.



Energy cannot be created or destroyed; it can only change forms (the first law).

الممسوحة ضوئيا بـ CamScanner

THERMODYNAMICS AND ENERGY-2

- **The second law of thermodynamics**: It asserts that energy has *quality* as well as *quantity*, and actual processes occur in the direction of decreasing quality of energy.



Heat flows in the direction of decreasing temperature.

Types of Thermodynamic Studies:

- **Classical thermodynamics**: A macroscopic approach to the study of thermodynamics that does not require a knowledge of the behavior of individual particles.
  - It provides a direct and easy way to the solution of engineering problems (used in this course).
- **Statistical thermodynamics**: A microscopic approach, based on the average behavior of large groups of individual particles (molecules).

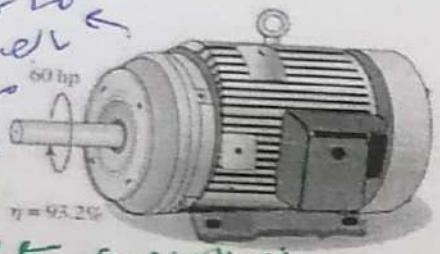
CamScanner الممسوحة ضوئيا بـ

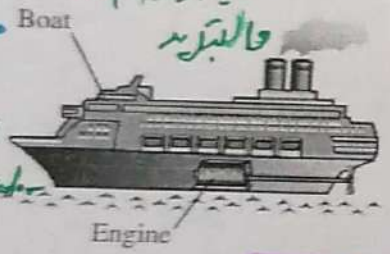
Applications of Thermodynamics

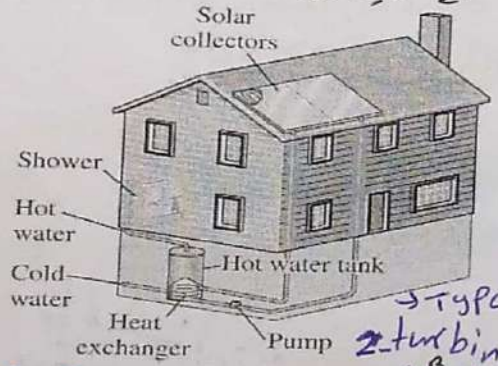
- **Thermodynamics** is encountered in many engineering systems and other aspects of life.
- The **heart** is constantly pumping blood to all parts of the human body, various energy conversions occur in trillions of body cells, and the body heat generated is constantly rejected to the environment.
- The **human comfort** is closely tied to the rate of this metabolic heat rejection (controlling heat transfer rate by adjusting clothing to environmental conditions).
- Many ordinary **household appliances** are designed, in whole or in part, by using the principles of **thermodynamics.** Some examples include electric or gas range, heating and air-conditioning systems, refrigerator, pressure cooker, water heater, computer, etc.
- **Thermodynamics** is basic in design and analysis of **automotive engines, rockets, jet engines, power plants, electrochemical cells, solar collectors, transportation vehicles from ordinary cars to airplanes.**
- **Energy-efficient home** that you may be living in is designed on the basis of minimizing heat loss in winter and heat gain in summer.
- Size, location, and power input of the **fan of your computer** is also selected after an analysis that involves **th**

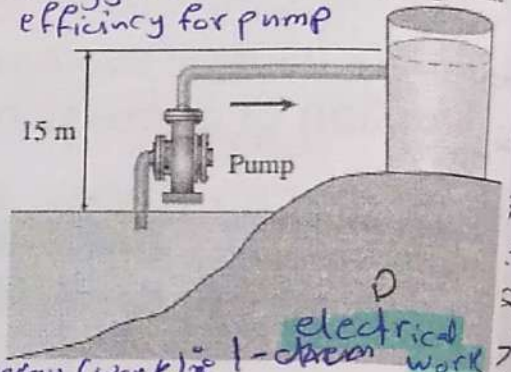
CamScanner الممسوحة ضوئيا بـ

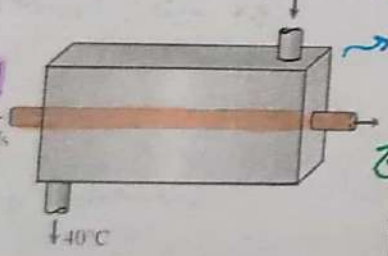
Applications of Thermodynamics



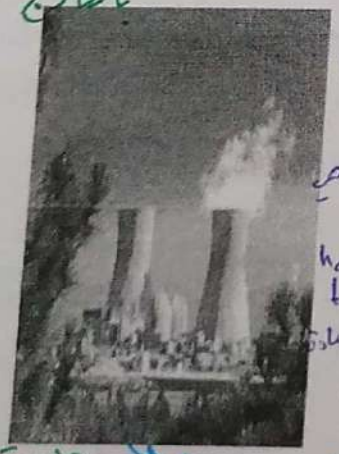


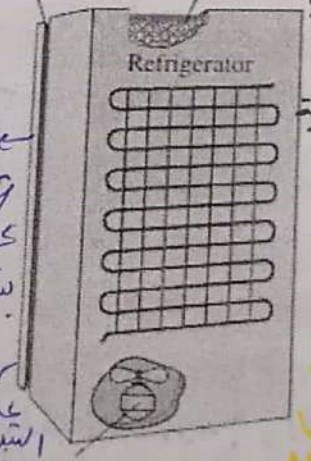


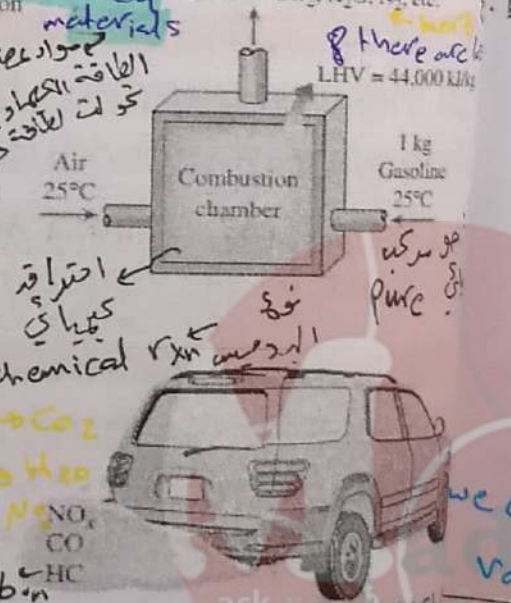












IMPORTANCE OF DIMENSIONS AND UNITS

Two types of units :-

- Any physical quantity can be characterized by **dimensions**.
- The magnitudes assigned to the dimensions are called **units**.
- Some basic dimensions such as **mass *m*, length *L*, time *t*, and temperature *T*** are selected as **primary** or **fundamental dimensions**.
- Others such as **velocity *V*, energy *E*, and volume *V*** are expressed in terms of the primary dimensions and are called **secondary dimensions**, or **derived dimensions**.

primary أي وحدة مشتقة من ال

TABLE 1–1

The seven fundamental (or primary) dimensions and their units in SI

Dimension	Unit
Length	meter (m)
Mass	kilogram (kg)
Time	second (s)
Temperature	kelvin (K)
Electric current	ampere (A)
Amount of light	candela (cd)
Amount of matter	mole (mol)

(kg · m · s)

TABLE 1–2

Standard prefixes in SI units

Multiple	Prefix
10^{12}	tera, T
10^{9}	giga, G
10^{6}	mega, M
10^{3}	kilo, k
10^{2}	hecto, h
10^{1}	deka, da
10^{-1}	deci, d
10^{-2}	centi, c
10^{-3}	milli, m
10^{-6}	micro, μ
10^{-9}	nano, n
10^{-12}	pico, p

ask & believe & recieve
CamScanner الممسوحة ضوئيا بـ

12/10/2023

SYSTEMS AND CONTROL VOLUMES

- **System**: A quantity of matter or a region in space chosen for study.
- **Surroundings**: The mass or region outside the system.
- **Boundary (Control Surface)**: The real or imaginary surface that separates the system from its surroundings.
- The boundary of a system can be *fixed* or *movable*.
- Systems may be considered to be *closed* or *open*.

Types of Systems

I) Closed (Control mass).

II) Open (Control volume).

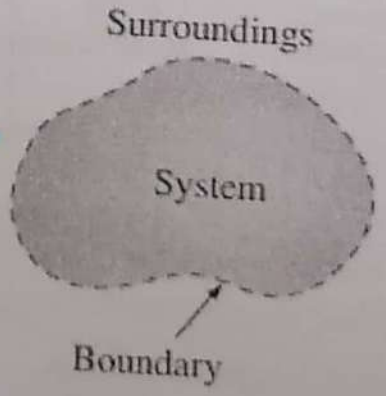


FIGURE 1–18
System, surroundings, and boundary.

Madar ask & believe & recieve
الممسوحة ضوئيا بـ CamScanner

* Closed Systems (Control Mass) *

* اذا ثبتت ال mass بغض النظر volume والعكس كذلك

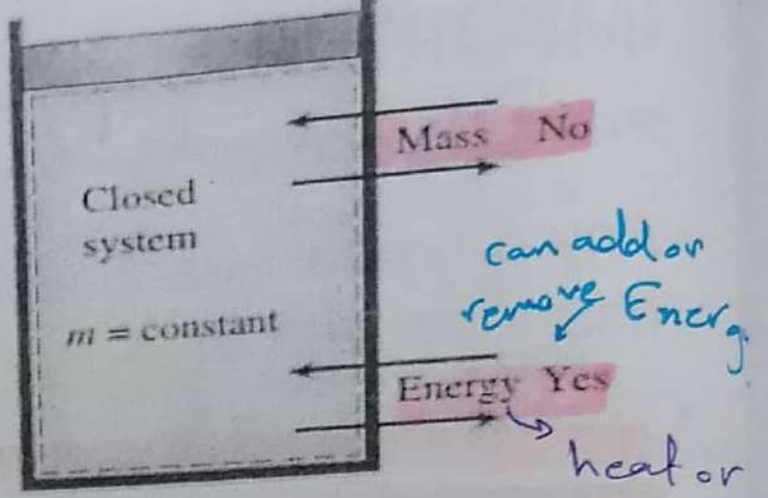


FIGURE 1–19
Mass cannot cross the boundaries of a closed system, but energy can.

- Energy, not Mass, crosses Closed System boundaries.

- **Example Applications:**

1) Piston-cylinder devices.
2) Batch reactor tank.
3) Refrigerator.
4) Air conditioner.
5) Small electric heater.

اذا حللت حرارة أو حللت ضغط بترتفع piston بتحرك

ماشيه ← عبر ثابتة الغاز

كمية الحارة فيه flow ثابتة

If we do mixing we add ing work

← مخانه الكهرباء العاديه في

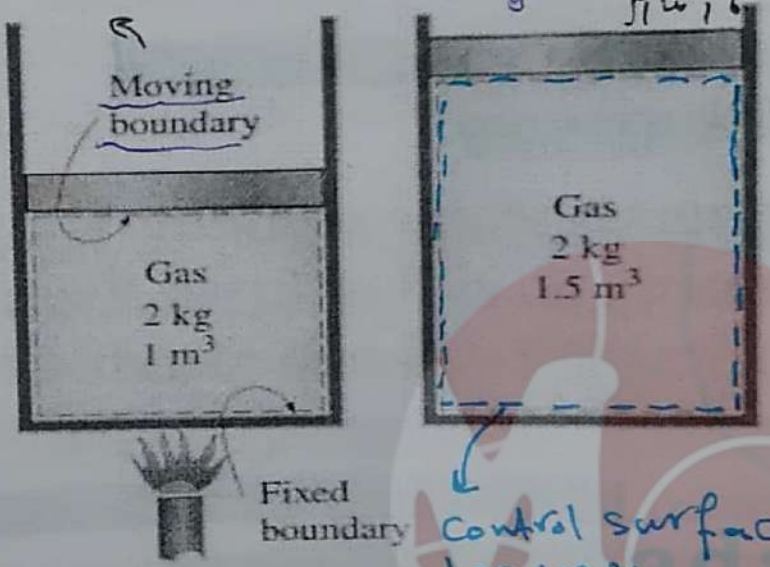


FIGURE 1–20
A closed system with a moving boundary.

لانه ال fixed sys بالتالي ما في ل طاقة ال kinetic و potential و heat و work بتضيف وبتوقف

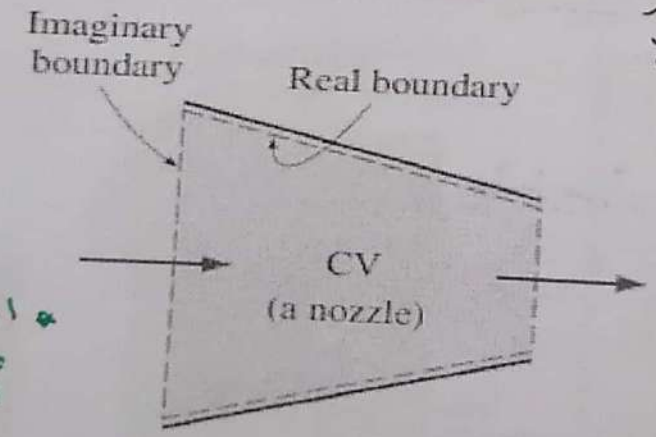
عند ال

CamScanner الممسوحة ضوئيا بـ

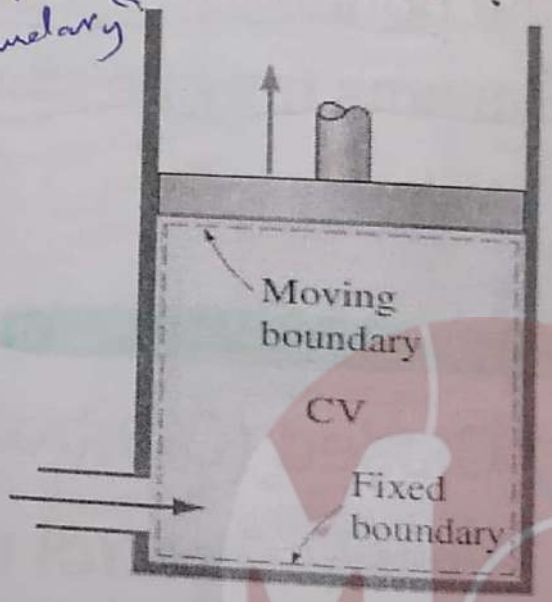
*Open Systems (Control Volume)

- Both Mass and Energy Cross Open System (Control Volume) Boundaries.
- Control surface: The boundaries of a control volume. It can be *real or imaginary.*
- **Example applications:**

1) Fluid flow in pipes, water pumps, air compressors, heat exchangers, etc.
2) Continuous-flow chemical reactors.
3) Automobile motor engines.
4) Power plant turbine systems.



(a) A control volume (CV) with real and imaginary boundaries



(b) A control volume (CV) with fixed and moving boundaries as well as real and imaginary boundaries

الممسوحة ضوئيا بـ CamScanner

PROPERTIES OF A SYSTEM

- **Property**: Any characteristic of a system.
- Some familiar properties are pressure P, temperature T, volume V, and mass m.
- Properties are considered to be either *intensive* or *extensive*.

❑ **Intensive properties**: Those that are *independent of the mass* of a system, such as temperature, pressure, and density.

❑ **Extensive properties**: Those whose values *depend on the size* (or extent) of the system.

- **Specific properties**: Extensive properties *per unit mass.*

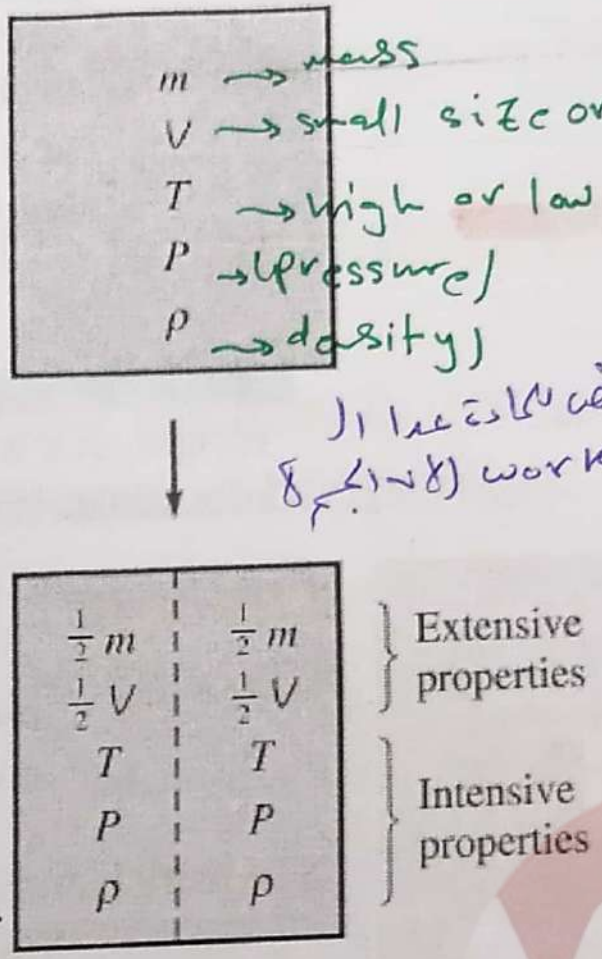


FIGURE 1–23
Criterion to differentiate intensive and extensive properties.

CamScanner الممسوحة ضوئيا بـ

properties *per unit mass.*

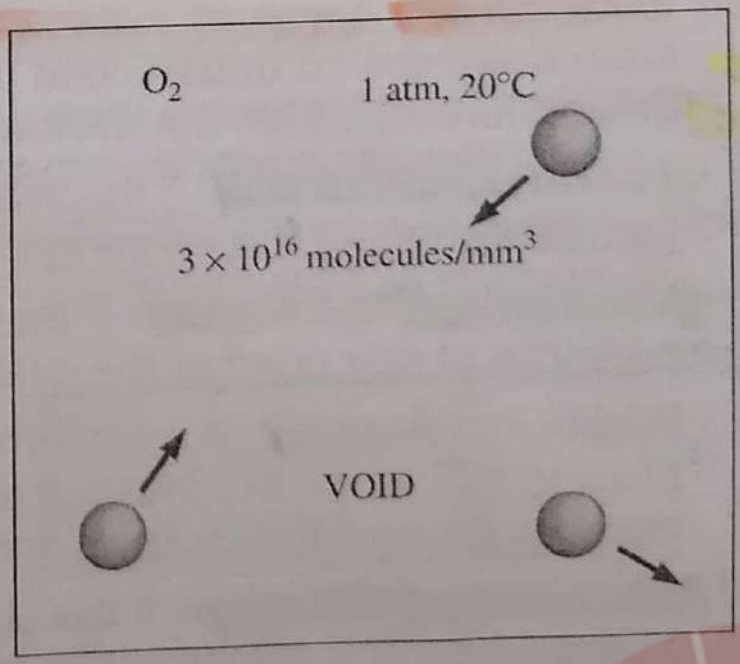
13

* الفرق بين Intensive properties و Extensive properties

* عكس الحجم النوعي specific volume (م³/كجم) المادة تتكون من molecules متفرقة (في الغازات) لكنه احنا بنتعاملها بنعتبره Continuous

Continuum

- Matter is made up of atoms that are widely spaced in the gas phase. Yet it is very convenient to disregard the atomic nature of a substance and view it as a *continuous, homogeneous matter* with no holes, that is, a ***continuum***.
- The continuum idealization allows us to treat properties as point functions and to assume the properties vary continually in space with no jump discontinuities.
- This idealization is valid as long as the size of the system we deal with is large relative to the space between the molecules.
- This is the case in practically all problems.
- In this text we will limit our consideration to substances that can be modeled as a ***continuum.***



Despite the large gaps between molecules, a substance can be treated as a *continuum* because of the very large number of molecules even in an extremely small volume.

14

Nadar ask & believe & recieve
الممسوحة ضوئيا بـ CamScanner

DENSITY AND SPECIFIC GRAVITY

Density

$$\rho = \frac{m}{V} \qquad (\text{kg/m}^3)$$

Specific volume

$$v = \frac{V}{m} = \frac{1}{\rho}$$

$V = 12\ \text{m}^3$
$m = 3\ \text{kg}$

$\rho = 0.25\ \text{kg/m}^3$

$v = \frac{1}{\rho} = 4\ \text{m}^3/\text{kg}$

Specific gravity: The ratio of the density of a substance to the density of some standard substance at a specified temperature (usually water at 4°C).

$$\text{SG} = \frac{\rho}{\rho_{H_2O}}$$

It is a ratio between ρ of any substance with ρ of water (dimentionless)

Specific weight: The weight of a unit volume of a substance.

$$\gamma_s = \rho g \qquad (\text{N/m}^3)$$

weight = mass * acc of gravity
$w = m * g$

→ Density is mass per unit volume;
→ specific volume is volume per unit mass.

TABLE 1–3

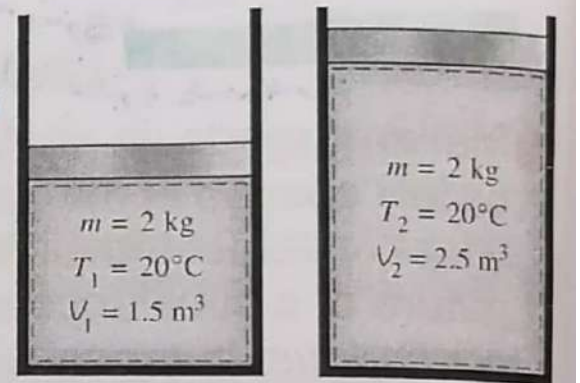
Specific gravities of some substances at 0°C

Substance	SG
Water	1.0
Blood	1.05
Seawater	1.025
Gasoline	0.7
Ethyl alcohol	0.79
Mercury	13.6
Wood	0.3–0.9
Gold	19.2
Bones	1.7–2.0
Ice	0.92
Air (at 1 atm)	0.0013

CamScanner الممسوحة ضوئيا بـ

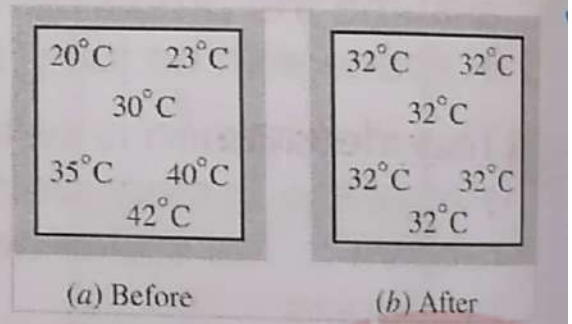
STATE AND EQUILIBRIUM

- Thermodynamics deals with ***equilibrium* states.**
- **Equilibrium:** A state of balance. In an equilibrium state there are no unbalanced potentials (or driving forces) within the system.
- **Thermal equilibrium:** If the temperature is the same throughout the entire system.
- **Mechanical equilibrium:** If there is no change in pressure at any point of the system with time.
- **Phase equilibrium:** If a system involves two phases and when the mass of each phase reaches an equilibrium level and stays there.
- **Chemical equilibrium:** If the chemical composition of a system does not change with time, that is, no chemical reactions occur.



(*a*) State 1 (*b*) State 2

A system at two different states



(*a*) Before (*b*) After

A closed system reaching thermal equilibrium.

❑ A system is said to be "in **thermodynamic equilibrium**" if it maintains:

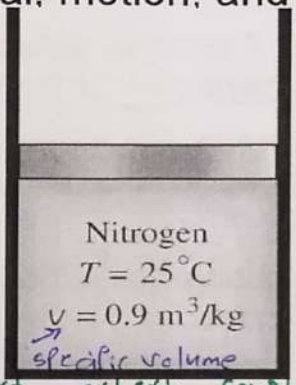
(1) thermal (uniform temp.), (2) mechanical (uniform pressure), (3) phase (mass of two phases, e.g., ice and liquid water, in equilibrium), and (4) chemical equilibrium (uniform composition).

الممسوحة ضوئيا بـ CamScanner

The State Postulate

- The state of a system is described by its properties.
- But, by experience not all properties must be known before the state is specified.
- The number of properties required to fix the state of a system is given by the **state postulate**:
  - *The state of a simple compressible system is completely specified by two independent, intensive properties.*
- **Simple compressible system:** If a system involves no electrical, magnetic, gravitational, motion, and surface tension effects.

The state of nitrogen is fixed by two independent, intensive properties.



equation of state : ideal gas law

$PV = nRT$

$P\hat{V} = RT$, $[v_m] = m^3/kmol$

molar volume (intensive) $[\hat{V}] = m^3/kg = \frac{v}{mass}$

PROCESSES AND CYCLES-1

Process: Any change that a system undergoes from one equilibrium state to another.

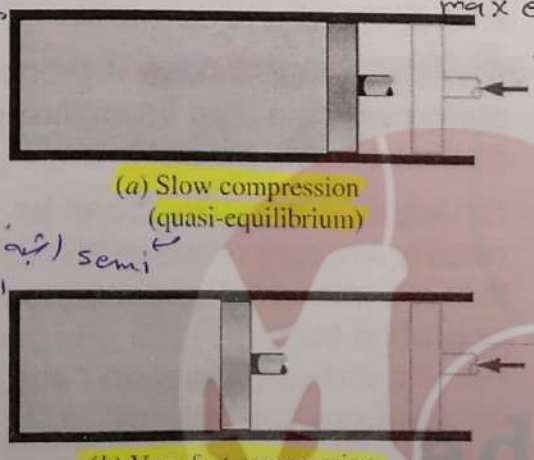
Path: The series of states through which a system passes during a process.

To describe a process completely, one should specify **the initial and final states**, as well as **the path** it follows, and the interactions with the surroundings.

Quasi-equilibrium process: When a process proceeds in such a manner that the system remains **infinitesimally close to an equilibrium** state at all times.

Characteristics:

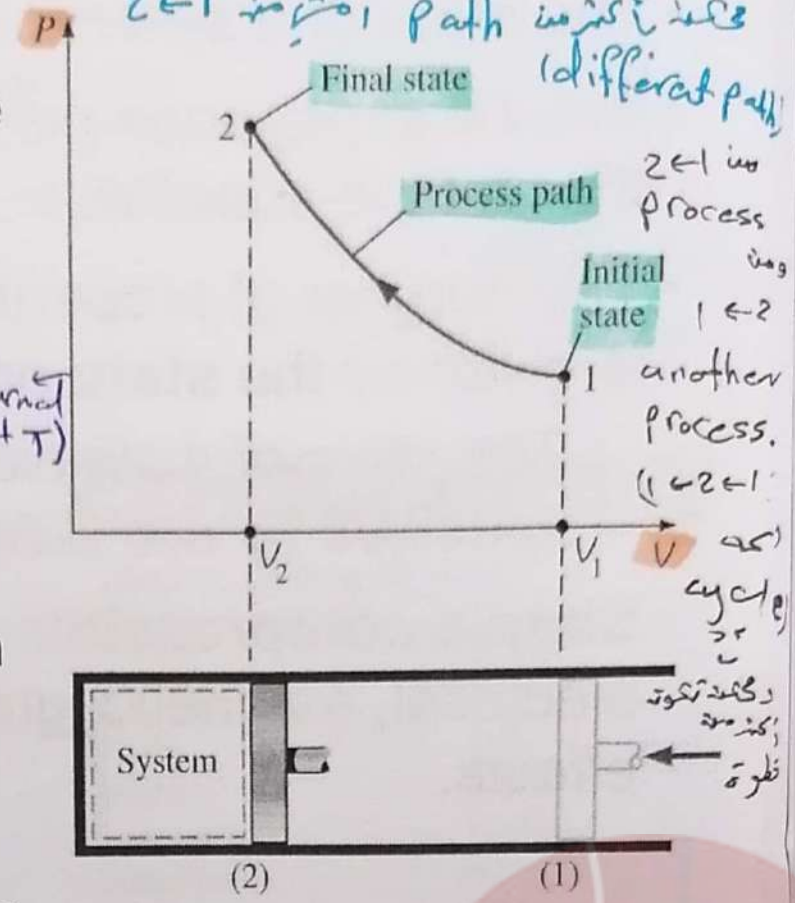
1) During a quasi-equilibrium (slow) process, the system remains practically at equilibrium at all times.
2) They are Easier to analyze (equations of state can apply).
3) Work-producing devices deliver the most work.
4) Work-consuming devices consume the least amount of work.



CamScanner الممسوحة ضوئيا بـ

PROCESSES AND CYCLES-2

- Process diagrams plotted by employing thermodynamic properties as coordinates are very useful in visualizing the processes.
- Some common properties that are used as coordinates are temperature T, pressure P, and volume V (or specific volume v).
- The prefix ***iso***- is often used to designate a process for which a particular property remains constant.
- **Isothermal process**: A process during which the temperature T remains constant.
- **Isobaric process**: A process during which the pressure P remains constant.
- **Isochoric (or isometric) process**: A process during which the specific volume v remains constant.
- **Cycle**: A process during which the initial and final states are identical.



The *P-V* diagram of a compression process.

The Steady-Flow Process

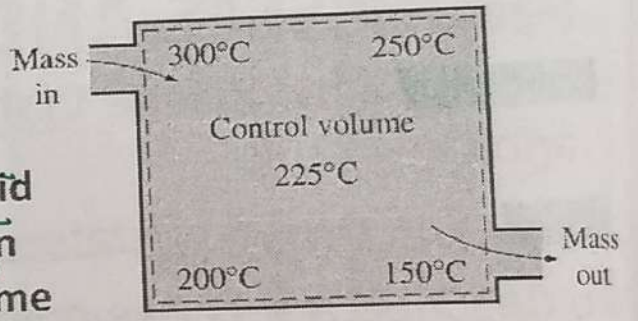
change with space → uniform

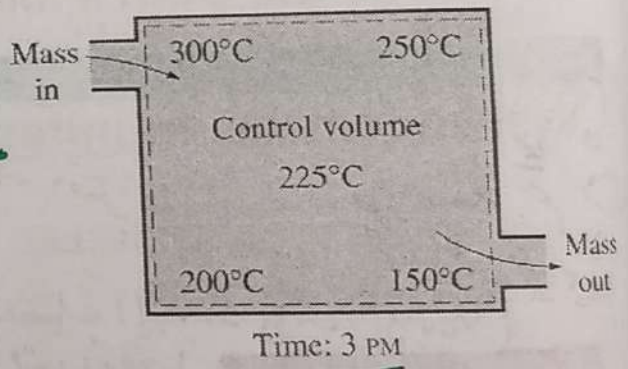
- The term *steady* implies *no change with time*. The opposite of steady is *unsteady*, or *transient*.
- A large number of engineering devices operate for long periods of time under the same conditions, and they are classified as *steady-flow devices*.
- **Steady-flow process**: A process during which a fluid flows through a control volume steadily.
- Steady-flow conditions can be closely approximated by devices that are intended for continuous operation such as turbines, pumps, boilers, condensers, and heat exchangers or power plants or refrigeration systems.

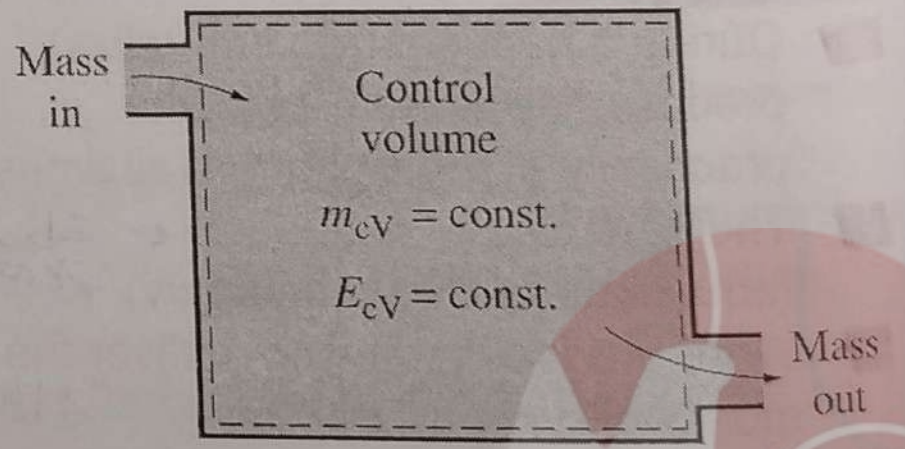
معظم اة اجهزة والمصانع تشتغل Steady state عند

During a steady-flow process, fluid properties within the control volume may change with position but not with time.

ما تتغير مع الزمن







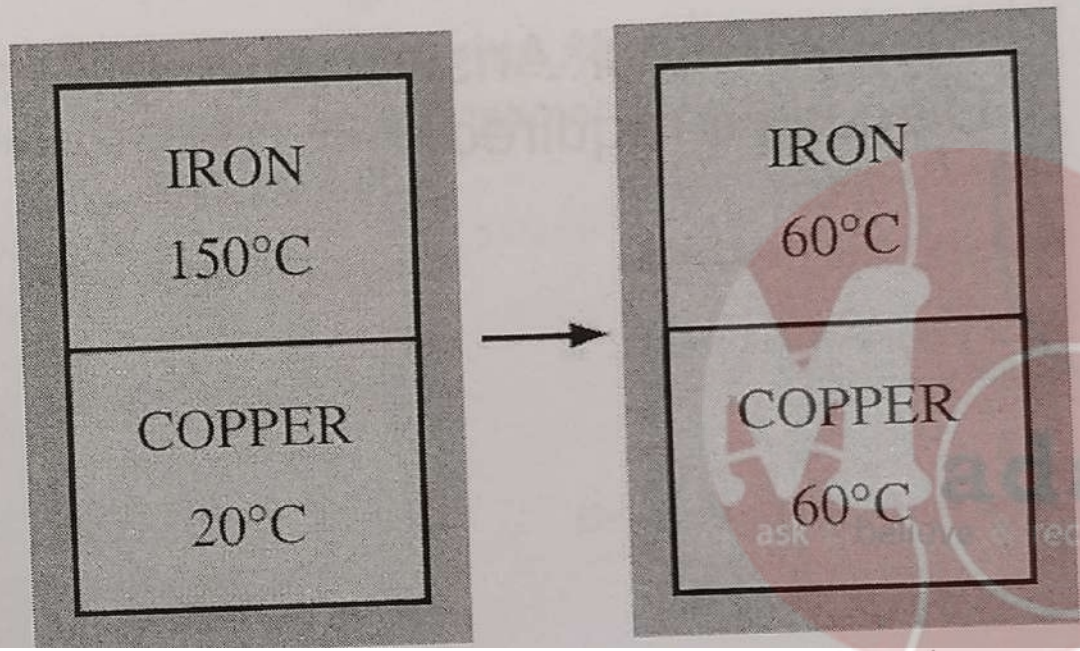
Under steady-flow conditions, the mass and energy contents of a control volume remain constant.

الممسوحة ضوئيا بـ CamScanner

TEMPERATURE AND THE ZEROTH LAW OF THERMODYNAMICS

thermal equilibrium نفس قانون ال

- **The zeroth law of thermodynamics**: If two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other.
- By replacing the third body with a thermometer, the zeroth law can be restated as *two bodies are in thermal equilibrium if both have the same temperature reading even if they are not in contact.*



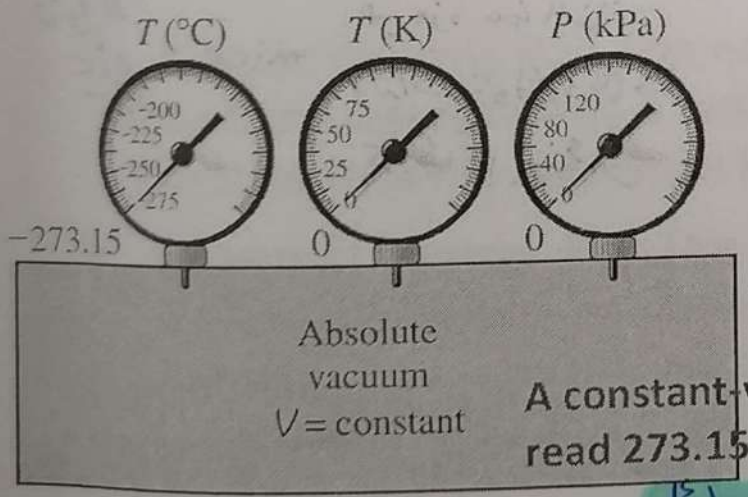
Two bodies reaching thermal equilibrium after being brought into contact in an isolated enclosure.

الممسوحة ضوئيا بـ CamScanner

absolute temp scale less relative temp scale

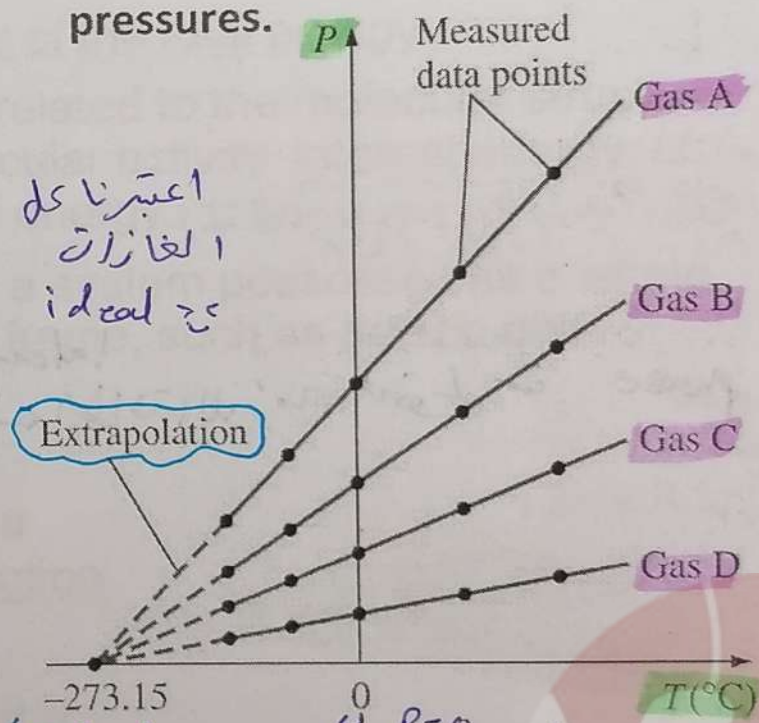
Temperature Scales

- All temperature scales are based on some easily reproducible states such as the freezing and boiling points of water: the *ice point* and the *steam point.*
- **Thermodynamic temperature scale**: A temperature scale that is independent of the properties of any substance.
- **Kelvin scale** (SI)
- A temperature scale nearly identical to the Kelvin scale is the **ideal-gas temperature scale**. The temperatures on this scale are measured using a constant-volume gas thermometer.



A constant-volume gas thermometer would read 273.15°C at absolute zero pressure.

P versus T plots of the experimental data obtained from a constant-volume gas thermometer using four different gases at different (but low) pressures.



CamScanner الممسوحة ضوئيا بـ

Forms of Energy

- Energy can exist in numerous forms such as thermal, mechanical, kinetic, potential, electric, magnetic, chemical, and nuclear, and their sum constitutes the total energy, E of a system.
- Thermodynamics deals with the *change* of the total energy.
- **Microscopic forms of energy**: Those related to the molecular structure of a system and the degree of the molecular activity. Internal energy, U: The sum of all the microscopic forms of energy.
- **Macroscopic forms of energy**: Those a system possesses as a whole with respect to some outside reference frame, such as *kinetic and potential energies*.

- **Kinetic energy, KE**: The energy that a system possesses as a result of its motion relative to some reference frame.
- **Potential energy, PE**: The energy that a system possesses as a result of its elevation in a gravitational field.

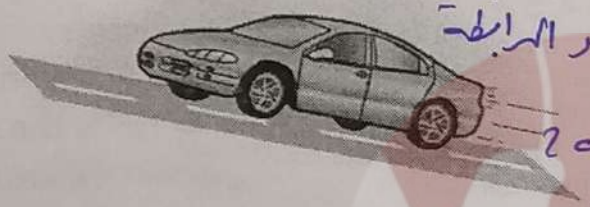


FIGURE 2–4
The macroscopic energy of an object changes with velocity and elevation.

CamScanner الممسوحة ضوئيا بـ

Energy ... numerous forms:

- Thermal
- Mechanical
- Kinetic
- Potential
- Electric
- Magnetic
- Chemical
- Nuclear

Their sum constitutes the total energy, E of a system

The total energy of a system on a unit mass:

$$e = \frac{E}{m} \quad (kJ/kg)$$

Those related to the molecular structure of a system and the degree of the molecular activity.

Internal energy, U

The sum of all the microscopic forms of energy.

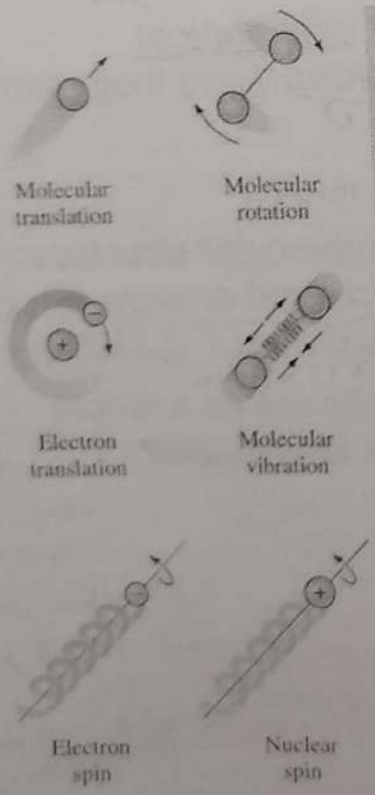
Kinetic energy, KE

The energy that a system possesses as a result of its motion relative to some reference frame.

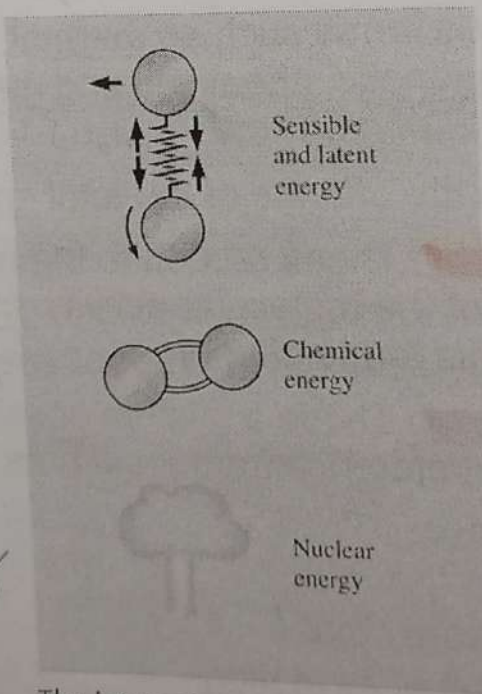
Potential energy, PE

The energy that a system possesses as a result of its elevation in a gravitational field.

Some Physical Insight to Internal Energy



The various forms of microscopic energies that make up ***sensible*** **energy.**



The internal energy of a system is the sum of all forms of the ***microscopic energies***.

Sensible energy: The portion of the internal energy of a system associated with the kinetic energies of the molecules.

Latent energy: The internal energy associated with the phase of a system.

Chemical energy: The internal energy associated with the atomi bonds in a molecule.

Nuclear energy: The tremendous amount of energy associated wit the strong bonds within the nucleus of the atom itself.

Thermal = Sensible + Latent

Internal = Sensible + Latent + Chemical + Nuclear

CamScanner الممسوحة ضوئيا بـ

* heat & work not properties for the sys (فقط process اثناء نظهر)

Energy of A System

*KE, PE & IE → are properties for the sys

1) The **total energy of a system**, can be *contained* or ***stored*** in a system, and thus can be viewed as the ***static* forms of energy**. like PE, KE, IE

2) The forms of energy ***not stored*** in a system can be viewed as the ***dynamic* forms of energy** or as ***energy interactions***. like heat & work

- ❑ The dynamic forms of energy are recognized at the system boundary as they cross it, and they represent the *energy gained or lost by a system during a process.* (عكزنه sys واثناء نظهرها boundary)
- ❑ The only two forms of energy interactions associated with a **closed system** are **heat transfer** and **work**.

3) The difference between **heat transfer** and **work:**

An energy interaction is heat transfer if its driving force is a temperature difference. Otherwise, it is work.

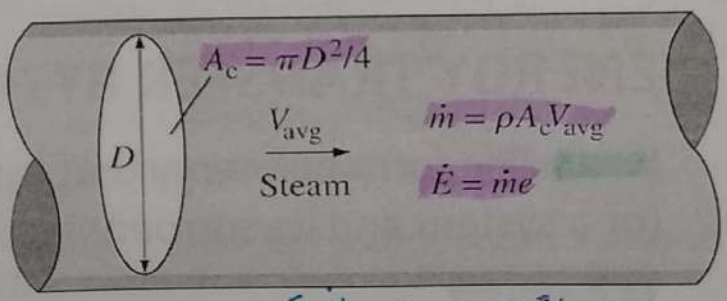
-: work اذا

1-piston rising (piston حركة)
2- rotation like mixers
3- wire passes through current

5

Energy of A System

(not energy balance)



Capital letter : tot energy
small : per unit mass

$$KE = m\frac{V^2}{2} \quad (kJ)$$ **Kinetic energy**

$$ke = \frac{V^2}{2} \quad (kJ/kg)$$ **Kinetic energy per unit mass**

$$PE = mgz \quad (kJ)$$ **Potential energy**

$$pe = gz \quad (kJ/kg)$$ **Potential energy per unit mass**

$$E = U + KE + PE = U + m\frac{V^2}{2} + mgz \quad (kJ)$$ **Total energy of a system**

Mass flow rate ← energy flow rate

$$\dot{m} = \rho\dot{V} = \rho A_c V_{avg} \quad (kg/s)$$

volume flow rate

Energy flow rate

$$\dot{E} = \dot{m}e \quad (kJ/s \text{ or } kW)$$

$A_c = \pi D^2/4$

$V_{avg} = \frac{\dot{V}}{A_c}$

الممسوحة ضوئيا بـ CamScanner

Energy of A System

(not energy balance)

Capital letter : tot energy
small " : per unit mass

$$KE = m\frac{V^2}{2} \quad (kJ)$$ Kinetic energy

$$ke = \frac{V^2}{2} \quad (kJ/kg)$$ Kinetic energy per unit mass

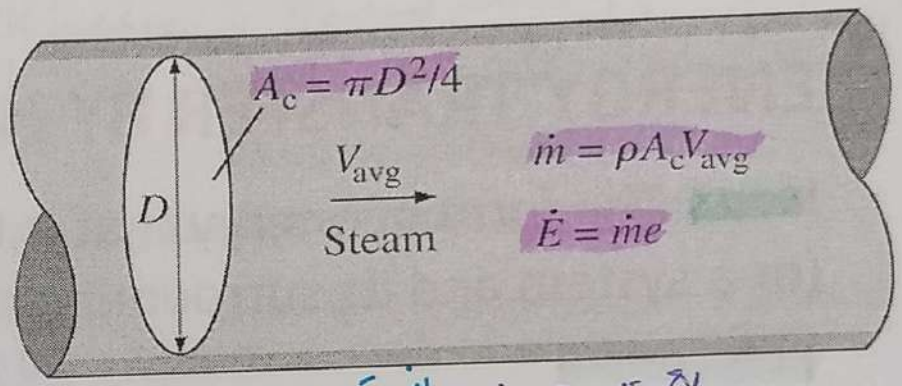
$$PE = mgz \quad (kJ)$$ Potential energy

$$pe = gz \quad (kJ/kg)$$ Potential energy per unit mass

$$E = U + KE + PE = U + m\frac{V^2}{2} + mgz \quad (kJ)$$ Total energy of a system

$$e = u + ke + pe = u + \frac{V^2}{2} + gz \quad (kJ/kg)$$ Energy of a system per unit mass

$$e = \frac{E}{m} \quad (kJ/kg)$$ Total energy per unit mass



Mass flow rate

$$\dot{m} = \rho\dot{V} = \rho A_c V_{avg} \quad (kg/s)$$

Energy flow rate

$$\dot{E} = \dot{m}e \quad (kJ/s \text{ or } kW)$$

ask : believe & recieve

الممسوحة ضوئيا بـ CamScanner

$$e = \frac{E}{m} \qquad (\text{kJ/kg})$$

Mechanical Energy

- **Mechanical energy:** The form of energy ***that can be converted to mechanical work completely*** and directly by an ideal mechanical device such as an ideal turbine.
- **Kinetic and potential energies:** The **familiar forms** of mechanical energy.

$$e_{\text{mech}} = \frac{P}{\rho} + \frac{V^2}{2} + gz$$

Mechanical energy of a flowing fluid per unit mass

$$\dot{E}_{\text{mech}} = \dot{m}e_{\text{mech}} = \dot{m}\left(\frac{P}{\rho} + \frac{V^2}{2} + gz\right)$$

Rate of mechanical energy of a flowing fluid

Mechanical energy change of a fluid during incompressible flow per unit mass

$$\Delta e_{\text{mech}} = \frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \qquad (\text{kJ/kg})$$

= rate of change

Rate of mechanical energy change of a fluid during incompressible flow

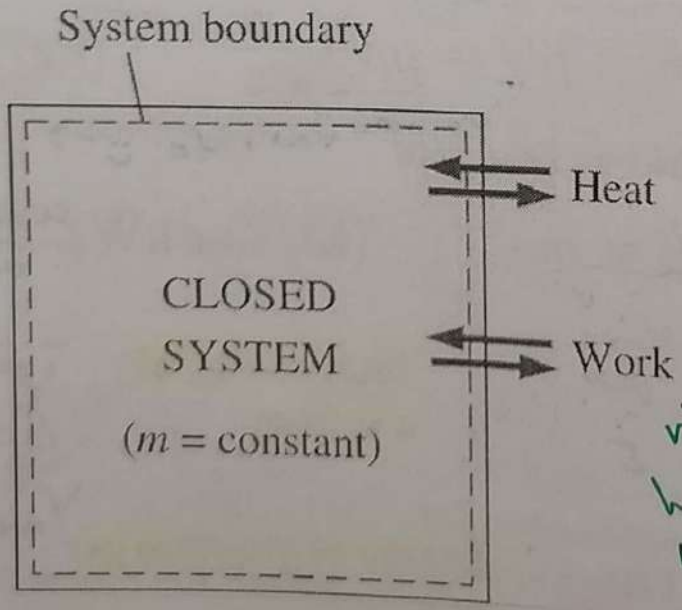
$$\Delta \dot{E}_{\text{mech}} = \dot{m}\Delta e_{\text{mech}} = \dot{m}\left(\frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right) \qquad (\text{kW})$$

(small P ∵) ≠ property of pressure

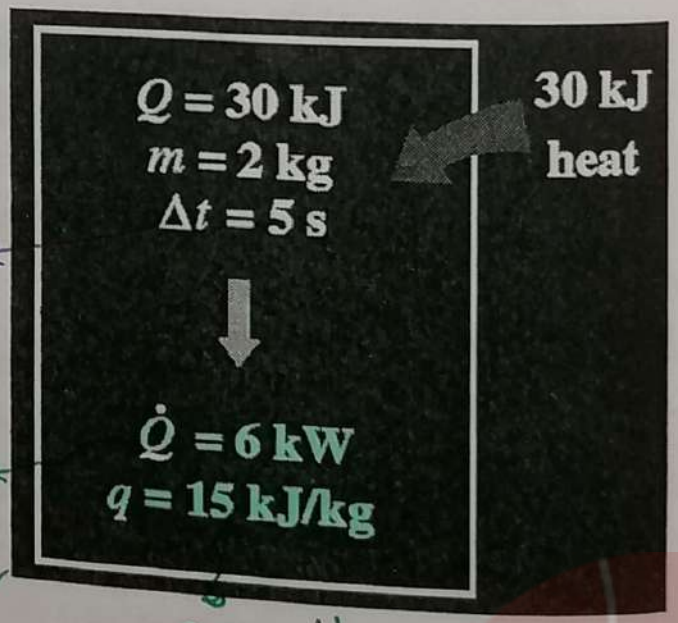
CamScanner الممسوحة ضوئيا بـ

ENERGY TRANSFER BY HEAT

Heat: The form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a *temperature difference.*



Energy can cross the boundaries of a closed system in the form of **heat** and **work.**



Heat transfer is expressed both:

- As time rate (kJ/s or KW), and
- As specific heat transfer, kJ/kg of system mass

heat & work can be express in two ways

ENERGY TRANSFER BY HEAT

$$q = \frac{Q}{m} \quad (\text{kJ/kg})$$

Heat transfer per unit mass

$$Q = \dot{Q}\,\Delta t \quad (\text{kJ})$$

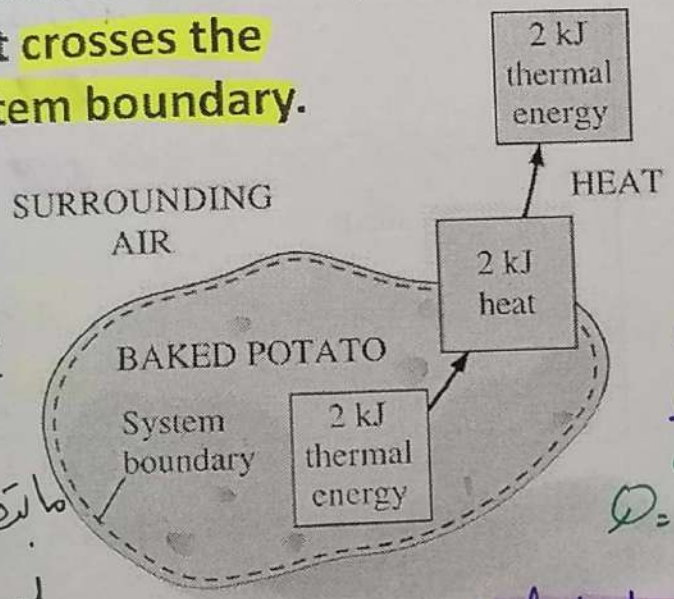
Amount of heat transfer when heat transfer rate is constant

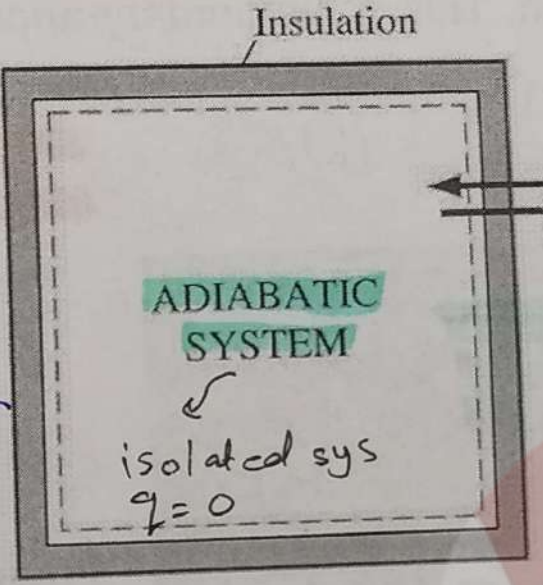
rate of heat transfer or specific heat

$$Q = \int_{t_1}^{t_2} \dot{Q}\,dt \quad (\text{kJ})$$

Amount of heat transfer when heat transfer rate changes with time

Energy is recognized as heat transfer only as it crosses the system boundary.





During an adiabatic process, a system exchanges no heat with its surroundings.

adiabatic = isentropic

CamScanner الممسوحة ضوئيا بـ

Kinetic & thermal energy مرتبطة
اذا كانت الحرارة قليلة في تفاعل

Historical Background on Heat

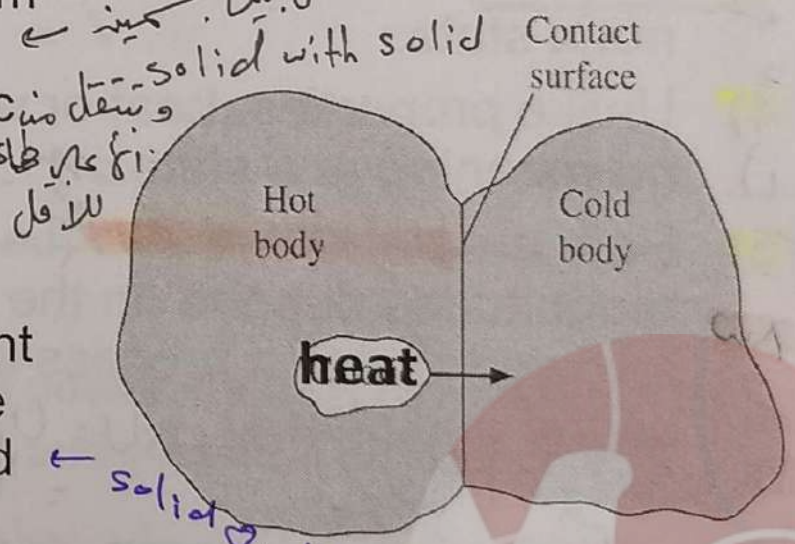
طاقة حركية
- **Kinetic theory**: Treats molecules as tiny balls that are in motion and thus possess kinetic energy.
  ال molecule
- **Heat**: The energy associated with the random motion of atoms and molecules.

كيف تنتقل الحرارة من ال sys لل surrounding والعكس!

Heat transfer mechanisms:

by 3 mechanisms :-

1. **Conduction**: The transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interaction between particles.
   انتقال بين جسمين ← solid with solid وتنتقل من الأعلى طاقة للأقل
2. **Convection**: The transfer of energy between a solid surface and the adjacent fluid that is in motion, and it involves the combined effects of conduction and fluid motion.
   الحمل الحرارة ← solid & liq phase
   فوتونات وانكاءات
3. **Radiation**: The transfer of energy due to the emission of electromagnetic waves (or photons). at high tem



(واحد بكون بارد وواحد بكون ساخن) السطح ساخن وننزل عليه بفلويد أو الفلويد ساخن بخلي السطح ساخن

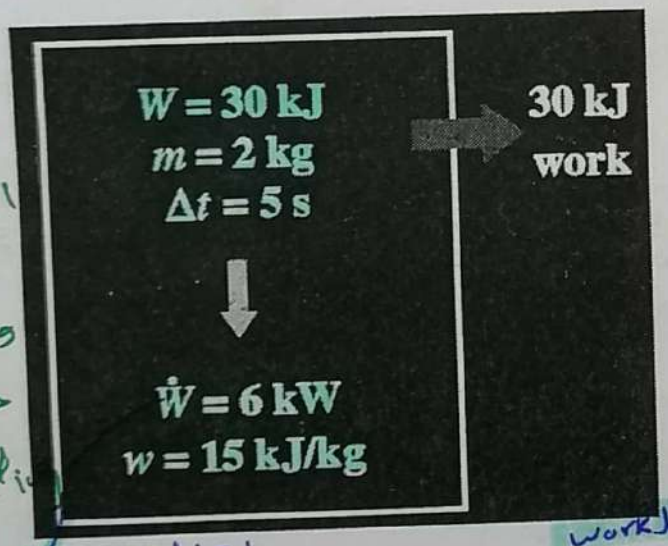
CamScanner الممسوحة ضوئيا بـ

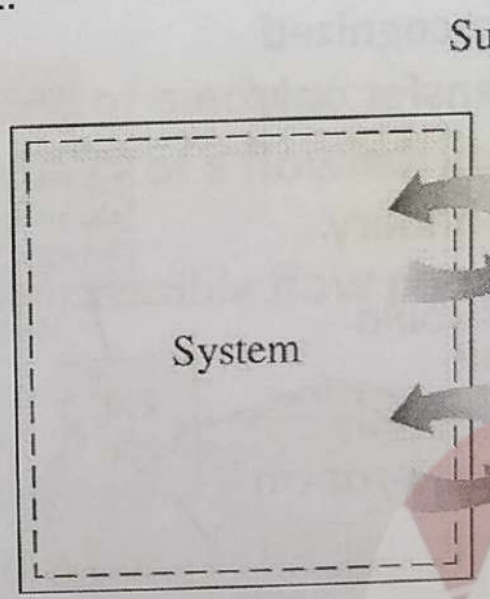
ENERGY TRANSFER BY WORK

- **Work:** The energy transfer associated with a force acting through a distance.
- **A rising piston, a rotating shaft, and an electric wire crossing the system boundaries** are all associated with work interactions
- **Formal sign convention**: *Heat transfer to a system and work done by a system are positive; heat transfer from a system and work done on a system are negative.*
- **Alternative to sign convention** is to use the subscripts ***in*** and ***out*** to indicate direction. This is the primary approach in this text.

$$w = \frac{W}{m} \qquad (\text{kJ/kg})$$

Work done per unit mass





Specifying the directions of heat and work.

Power is the work done per unit time (kW)

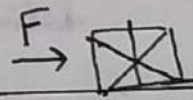
$$\dot{W} = \frac{\delta W}{\delta t}$$

$$\dot{W} = \frac{dW}{dt}$$

$$\dot{W} = F \cdot V$$

$$dW = F\,dL$$

$$W = \int F\,dL$$



heat and work.

rate of work transfer = power

$dW = F\,dL$ (function) — أول تعريف للـ work

$W = \int F\,dL$ (for solid)

Heat and Work مقارنة بينهم

1) Both are recognized at the boundaries of a system as they cross the boundaries. That is, both heat and work are *boundary* phenomena.

2) Systems possess energy, but **not** heat or work.

3) Both are associated with a *process*, not a state.

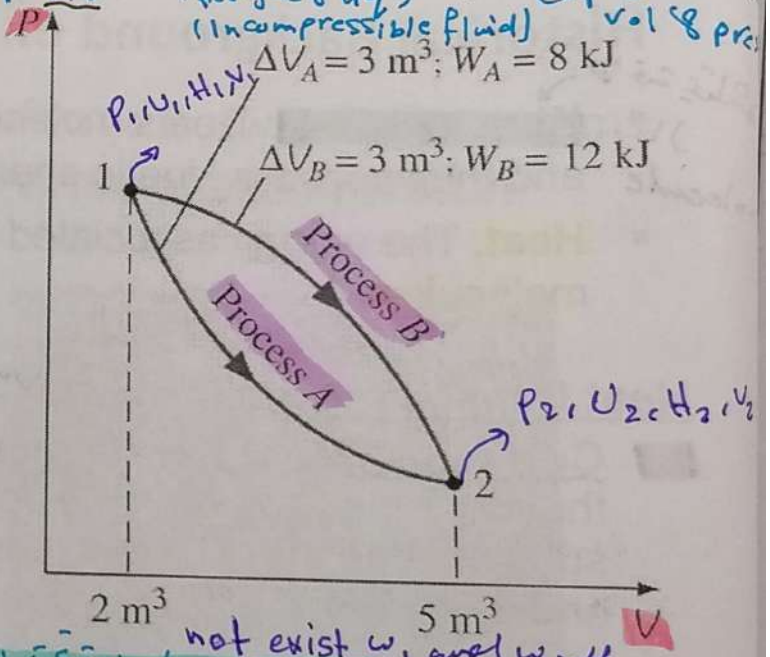
4) Unlike properties, heat or work has no meaning at a state.

5) Both are *path functions* (i.e., their magnitudes depend on the path followed during a process as well as the end states).

$dW = P(A\,dL)$

$W = \int P\,dV$ (for gas & liq) (incompressible fluid)

for gas we express it with vol & pressure



Properties are point functions; but heat and work are path functions (their magnitudes depend on the path followed).

not exist w_1 and w_2 — الـ work مش بالحالة دي

curve يتكون w_{12}

$\Delta U = U_2 - U_1 = \int_{P_1}^{P_2} dP$

w_1 & w_2 q_1 & q_2 ✗

$$\int_1^2 dV = V_2 - V_1 = \Delta V$$

تفاضل كامل

$$\int_1^2 \delta W = W_{12} \quad (not\ \Delta W)$$

inexact يعني تفاضل غير تامة

Properties are point functions; they have exact differentials (d)

Path functions have inexact differentials (δ)

الممسوحة ضوئيا بـ CamScanner

Forms of Work

❑ **Various forms of work are expressed as follows:**

› ***Electrical work:***
$$W_e = VI\Delta t \quad \textbf{(kJ)}$$

› ***Boundary work:*** or (flow work)
$$W_b = \int_1^2 P dV$$

› ***Gravitational work*** **(= ΔPE):**
$$W_g = mg(z_2 - z_1)$$

› ***Acceleration work*** **(= ΔKE):**
$$W_a = \frac{1}{2} m(\vec{V}_2^2 - \vec{V}_1^2)$$

› ***Shaft (stirring) work:***
$$W_{sh} = 2\pi n \tau$$

› ***Spring work:***
$$W_{spring} = \frac{1}{2} k(x_2^2 - x_1^2)$$

CamScanner الممسوحة ضوئيا بـ

قانون أوم: التيار يتناسب طردياً مع فرق الجهد أي يعني ← طاقة كهربائية

$V = IR$ ∴

Electrical Work

Electrical work — كمية الكهرباء

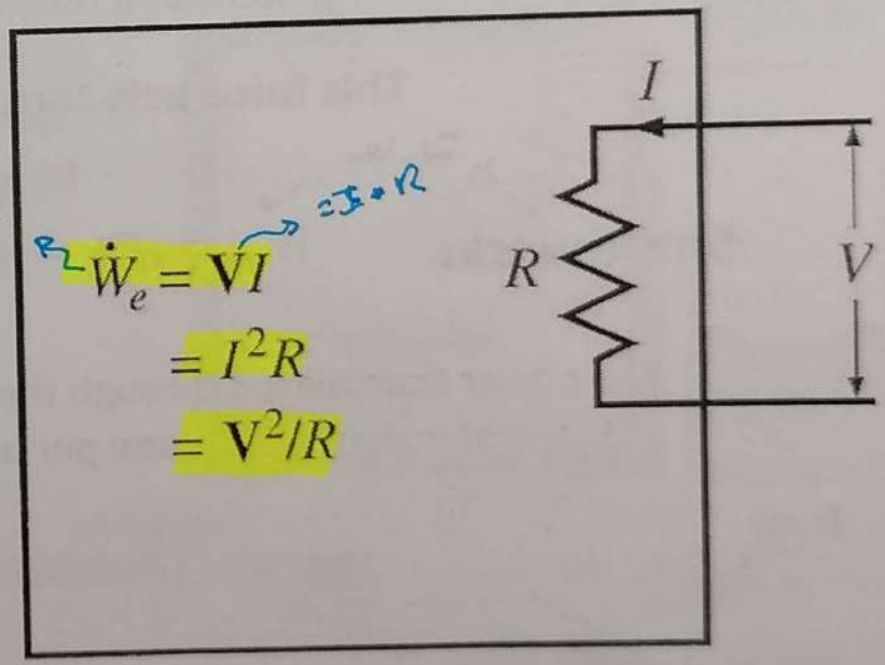
$$W_e = VN$$

V: voltage (volt)

Electrical power

$$\dot{W}_e = VI \quad (W)$$

I: current (A)



$\dot{W}_e = VI = I \cdot R$

$= I^2R$

$= V^2/R$

قسمنا على الزمن

When potential difference and current change with time

$$W_e = \int_1^2 VI\,dt \quad (kJ)$$

dt: In second

When potential difference and current remain constant

$$W_e = VI\,\Delta t \quad (kJ)$$

Electrical power in terms of resistance R, current I, and potential difference V.

→ N = coulombs of electrons move through a potential difference V

$N = I \cdot \Delta t$ ←

1 coulomb = 1 Ampere * 1 second

ohm's law: $V = I * R$

1 Joule = 1 Volt * 1 coulomb

قاس بالكولوم — قانون فاراداي: كمية الكهرباء = التيار * الزمن

$Q = I t$

[Colomb] = A * Sec

Qadar recieve

الممسوحة ضوئيا بـ CamScanner

MECHANICAL FORMS OF WORK

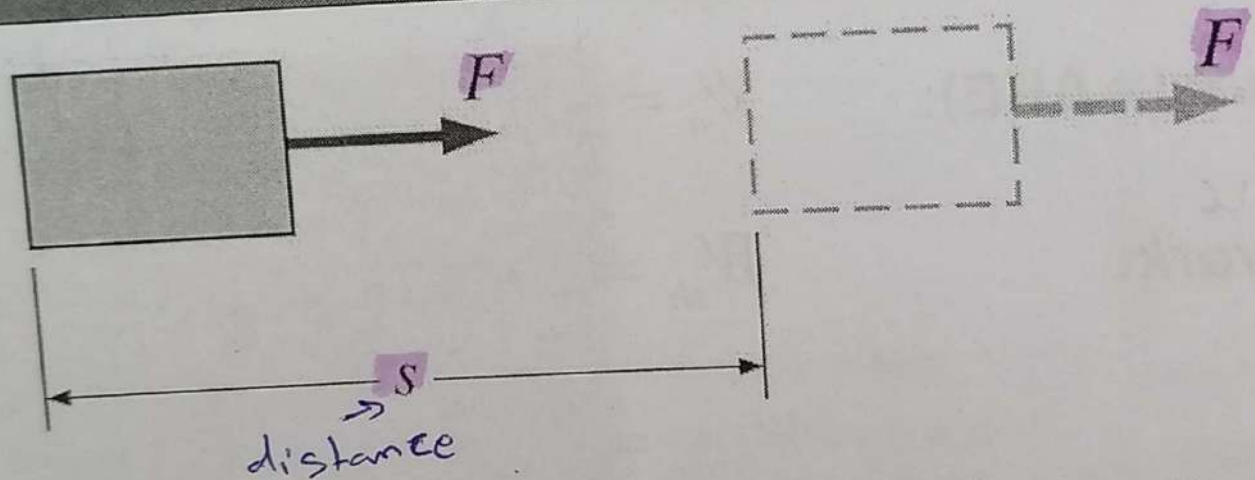
- There are two requirements for a work interaction between a system and its surroundings to exist:
  - there must be a ***force*** acting on the boundary.
  - the boundary must ***move***.

Work = Force × Distance

$$W = Fs \qquad \text{(kJ)}$$

When force is not constant

$$W = \int_1^2 F\, ds \qquad \text{(kJ)}$$



The work done is proportional to the force applied (*F*) and the distance traveled (*s*).

CamScanner الممسوحة ضوئيا بـ

قانون أوم: التيار يتناسب طردياً مع فرق الجهد أي يعني ← طاقة كهربائية

$V = IR$ ∴

Electrical Work

Electrical work — كمية الكهرباء

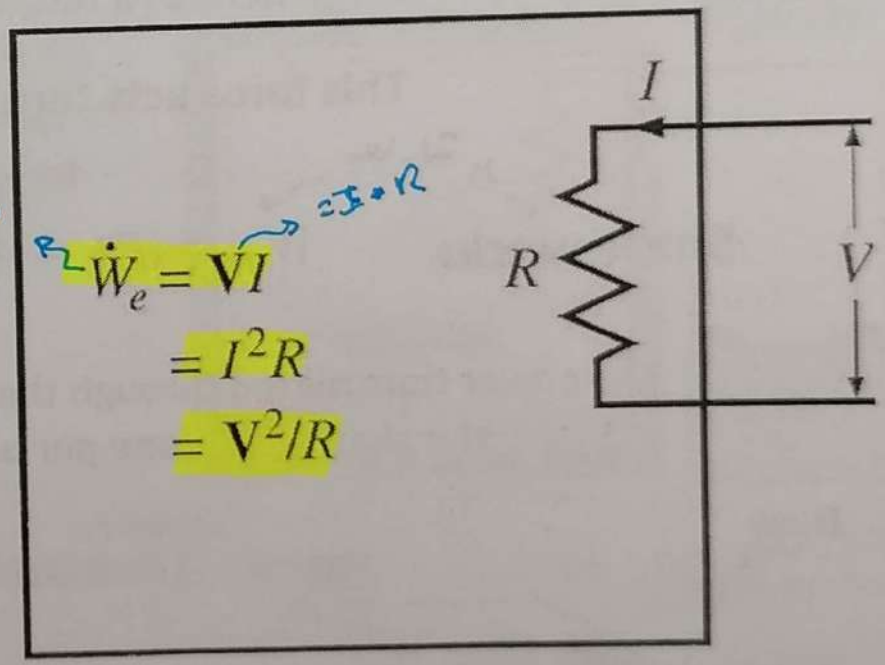
$$W_e = VN$$

V: voltage (volt)

Electrical power

$$\dot{W}_e = VI \quad (W)$$

I: current (A)



$\dot{W}_e = VI = I \cdot R$

$= I^2R$

$= V^2/R$

قسمنا على الزمن

When potential difference and current change with time

$$W_e = \int_1^2 VI\,dt \quad (kJ)$$

dt: In second

When potential difference and current remain constant

$$W_e = VI\,\Delta t \quad (kJ)$$

Electrical power in terms of resistance R, current I, and potential difference V.

→ N = coulombs of electrons move through a potential difference V

$N = I \cdot \Delta t$ ←

1 coulomb = 1 Ampere * 1 second

ohm's law: $V = I * R$

1 Joule = 1 Volt * 1 coulomb

قاس بالكولوم — قانون فاراداي: كمية الكهرباء = التيار * الزمن

$Q = I t$

[Colomb] = A * Sec

Qadar recieve

الممسوحة ضوئيا بـ CamScanner

Shaft Work

A force F acting through a moment arm r generates a torque T

$$T = Fr \quad \rightarrow \quad F = \frac{T}{r}$$

This force acts through a distance s

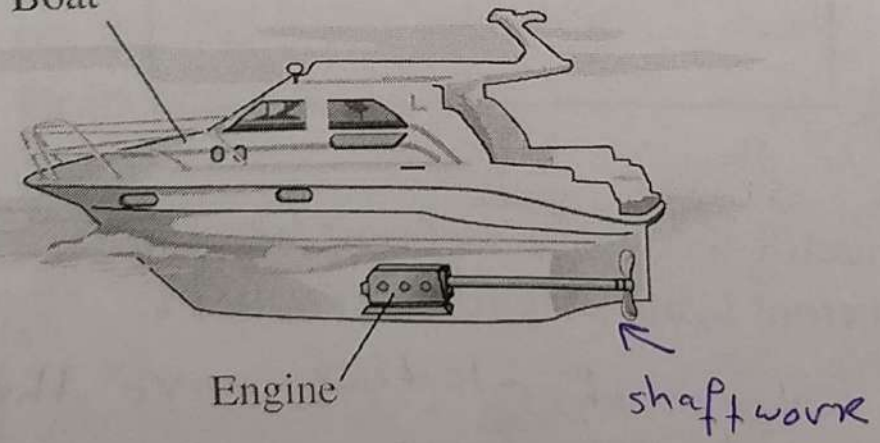
$$s = (2\pi r)n$$

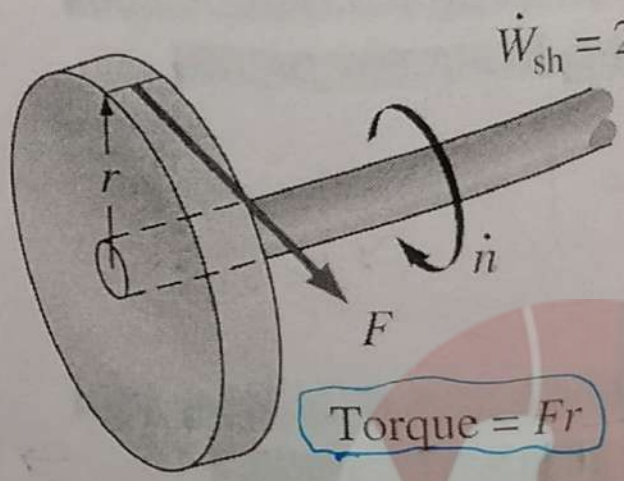
Shaft work:

$$W_{sh} = Fs = \left(\frac{T}{r}\right)(2\pi r n) = 2\pi n T \quad \text{(kJ)}$$

The power transmitted through the shaft is the shaft work done per unit time

$$\dot{W}_{sh} = 2\pi \dot{n} T \quad \text{(kW)}$$





Energy transmission through rotating shafts is commonly encountered in practice.

Shaft work is proportional to the torque applied and the number of revolutions of the shaft.

CamScanner الممسوحة ضوئيا بـ

THE FIRST LAW OF THERMODYNAMICS

- The *first law of thermodynamics* (***the conservation of energy principle***) provides a sound basis for studying the relationships among the various forms of energy and energy interactions.
- The first law states that ***energy can be neither created nor destroyed during a process; it can only change forms.***
- The *First Law*: For all adiabatic processes between two specified states of a closed system, the net work done is the same regardless of the nature of the closed system and the details of the process.

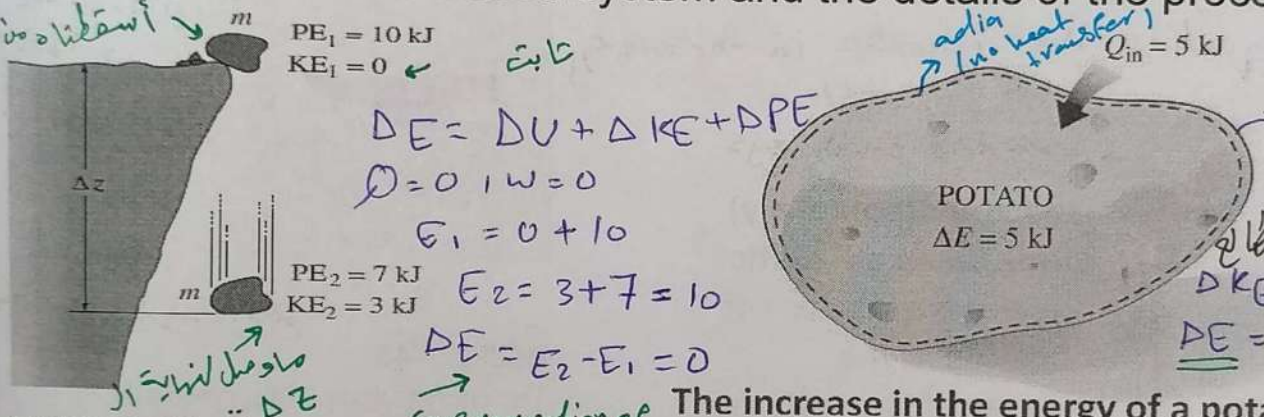
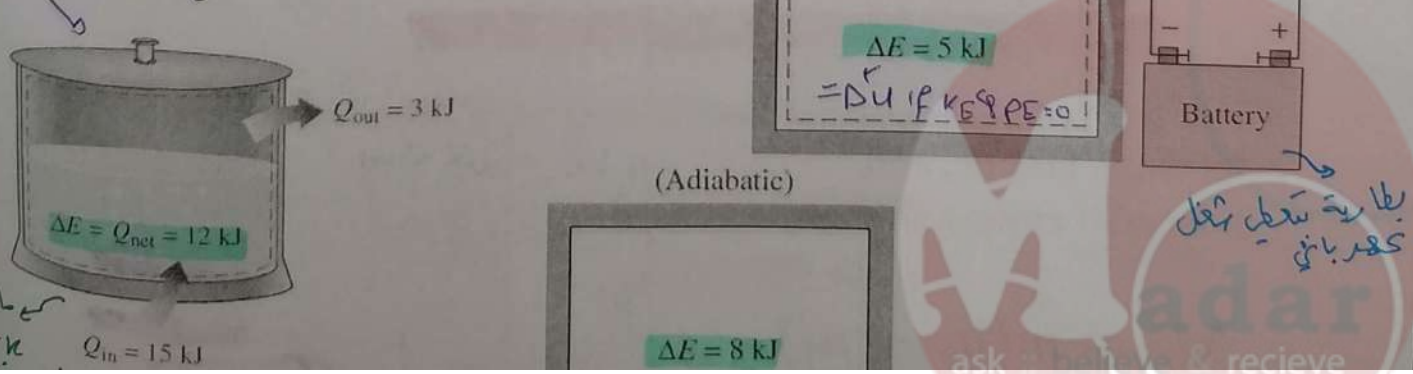


FIGURE 2–39
Energy cannot be created or destroyed; it can only change forms.

The increase in the energy of a potato in an oven is equal to the amount of heat transferred to it.

THE FIRST LAW OF THERMODYNAMICS

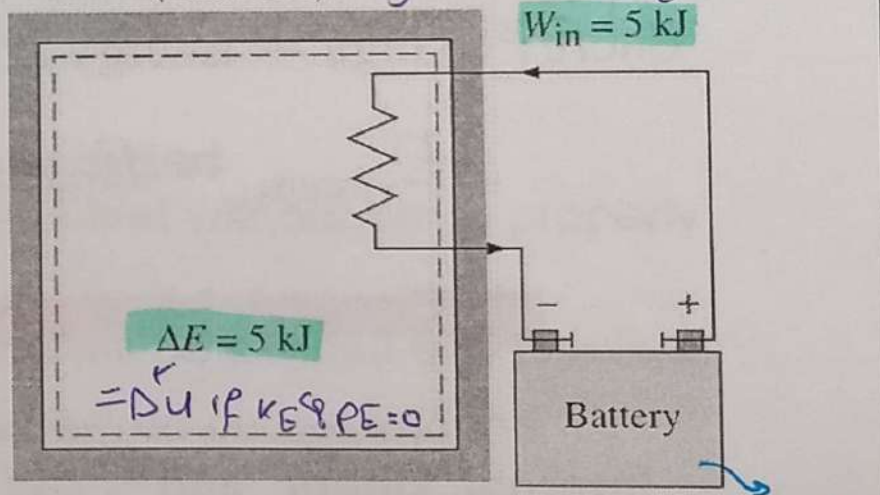
The work (electrical) done on an adiabatic system is equal to the increase in the energy of the system.



CamScanner الممسوحة ضوئيا بـ

THE FIRST LAW OF THERMODYNAMICS

The work (electrical) done on an adiabatic system is equal to the increase in the energy of the system.



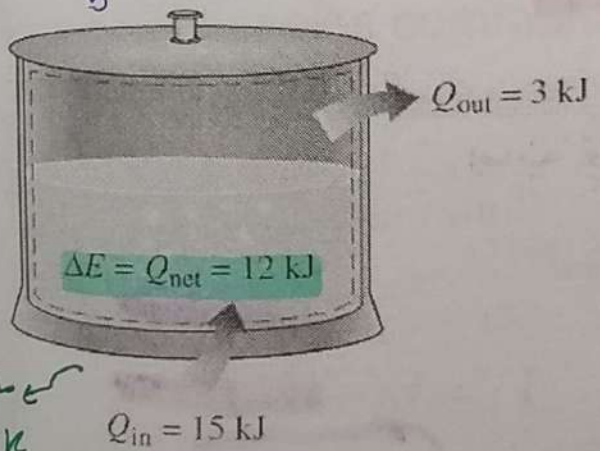
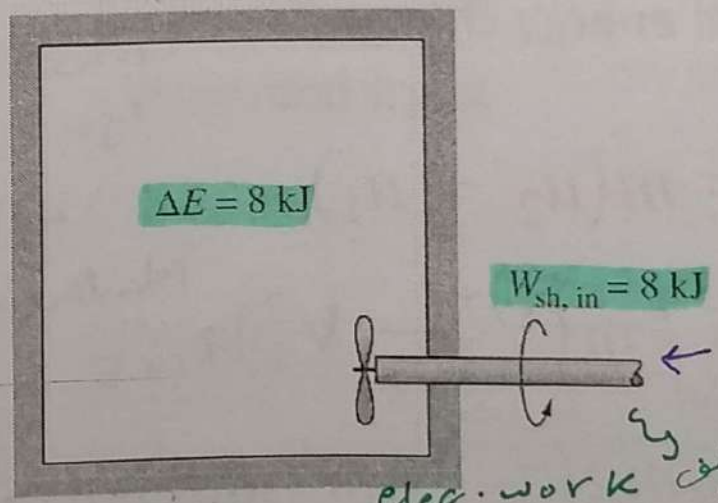


FIGURE 2–41
In the absence of any work interactions, the energy change of a system is equal to the net heat transfer.



The work (shaft) done on an adiabatic system is equal to the increase in the energy of the system.

CamScanner الممسوحة ضوئيا بـ

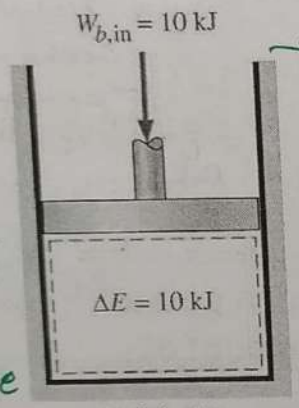
Energy Balance

*The net change (increase or decrease) in the **total energy** of the system during a process is equal to the difference between the total energy entering and the total energy leaving the system during that process.*

$$\begin{pmatrix}\text{Total energy}\\ \text{entering the system}\end{pmatrix} - \begin{pmatrix}\text{Total energy}\\ \text{leaving the system}\end{pmatrix} = \begin{pmatrix}\text{Change in the total}\\ \text{energy of the system}\end{pmatrix}$$

$$E_{in} - E_{out} = \Delta E_{system}$$

The boundary work done on an adiabatic sys is equal to the increase in the energy of the system



work done on the sys

The work (boundary) done on an adiabatic system is equal to the increase in the energy of the system.

$\Delta E = \Delta U = Q - W$

$0 - (-10) = 10$

OR: $\Delta E = \Delta U = W_{in} - W_{out}$

$= 10 - 0$

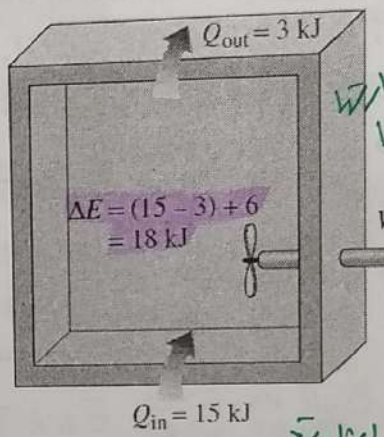


FIGURE 2–45
The energy change of a system during a process is equal to the *net* work and heat transfer between the system and its surroundings.

Energy Change of a System, ΔE_{system}

Energy change = Energy at final state − Energy at initial state

$$\Delta E_{system} = E_{final} - E_{initial} = E_2 - E_1$$

$$\Delta E = \Delta U + \Delta KE + \Delta PE$$

Internal, kinetic, and potential energy changes

$$\Delta U = m(u_2 - u_1)$$

$$\Delta KE = \frac{1}{2}m(V_2^2 - V_1^2)$$

Stationary Systems

$z_1 = z_2 \rightarrow \Delta PE = 0$

$V_1 = V_2 \rightarrow \Delta KE = 0$

$\Delta E = \Delta U$

ask recieve

الممسوحة ضوئيا بـ CamScanner

Energy Change of a System, ΔE_{system}

Energy change = Energy at final state − Energy at initial state

$$\Delta E_{system} = E_{final} - E_{initial} = E_2 - E_1$$

$$\Delta E = \Delta U + \Delta KE + \Delta PE$$

Internal, kinetic, and potential energy changes

$$\Delta U = m(u_2 - u_1)$$

$$\Delta KE = \frac{1}{2}m(V_2^2 - V_1^2)$$

$$\Delta PE = mg(z_2 - z_1)$$

Stationary Systems

$z_1 = z_2 \rightarrow \Delta PE = 0$

$V_1 = V_2 \rightarrow \Delta KE = 0$

$\Delta E = \Delta U$

Nadar ask & believe & recieve

الممسوحة ضوئيا بـ CamScanner

$\Delta = \text{In} - \text{out}$

energy balance

$\Delta T = T_2 - T_1$

$\Delta P = P_2 - P_1$

Mechanisms of Energy Transfer, E_{in} and E_{out}

$$E_{in} - E_{out} = (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass,in} - E_{mass,out}) = \Delta E_{system}$$

energy balance

1) Heat transfer
2) Work transfer
3) Mass flow

just for open sys

A closed mass involves only *heat transfer* and work.

$$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic, potential, etc., energies}} \quad \text{(kJ)}$$

الطاقة المخزنة بالجسم ونتاجة بسبب الحركة

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} \quad \text{(kW)}$$

$$Q = \dot{Q}\,\Delta t \ \text{(kJ)} \qquad W = \dot{W}\,\Delta t \qquad \Delta E = (dE/dt)\,\Delta t$$

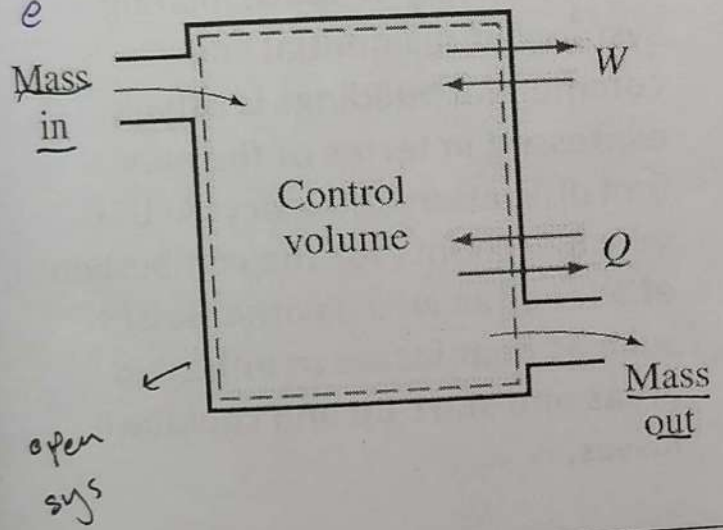
معدل تغير الـ energy

$$e_{in} - e_{out} = \Delta e_{system} \quad \text{(kJ/kg)}$$

energy per unit mass

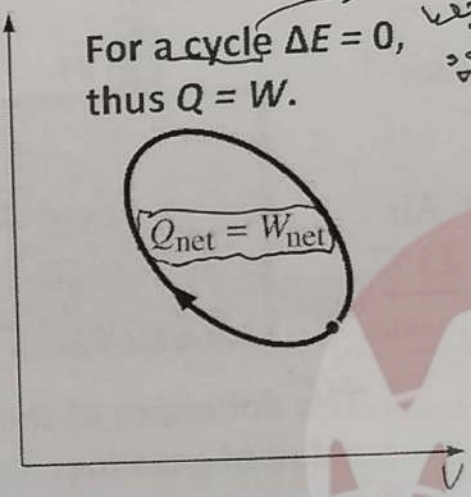
$$\delta E_{in} - \delta E_{out} = dE_{system} \qquad \delta e_{in} - \delta e_{out} = de_{system}$$

$$\dot{W}_{net,out} = \dot{Q}_{net,in} \quad \text{(for a cycle)}$$



open sys

The energy content of a control volume can be changed by mass flow as well as heat and work interactions.



For a cycle $\Delta E = 0$, thus $Q = W$.

كنا عند نقطة درجة عندما ...

ask recieve
CamScanner الممسوحة ضوئيا بـ

ENERGY CONVERSION EFFICIENCIES

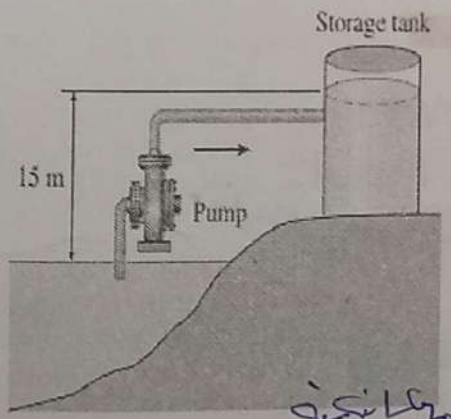
- *Efficiency* is one of the most frequently used terms in thermo-dynamics, and it indicates how well an energy conversion or transfer process is accomplished.
- *Efficiency* is also one of the most frequently misused terms in thermodynamics, because it is often used without being properly defined first.
- Some efficiencies commonly used in practice will be defined and clarified.
- *Efficiency* can be expressed in terms of the desired output and the required input as:

(In general equation) →

$$\text{Efficiency} = \frac{\text{Desired output}}{\text{Required input}}$$

← عم حطت مقارنة بالي حطيتيه

Example:



← رفعت الي من مكان لمكان عن طريق طاقة ميكانيكية

$$\eta_{\text{pump}} = \frac{\Delta \dot{E}_{\text{mech,fluid}}}{\dot{W}_{\text{shaft,in}}} = \frac{\dot{W}_{\text{pump},u}}{\dot{W}_{\text{pump}}}$$

useful

الـ shaftwork تحولت إلى طاقة ميكانيكية مخزنة بالي

ask & believe & recieve
الممسوحة ضوئيا بـ CamScanner

losses

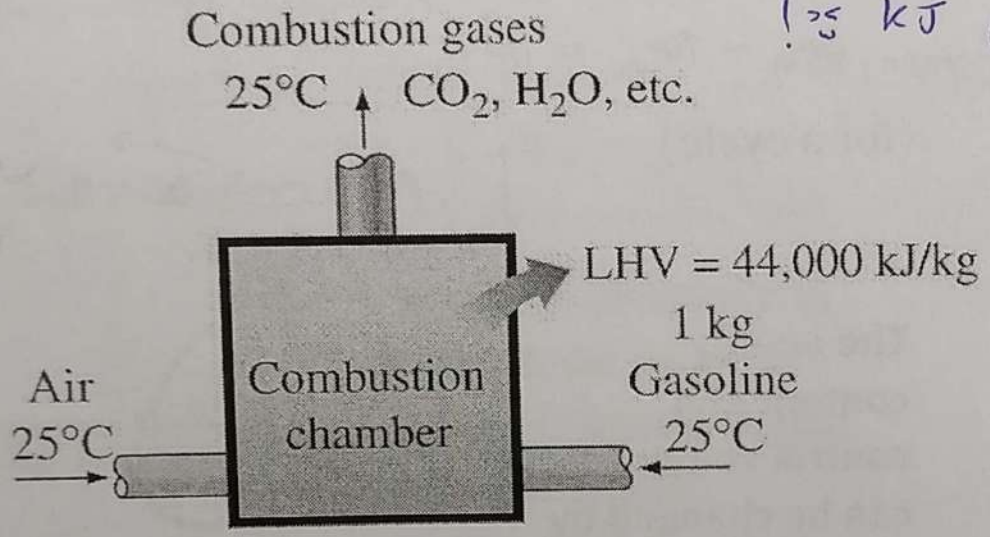
Combustion

$$\eta_{combustion} = \frac{Q}{HV} = \frac{\text{Amount of heat released during combustion}}{\text{Heating value of the fuel burned}}$$

Heating value of the fuel: The amount of heat released when a unit amount of fuel at room temperature is completely burned, and the combustion products are cooled to the room temperature.

Lower heating value (LHV): When the water leaves as a vapor.

Higher heating value (HHV): When the water in the combustion gases is completely condensed and thus the heat of vaporization is also recovered.

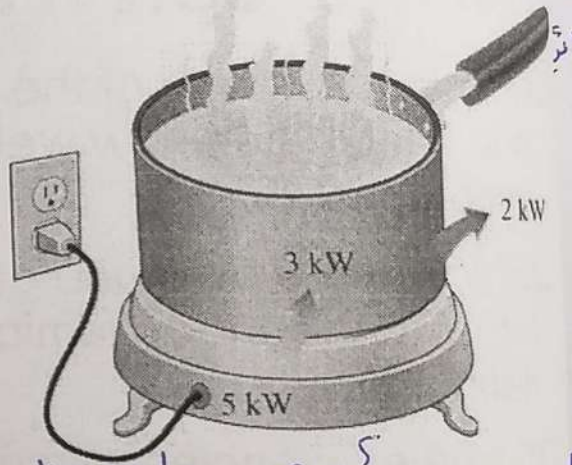


The definition of the heating value of gasoline.

The efficiency of space heating systems of residential and commercial buildings is usually expressed in terms of the annual fuel utilization efficiency (AFUE), which accounts for the combustion efficiency as well as other losses such as heat losses to unheated areas and start-up and cooldown losses.

CamScanner الممسوحة ضوئيا بـ

The efficiency of a **cooking appliance** represents the fraction of the energy supplied to the appliance that is transferred to the food.



$$\text{Efficiency} = \frac{\text{Energy utilized}}{\text{Energy supplied to appliance}}$$

$$= \frac{3\ \text{kWh}}{5\ \text{kWh}} = 0.60$$

Power Plants

- **Generator:** A device that converts mechanical energy to electrical energy.
- **Generator efficiency:** The ratio of the electrical power output to the mechanical power input.
- **Thermal efficiency of a power plant:**

  The ratio of the net electrical power output to the rate of fuel energy input:

$$\eta_{overall} = \eta_{combustion}\,\eta_{thermal}\,\eta_{generator} = \frac{\dot{W}_{net,electric}}{HHV \times \dot{m}_{fuel}}$$

$$\dot{W}_{net,mech} \times \frac{\dot{W}_{net,elect}}{\dot{W}_{net,mech}} =$$

CamScanner المسوحة ضوئيا بـ

Efficiencies of Mechanical and Electrical Devices

Mechanical efficiency

$$\eta_{mech} = \frac{\text{Mechanical energy output}}{\text{Mechanical energy input}} = \frac{E_{mech,out}}{E_{mech,in}} = 1 - \frac{E_{mech,loss}}{E_{mech,in}}$$

The effectiveness of the conversion process between the mechanical work supplied or extracted and the mechanical energy of the fluid is expressed by the pump efficiency and turbine efficiency:

$$\eta_{pump} = \frac{\text{Mechanical energy increase of the fluid}}{\text{Mechanical energy input}} = \frac{\Delta \dot{E}_{mech,fluid}}{\dot{W}_{shaft,in}} = \frac{\dot{W}_{pump,u}}{\dot{W}_{pump}}$$

$$\Delta \dot{E}_{mech,fluid} = \dot{E}_{mech,out} - \dot{E}_{mech,in}$$

$$\eta_{turbine} = \frac{\text{Mechanical energy output}}{\text{Mechanical energy decrease of the fluid}} = \frac{\dot{W}_{shaft,out}}{|\Delta \dot{E}_{mech,fluid}|} = \frac{\dot{W}_{turbine}}{\dot{W}_{turbine,e}}$$

$$|\Delta \dot{E}_{mech,fluid}| = \dot{E}_{mech,in} - \dot{E}_{mech,out}$$

$$\eta_{motor} = \frac{\text{Mechanical power output}}{\text{Electric power input}} = \frac{\dot{W}_{shaft,out}}{\dot{W}_{elect,in}}$$

Pump efficiency

$$\eta_{pump} = \frac{\dot{W}_{pump,u}}{\dot{W}_{shaft,in}} = \frac{\Delta \dot{E}_{mech,fluid}}{\dot{W}_{shaft,in}}$$

Generator efficiency

$$\eta_{generator} = \frac{\text{Electric power output}}{\text{Mechanical power input}} = \frac{\dot{W}_{elect,out}}{\dot{W}_{shaft,in}}$$

Pump-Motor overall efficiency

$$\eta_{pump-motor} = \eta_{pump}\eta_{motor} = \frac{\dot{W}_{pump,u}}{\dot{W}_{elect,in}} = \frac{\Delta \dot{E}_{mech,fluid}}{\dot{W}_{elect,in}}$$

Turbine-Generator overall efficiency

$$\eta_{turbine-gen} = \eta_{turbine}\eta_{generator} = \frac{\dot{W}_{elect,out}}{\dot{W}_{turbine,e}} = \frac{\dot{W}_{elect,out}}{|\Delta \dot{E}_{mech,fluid}|}$$

$\eta_{turbine} = 0.75 \quad \eta_{generator} = 0.97$

الممسوحة ضوئيا بـ CamScanner

$|\Delta E_{\text{mech,fluid}}|$ $E_{\text{mech,in}}$ $E_{\text{mech,out}}$

generator

useful work وبستفيد منه ... مش كل الـ shaft بعطينا

Motor efficiency

$$\eta_{\text{motor}} = \frac{\text{Mechanical power output}}{\text{Electric power input}} = \frac{\dot{W}_{\text{shaft,out}}}{\dot{W}_{\text{elect,in}}}$$

Pump efficiency

$$\eta_{\text{pump}} = \frac{\Delta \dot{E}_{\text{mech,fluid}}}{\dot{W}_{\text{shaft}}}$$

Generator efficiency

$$\eta_{\text{generator}} = \frac{\text{Electric power output}}{\text{Mechanical power input}} = \frac{\dot{W}_{\text{elect,out}}}{\dot{W}_{\text{shaft,in}}}$$

Pump-Motor overall efficiency

$$\eta_{\text{pump-motor}} = \eta_{\text{pump}}\eta_{\text{motor}} = \frac{\dot{W}_{\text{pump},u}}{\dot{W}_{\text{elect,in}}} = \frac{\Delta \dot{E}_{\text{mech,fluid}}}{\dot{W}_{\text{elect,in}}}$$

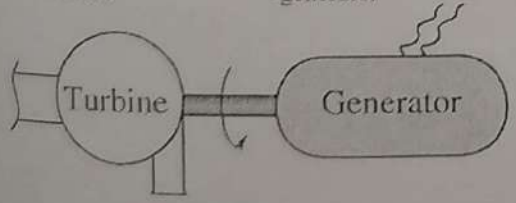
this is the system

Turbine-Generator overall efficiency

$$\eta_{\text{turbine-gen}} = \eta_{\text{turbine}}\eta_{\text{generator}} = \frac{\dot{W}_{\text{elect,out}}}{\dot{W}_{\text{turbine},e}} = \frac{\dot{W}_{\text{elect,out}}}{|\Delta \dot{E}_{\text{mech,fluid}}|}$$

flowrate — heat

$\eta_{\text{turbine}} = 0.75$ $\eta_{\text{generator}} = 0.97$



$$\eta_{\text{turbine-gen}} = \eta_{\text{turbine}}\eta_{\text{generator}} = 0.75 \times 0.97 = 0.73$$

The overall efficiency of a turbine–generator is **the product of** the efficiency of the turbine and the efficiency of the generator and represents the fraction of the mechanical energy of the fluid converted to electric energy.

working fluid ... steam

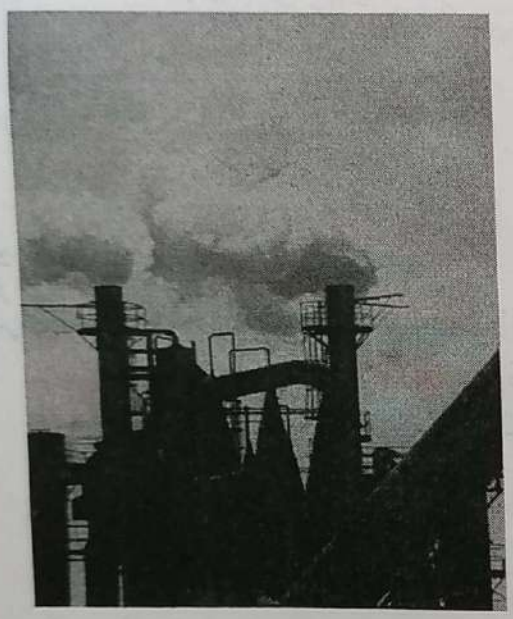
(working fluid) ما في إنتاج طاقة إلا فيه فلويد

Qadar ask · believe & recieve
الممسوحة ضوئيا بـ CamScanner

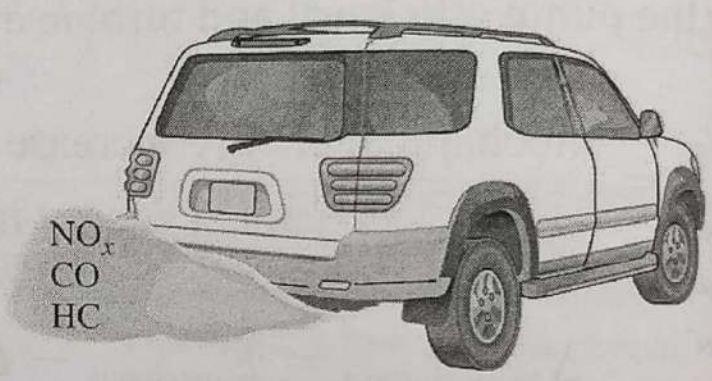
ENERGY AND ENVIRONMENT

Reading

- The conversion of energy from one form to another often affects the environment and the air we breathe in many ways, and thus the study of energy is not complete without considering its impact on the environment.
- Pollutants emitted during the combustion of fossil fuels are responsible for **smog**, **acid rain**, and **global warming**.
- The environmental pollution has reached such high levels that it became a serious threat to **vegetation**, **wildlife**, and **human health**.



Energy conversion processes are often accompanied by environmental pollution.



Motor vehicles are the largest source of air pollution.

EXAMPLE 2–2 **Wind Energy**

A site evaluated for a wind farm is observed to have steady winds at a speed of 8.5 m/s (Fig. 2–13). Determine the wind energy (*a*) per unit mass, (*b*) for a mass of 10 kg, and (*c*) for a flow rate of 1154 kg/s for air.

SOLUTION A site with a specified wind speed is considered. Wind energy per unit mass, for a specified mass, and for a given mass flow rate of air are to be determined.

Assumptions Wind flows steadily at the specified speed.

Analysis The only harvestable form of energy of atmospheric air is the kinetic energy, which is captured by a wind turbine.

(a) Wind energy per unit mass of air is

$$e = \text{ke} = \frac{V^2}{2} = \frac{(8.5\ \text{m/s})^2}{2}\left(\frac{1\ \text{J/kg}}{1\ \text{m}^2/\text{s}^2}\right) = 36.1\ \text{J/kg}$$

(b) Wind energy for an air mass of 10 kg is

الممسوحة ضوئيا بـ CamScanner

EXAMPLE 2–2 **Wind Energy**

A site evaluated for a wind farm is observed to have steady winds at a speed of 8.5 m/s (Fig. 2–13). Determine the wind energy (*a*) per unit mass, (*b*) for a mass of 10 kg, and (*c*) for a flow rate of 1154 kg/s for air.

SOLUTION A site with a specified wind speed is considered. Wind energy per unit mass, for a specified mass, and for a given mass flow rate of air are to be determined.

Assumptions Wind flows steadily at the specified speed.

Analysis The only harvestable form of energy of atmospheric air is the kinetic energy, which is captured by a wind turbine.

(a) Wind energy per unit mass of air is

$$e = \text{ke} = \frac{V^2}{2} = \frac{(8.5\ \text{m/s})^2}{2}\left(\frac{1\ \text{J/kg}}{1\ \text{m}^2/\text{s}^2}\right) = 36.1\ \text{J/kg}$$

(b) Wind energy for an air mass of 10 kg is

$$E = me = (10\ \text{kg})(36.1\ \text{J/kg}) = 361\ \text{J}$$

(c) Wind energy for a mass flow rate of 1154 kg/s is

$$\dot{E} = \dot{m}e = (1154\ \text{kg/s})(36.1\ \text{J/kg})\left(\frac{1\ \text{kW}}{1000\ \text{J/s}}\right) = 41.7\ \text{kW}$$



CamScanner الممسوحة ضوئيا بـ

EXAMPLE 2–10 Cooling of a Hot Fluid in a Tank

A rigid tank contains a hot fluid that is cooled while being stirred by a paddle wheel. Initially, the internal energy of the fluid is 800 kJ. During the cooling process, the fluid loses 500 kJ of heat, and the paddle wheel does 100 kJ of work on the fluid. Determine the final internal energy of the fluid. Neglect the energy stored in the paddle wheel.

SOLUTION A fluid in a rigid tank looses heat while being stirred. The final internal energy of the fluid is to be determined.

Assumptions 1 The tank is stationary and thus the kinetic and potential energy changes are zero, $\Delta KE = \Delta PE = 0$. Therefore, $\Delta E = \Delta U$ and internal energy is the only form of the system's energy that may change during this process. 2 Energy stored in the paddle wheel is negligible.

Analysis Take the contents of the tank as the system (Fig. 2–49). This is a *closed system* since no mass crosses the boundary during the process.

We observe that the volume of a rigid tank is constant, and thus there is no moving boundary work. Also, heat is lost from the system and shaft work is done on the system. Applying the energy balance on the system gives

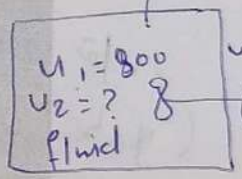
$$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic, potential, etc., energies}}$$

$$W_{sh,in} - Q_{out} = \Delta U = U_2 - U_1$$

$$100 \text{ kJ} - 500 \text{ kJ} = U_2 - 800 \text{ kJ}$$

$$U_2 = 400 \text{ kJ}$$

Therefore, the final internal energy of the system is 400 kJ.



EXAMPLE 2–15 Power Generation from a Hydroelectric Plant

Electric power is to be generated by installing a hydraulic turbine–generator at a site 70 m below the free surface of a large water reservoir that can supply water at a rate of 1500 kg/s steadily (Fig. 2–60). If the mechanical power output of the turbine is 800 kW and the electric power generation is 750 kW, determine the turbine efficiency and the combined turbine–generator efficiency of this plant. Neglect losses in the pipes.

SOLUTION A hydraulic turbine-generator installed at a large reservoir is to generate electricity. The combined turbine–generator efficiency and the turbine efficiency are to be determined.

Assumptions 1 The water elevation in the reservoir remains constant. 2 The mechanical energy of water at the turbine exit is negligible.

Analysis We take the free surface of water in the reservoir to be point 1

CamScanner الممسوحة ضوئيا بـ

EXAMPLE 2–15 Power Generation from a Hydroelectric Plant

Electric power is to be generated by installing a hydraulic turbine–generator at a site 70 m below the free surface of a large water reservoir that can supply water at a rate of 1500 kg/s steadily (Fig. 2–60). If the mechanical power output of the turbine is 800 kW and the electric power generation is 750 kW, determine the turbine efficiency and the combined turbine–generator efficiency of this plant. Neglect losses in the pipes.

SOLUTION A hydraulic turbine-generator installed at a large reservoir is to generate electricity. The combined turbine–generator efficiency and the turbine efficiency are to be determined.

Assumptions 1 The water elevation in the reservoir remains constant. 2 The mechanical energy of water at the turbine exit is negligible.

Analysis We take the free surface of water in the reservoir to be point 1 and the turbine exit to be point 2. We also take the turbine exit as the reference level ($z_2 = 0$) so that the potential energies at 1 and 2 are $pe_1 = gz_1$ and $pe_2 = 0$. The flow energy P/ρ at both points is zero since both 1 and 2 are open to the atmosphere ($P_1 = P_2 = P_{atm}$). Further, the kinetic energy at both points is zero ($ke_1 = ke_2 = 0$) since the water at point 1 is essentially motionless, and the kinetic energy of water at turbine exit is assumed to be negligible. The potential energy of water at point 1 is

adar ask · believe & recieve
الممسوحة ضوئيا بـ CamScanner

$$pe_1 = gz_1 = (9.81\ \text{m/s}^2)(70\ \text{m})\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = 0.687\ \text{kJ/kg}$$

Then the rate at which the mechanical energy of water is supplied to the turbine becomes

$$|\Delta \dot{E}_{\text{mech, fluid}}| = \dot{m}(e_{\text{mech, in}} - e_{\text{mech, out}}) = \dot{m}(pe_1 - 0) = \dot{m}pe_1$$
$$= (1500\ \text{kg/s})(0.687\ \text{kJ/kg})$$
$$= 1031\ \text{kW}$$

The combined turbine–generator and the turbine efficiency are determined from their definitions to be

$$\eta_{\text{turbine-gen}} = \frac{\dot{W}_{\text{elect, out}}}{|\Delta \dot{E}_{\text{mech, fluid}}|} = \frac{750\ \text{kW}}{1031\ \text{kW}} = 0.727 \text{ or } 72.7\%$$

$$\eta_{\text{turbine}} = \frac{\dot{W}_{\text{elect, out}}}{|\dot{E}_{\text{mech, fluid}}|} = \frac{800\text{kW}}{1031\text{kW}} = 0.776 \text{ or } 77.6\%$$

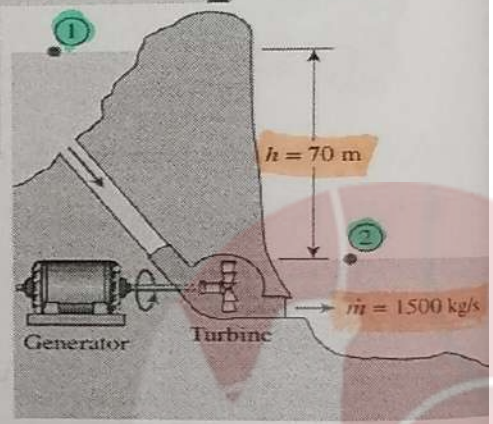


FIGURE 2-60
Schematic for Example 2-15

Mazar
ask & believe & recieve

الممسوحة ضوئيا بـ CamScanner



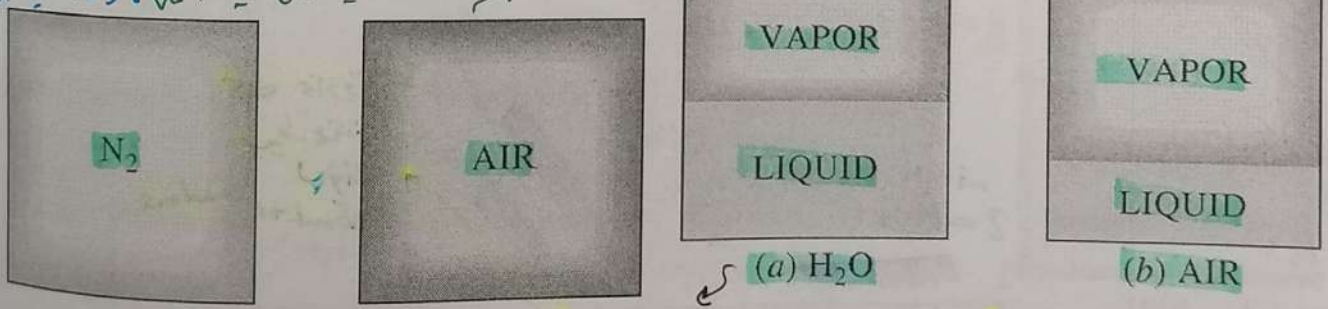
SUBSTANCES

Thermodynamics: An Engineering Approach
Yunus A. Cengel, Michael A. Boles, Mehmet Kanoglu
McGraw-Hill

Dr. Ahmad M. AbuYaghi
October 2023

PURE SUBSTANCE

- **Pure substance**: A substance that has a fixed chemical composition throughout.
- Air is a mixture of several gases, but it is considered to be a pure substance.

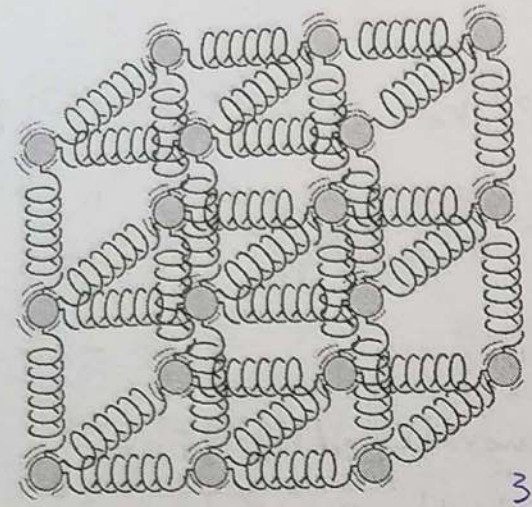


Nitrogen and gaseous air are pure substances.

A mixture of liquid and gaseous water is a pure substance, but a mixture of liquid and gaseous air is not.

* PHASES OF A PURE SUBSTANCE *

Inter & Intra molecular



The molecules in a solid are kept at their positions by the large springlike inter-molecular forces.



→ If we break it will get :-

Intramolecular $H_2O \rightarrow H_2 + \frac{1}{2} O_2$

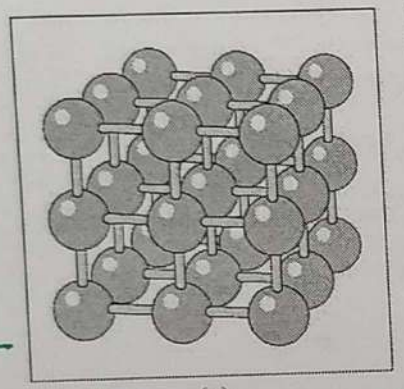
$H_2O - H_2O$ → If we break it will get s → L → g

Intermolecular

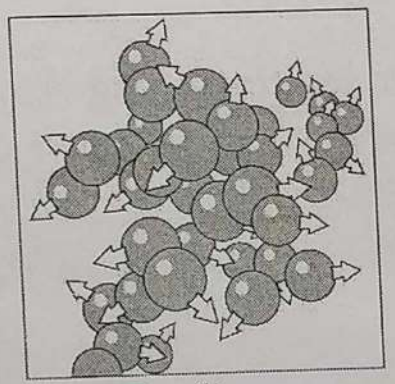
3 Types of substance :-

(3 phase change)

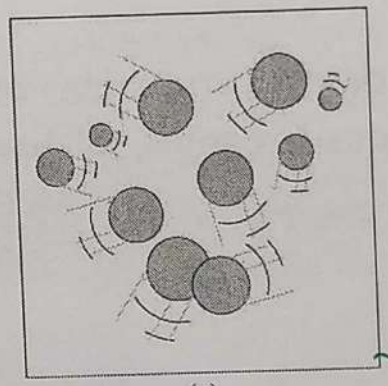
In a solid, the attractive and repulsive forces between the molecules tend to maintain them at relatively constant distances from each other.



Solid (a)



(b) liq



(c) gas

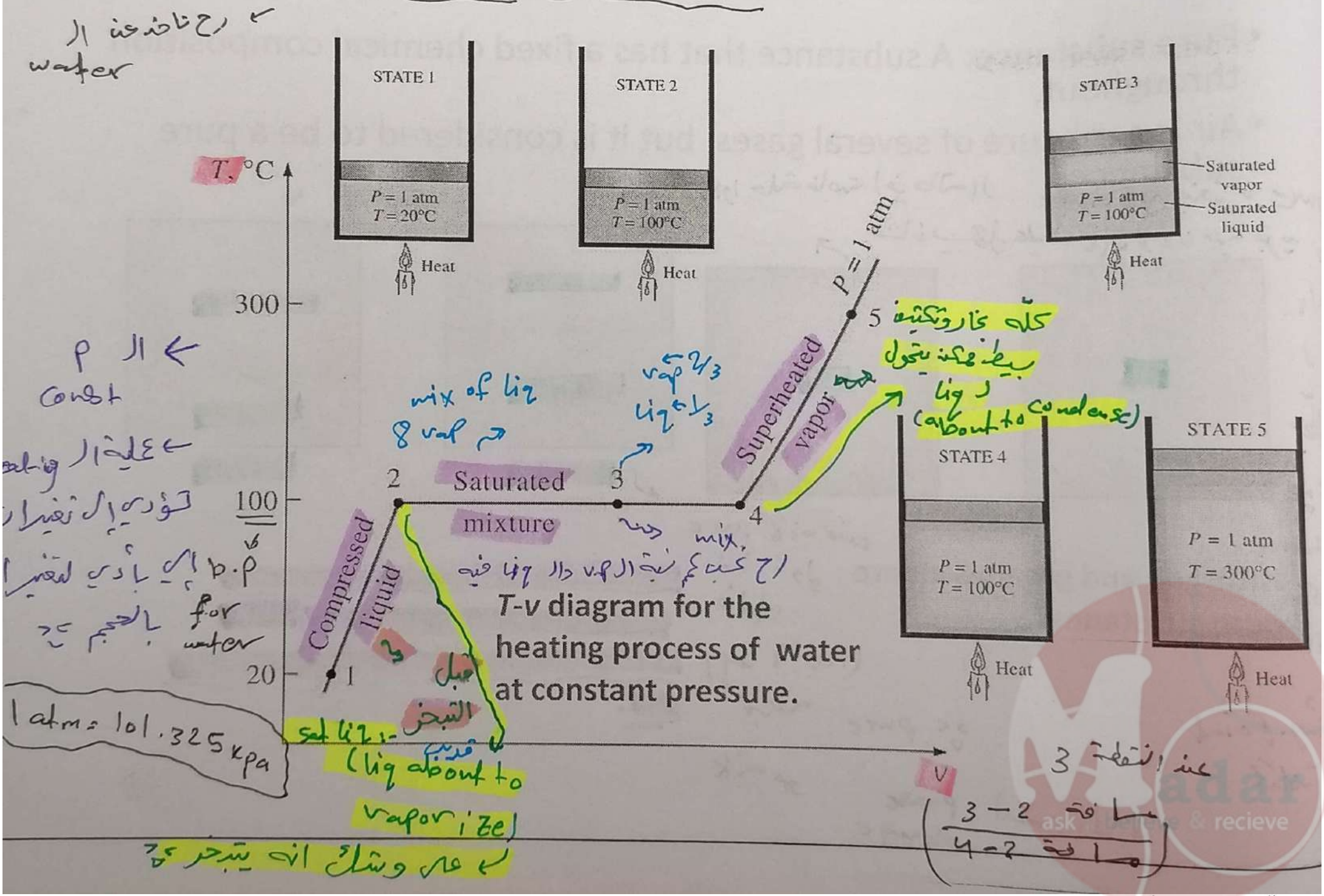
كل ما نعطي حرارة للمادة كل molecule بياخدها طاقة حركة ف بتبعد عن بعض وبتكسر الـ Intermolecular forces وبتتحول لـ liq وبعدين لـ gas

The arrangement of atoms in different phases: (*a*) molecules are at relatively fixed positions in a solid, (*b*) groups of molecules move about each other in the liquid phase, and (*c*) molecules move about at random in the gas phase.

Madar ask & believe & recieve

الممسوحة ضوئيا بـ CamScanner

PHASE-CHANGE PROCESSES OF PURE SUBSTANCES

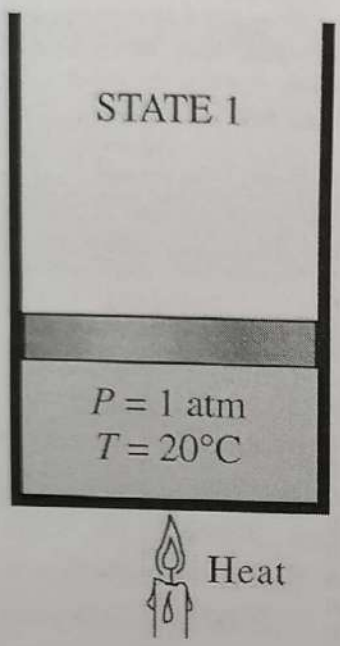


T-v diagram for the heating process of water at constant pressure.

Scanned with CamScanner
الممسوحة ضوئيا بـ CamScanner

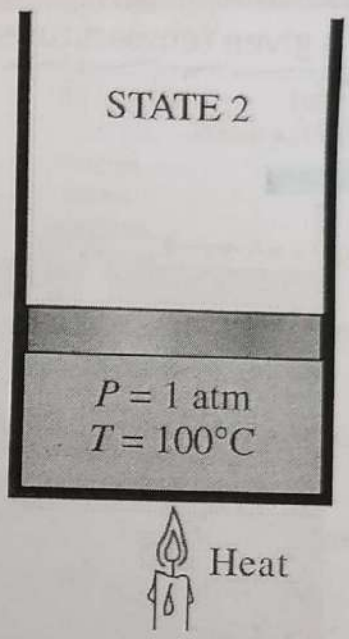
PHASE-CHANGE PROCESSES OF PURE SUBSTANCES

- **Compressed liquid (subcooled liquid)**: A substance that it is *not about to vaporize.*
- **Saturated liquid**: A liquid that is *about to vaporize.*

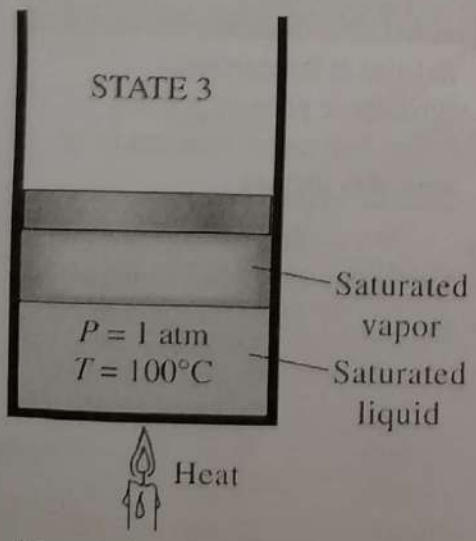


At 1 atm and 20°C, water exists in the liquid phase (***compressed liquid***).

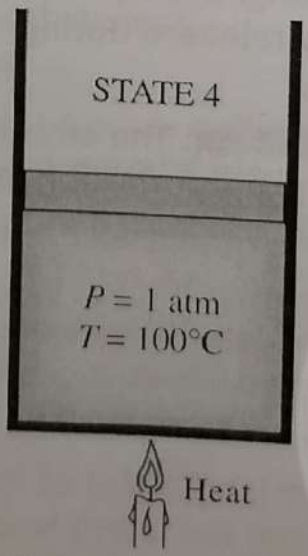
At 1 atm pressure and 100°C, water exists as a liquid that is ready to vaporize (***saturated liquid***).



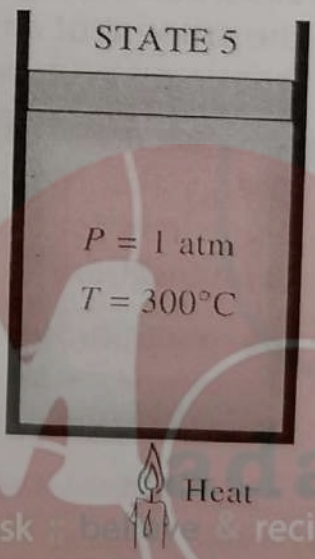
- **Saturated vapor**: A vapor that is *about to condense.*
- **Saturated liquid–vapor mixture**: The state at which the *liquid and vapor phases coexist* in equilibrium.
- **Superheated vapor**: A vapor that is *not about to condense* (i.e., not a saturated vapor).



As more heat is transferred, part of the saturated liquid vaporizes



At 1 atm pressure, the temperature remains constant

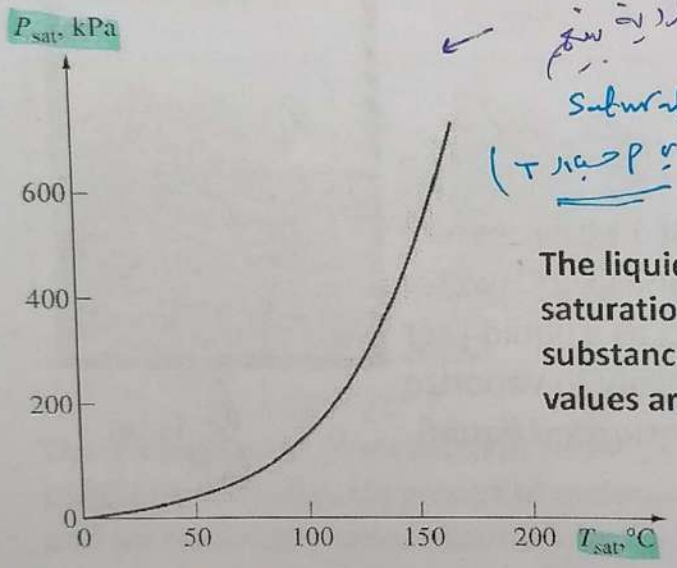


As more heat is transferred, the

ask & believe & recieve
CamScanner الممسوحة ضوئيا بـ

Saturation Temperature and Saturation Pressure

- The temperature at which water starts boiling depends on the pressure; therefore, if the pressure is fixed, so is the boiling temperature.
- Water boils at 100°C at 1 atm pressure.
- **Saturation temperature T_{sat}**: The temperature at which a pure substance changes phase at a given pressure.
- **Saturation pressure P_{sat}**: The pressure at which a pure substance changes phase at a given temperature.



The liquid–vapor saturation curve of a pure substance (numerical values are for water).

TABLE 3–1

Saturation (boiling) pressure of water at various temperatures

Temperature, T, °C	Saturation pressure, P_{sat}, kPa
−10	0.26
−5	0.40
0	0.61
5	0.87
10	1.23
15	1.71
20	2.34
25	3.17
30	4.25
40	7.39
50	12.35
100	101.4
150	476.2
200	1555
250	3976
300	8588

- **Latent heat**: The amount of energy absorbed or released during a phase-change process.
- **Latent heat of fusion**: The amount of energy absorbed during melting. It is equivalent to the amount of energy released during freezing.
- **Latent heat of vaporization**: The amount of energy absorbed during vaporization, and it is equivalent to the energy released during condensation.
- The magnitudes of the latent heats depend on the temperature or pressure at which the phase change occurs.
- At 1 atm pressure, the latent heat of fusion of water is 333.7 kJ/kg and the latent

TABLE 3–2

Variation of the standard atmospheric pressure and the boiling (saturation) temperature of water with altitude

Elevation, m	Atmospheric pressure, kPa	Boiling temperature, °C
0	101.33	100.0
1,000	89.55	96.5
2,000		

CamScanner الممسوحة ضوئيا بـ

- **Latent heat**: The amount of energy absorbed or released during a phase-change process.
- **Latent heat of fusion**: The amount of energy absorbed during melting. It is equivalent to the amount of energy released during freezing.
- **Latent heat of vaporization**: The amount of energy absorbed during vaporization, and it is equivalent to the energy released during condensation.
- The magnitudes of the latent heats depend on the temperature or pressure at which the phase change occurs.
- At 1 atm pressure, the latent heat of fusion of water is 333.7 kJ/kg and the latent heat of vaporization is 2256.5 kJ/kg.
- The atmospheric pressure, and thus the boiling temperature of water, decreases with elevation.

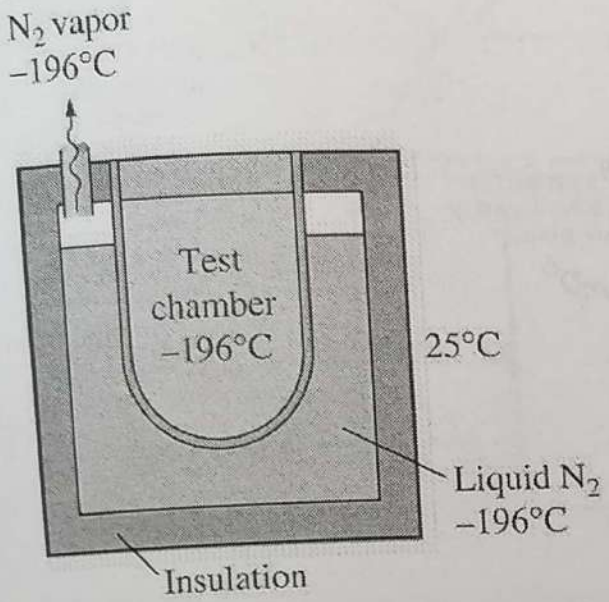
TABLE 3–2

Variation of the standard atmospheric pressure and the boiling (saturation) temperature of water with altitude

Elevation, m	Atmospheric pressure, kPa	Boiling temperature, °C
0	101.33	100.0
1,000	89.55	96.5
2,000	79.50	93.3
5,000	54.05	83.3
10,000	26.50	66.3
20,000	5.53	34.7

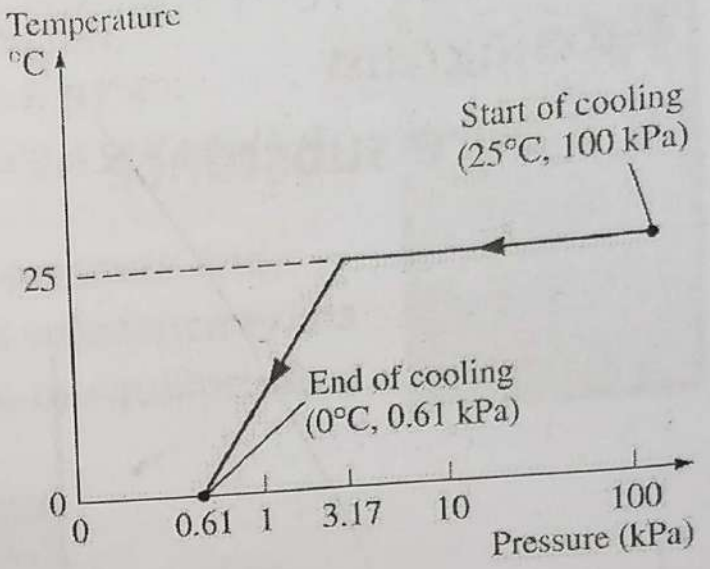
CamScanner الممسوحة ضوئيا بـ

Some Consequences of T_{sat} and P_{sat} Dependence

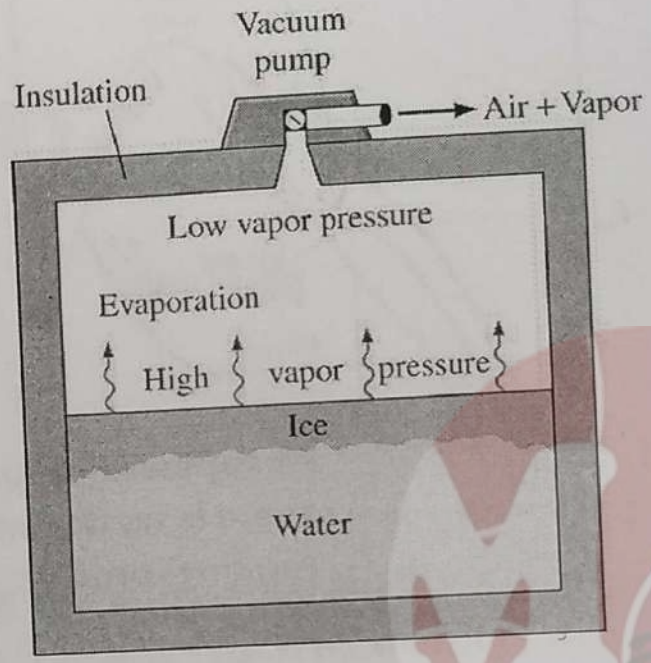


The temperature of liquid nitrogen exposed to the atmosphere remains constant at 196°C, and thus it maintains the test chamber at 196°C.

The variation of the temperature of fruits and vegetables with pressure during vacuum cooling from 25°C to 0°C.



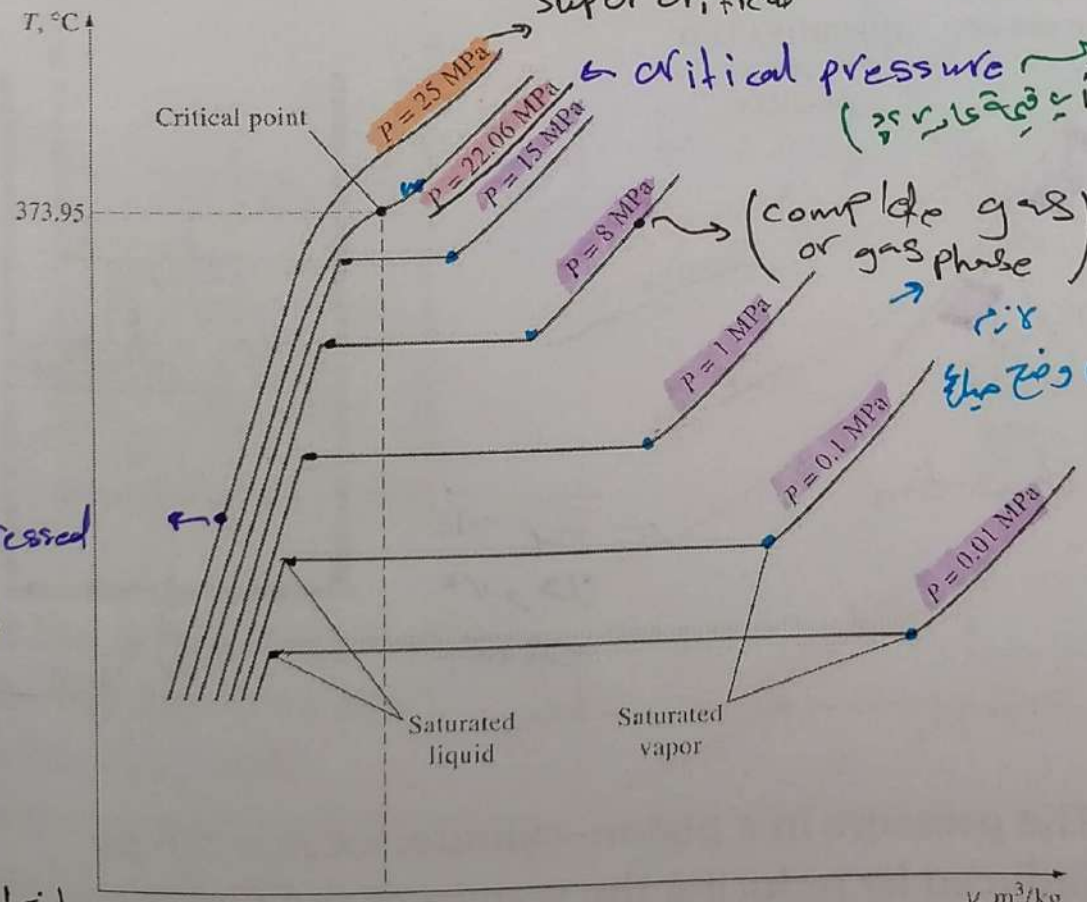
In 1775, ice was made by evacuating the air space in a water tank.



CamScanner الممسوحة ضوئيا بـ

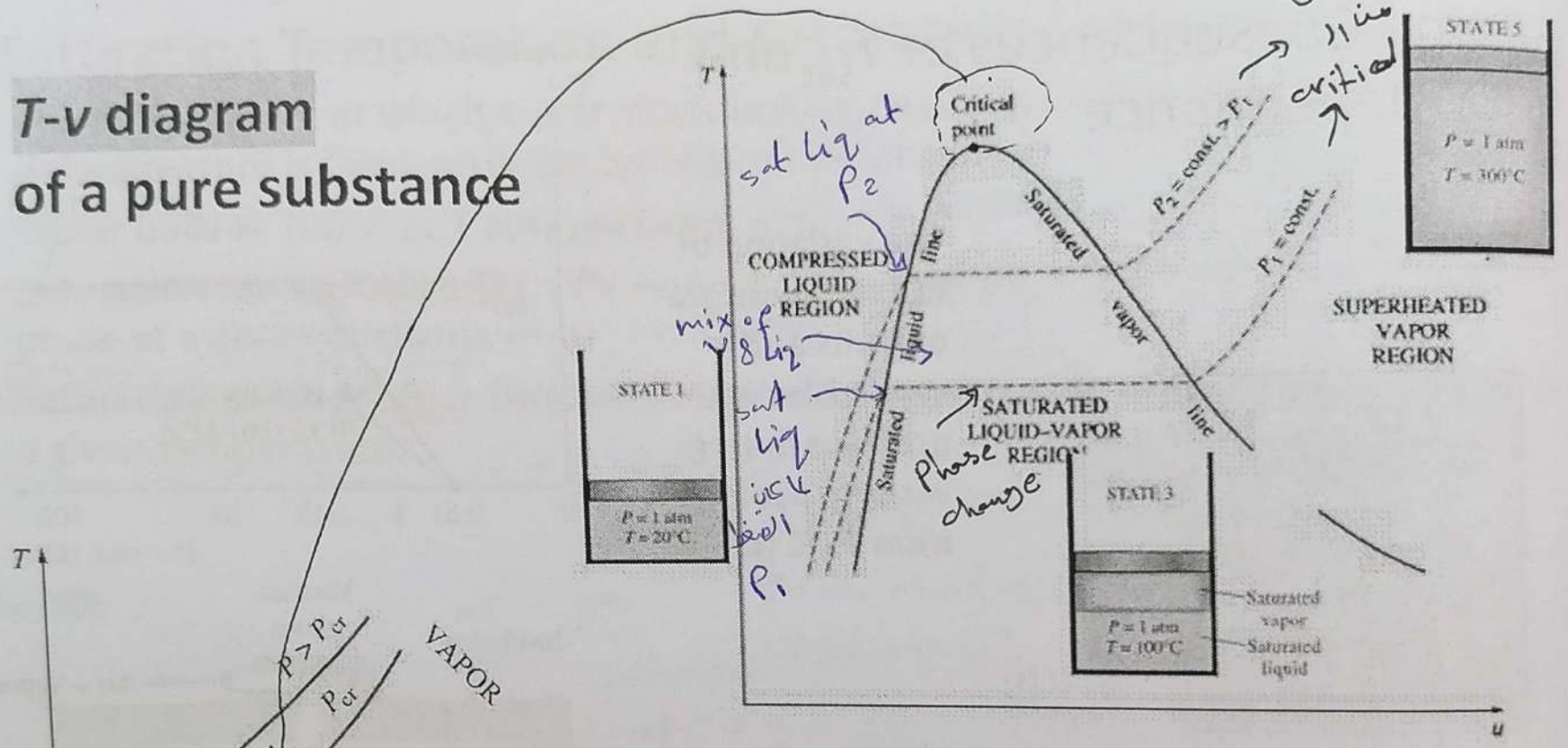
PROPERTY DIAGRAMS FOR PHASE-CHANGE PROCESSES

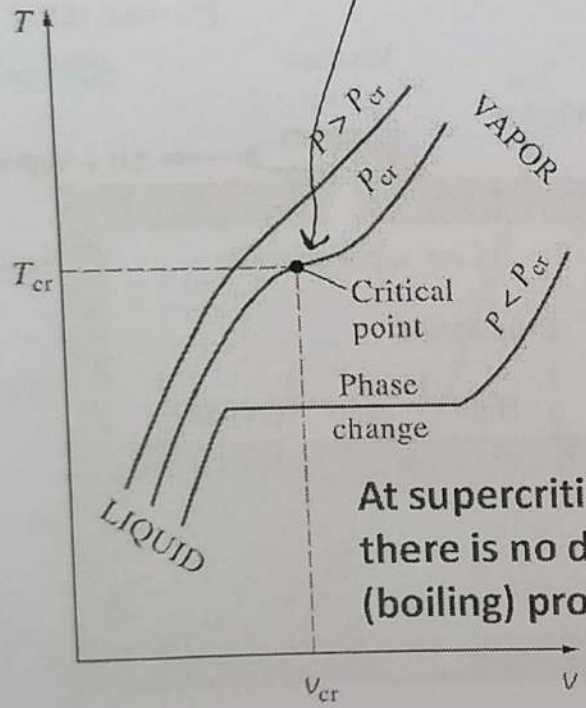
- The variations of properties during phase-change processes are best studied and understood with the help of property diagrams such as the ***T-v*, *P-v*, and *P-T* diagrams** for pure substances.



T-v diagram of constant-pressure phase-change processes of a pure substance at various pressures (numerical values are for water).

T-v diagram of a pure substance





At supercritical pressures ($P > P_{cr}$), there is no distinct phase-change (boiling) process.

Critical point: The point at which the saturated liquid and saturated vapor states are identical.

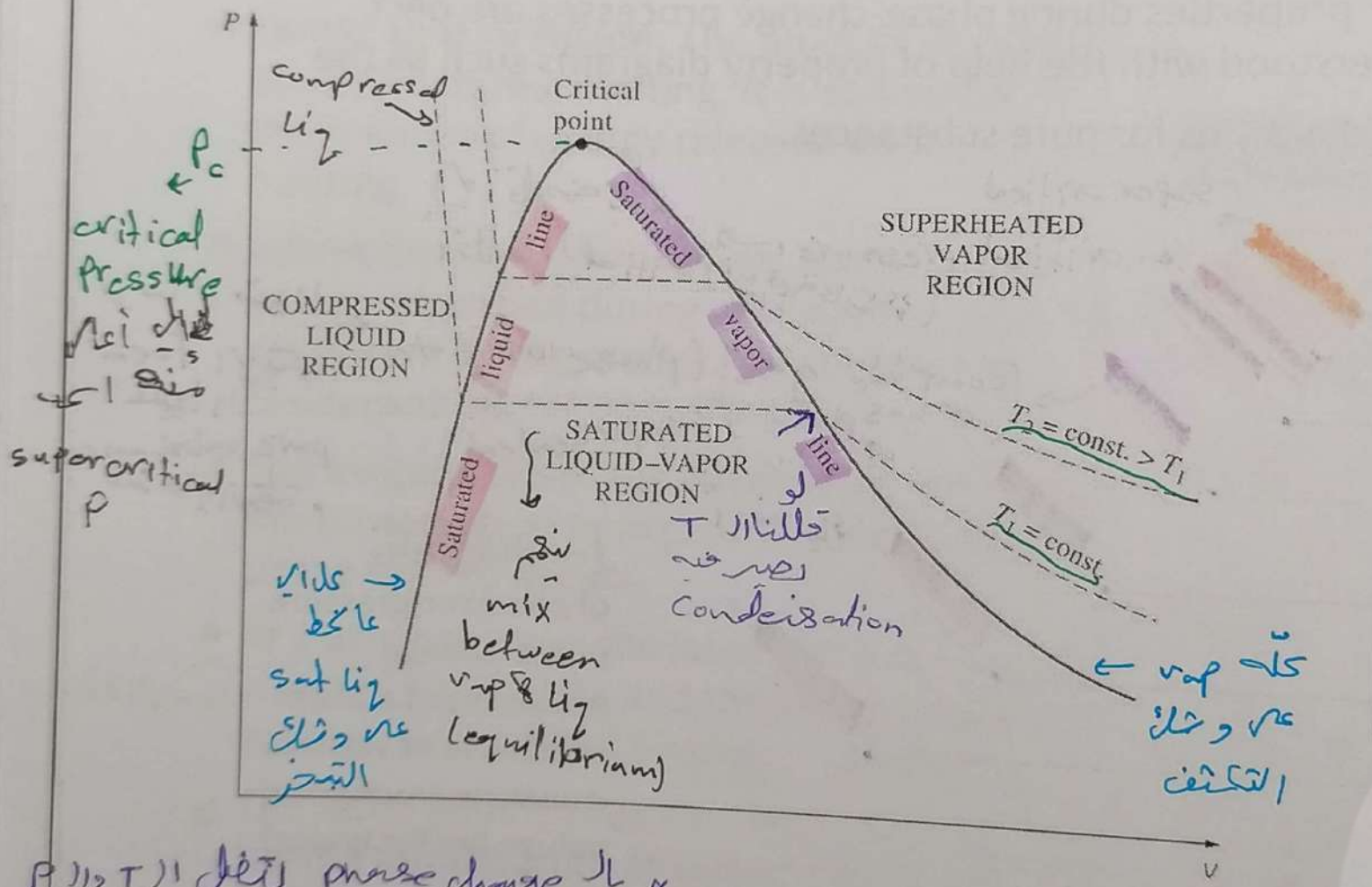
For water

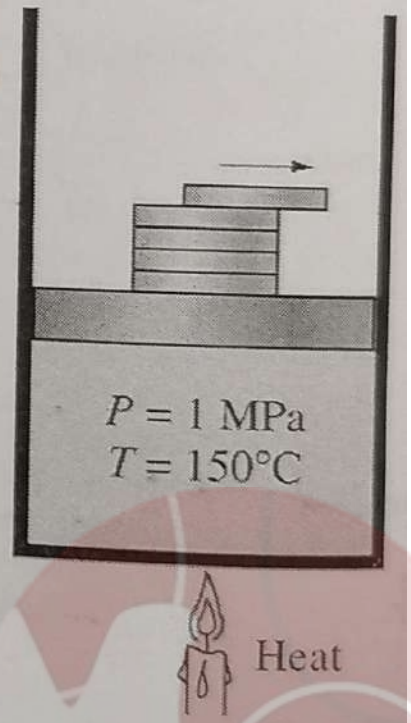
$T_c = 374\ c^\circ$

$P_c = 22.06\ MPa \simeq 22000\ KPa$

الممسوحة ضوئيا بـ CamScanner

P-v diagram of a pure substance.



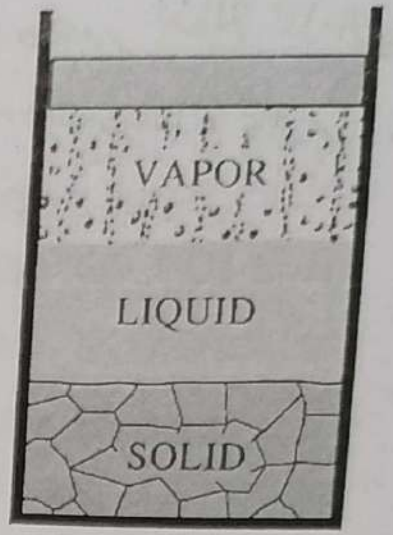


The pressure in a piston–cylinder device can be reduced by reducing the weight of the piston.

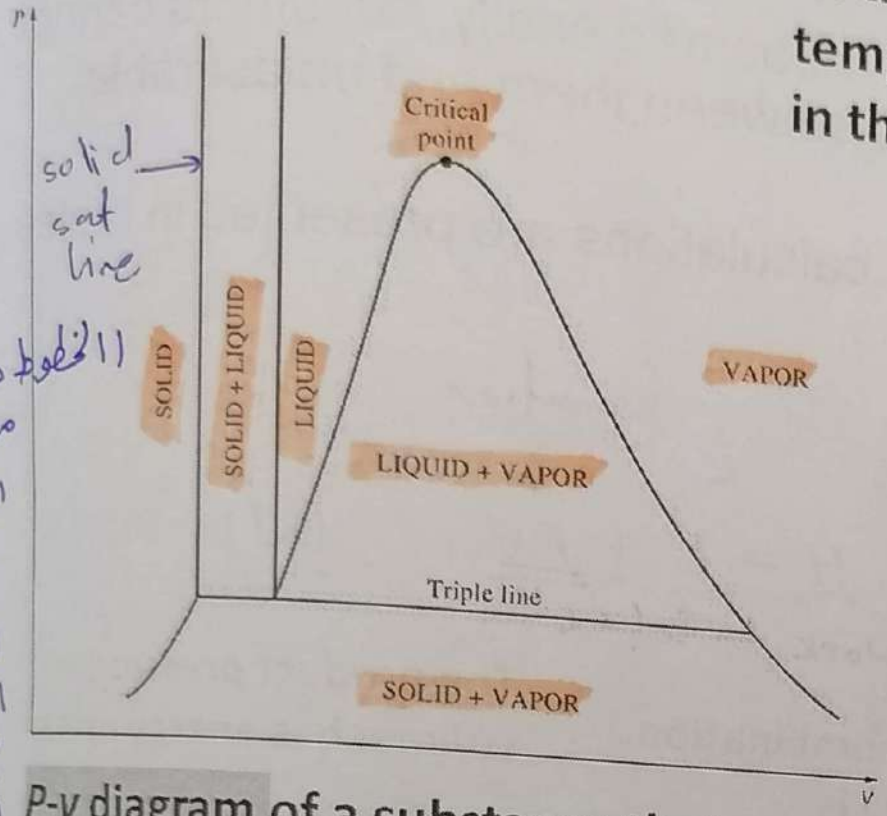
CamScanner الممسوحة ضوئيا بـ

Extending Diagrams to Include Solid Phase

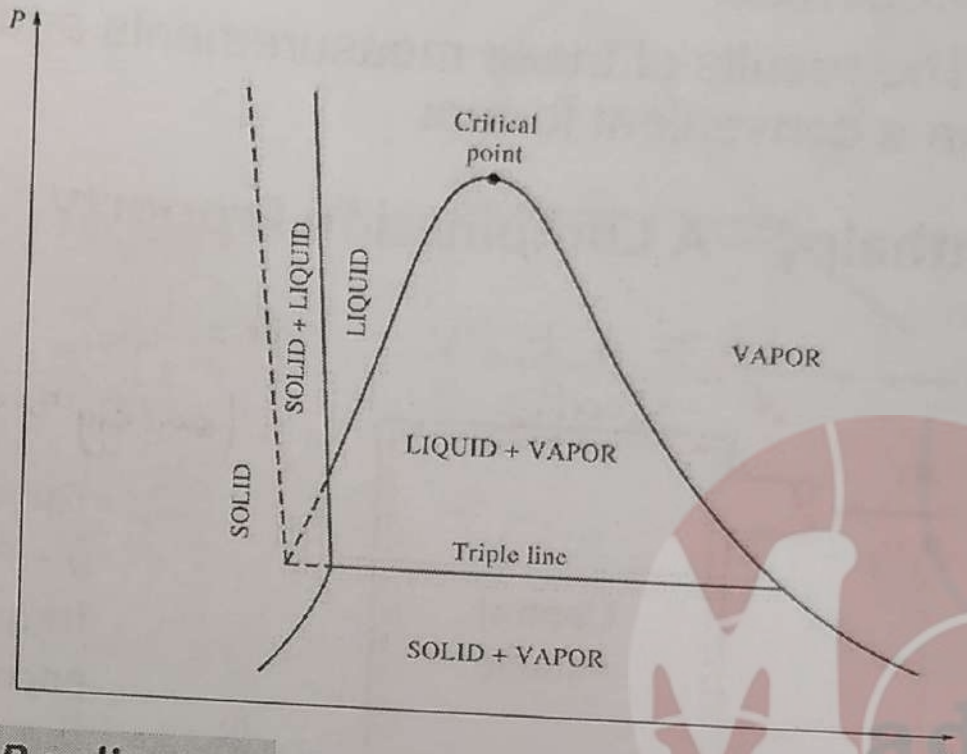
For water,
$T_{tp} = 0.01°C$
$P_{tp} = 0.6117$ kPa



At triple-point pressure and temperature, a substance exists in three phases in equilibrium.



P-v diagram of a substance that contracts on freezing.

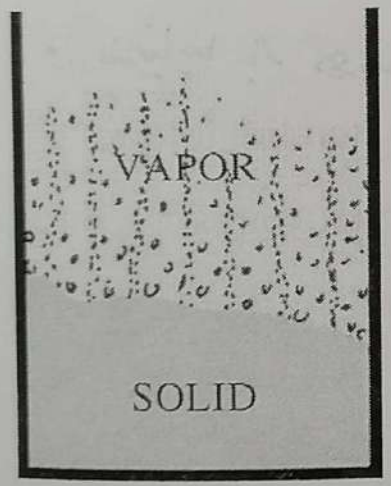


P-v diagram of a substance that expands on freezing (such as water).

CamScanner الممسوحة ضوئيا بـ

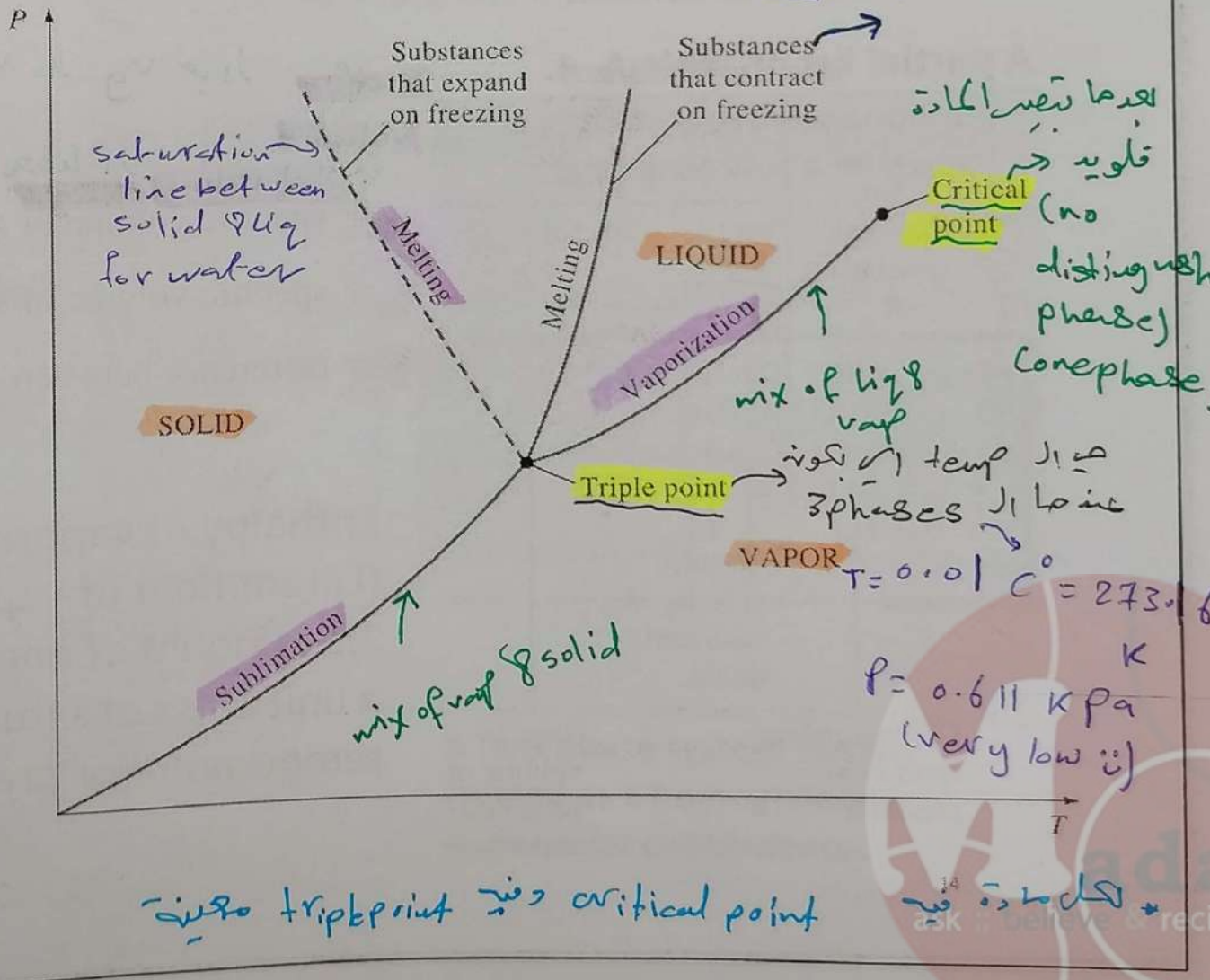
the first graph for study

Sublimation:
Passing from the solid phase directly into the vapor phase.



At low pressures (**below the triple-point value**), solids evaporate without melting first (*sublimation*).

P-T diagram of pure substances



هاد الخط لمعظم المواد ما عدا الـ H_2O

saturation line between solid & liq for water

بعدها بتصير المادة غازية (no distinguish phase/ one phase)

mix of liq & vap

عند هاد الـ temp بتكون 3 phases

$T = 0.01\ C^\circ = 273.16\ K$

$P = 0.611\ kPa$ (very low)

mix of vap & solid

* لكل مادة triple point و critical point معينة

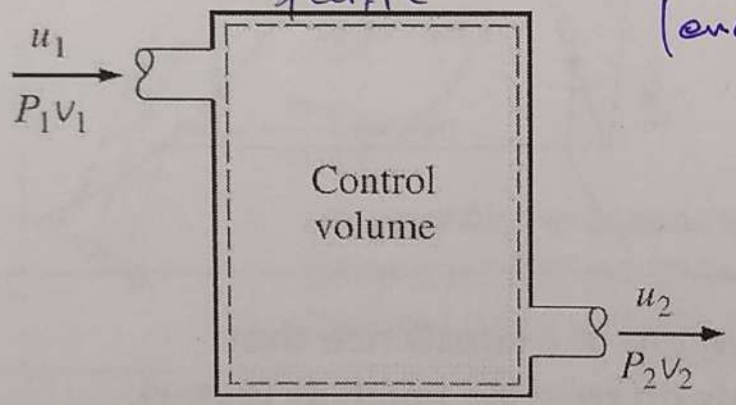
CamScanner الممسوحة ضوئيا بـ

PROPERTY TABLES

- For most substances, the relationships among thermodynamic properties are too complex to be expressed by simple equations.
- Therefore, properties are frequently presented in the form of tables.
- Some thermodynamic properties can be measured easily, but others cannot and are calculated by using the relations between them and measurable properties.
- The results of these measurements and calculations are presented in tables in a convenient format.

Enthalpy—A Combination Property

$$h = u + Pv \quad (\text{kJ/kg}) \qquad H = U + PV \quad (\text{kJ})$$



The combination *u + Pv* is frequently encountered in the analysis of control volumes.

The product *pressure* × *volume* has energy units.

$$\text{kPa} \cdot \text{m}^3 \equiv \text{kJ}$$
$$\text{kPa} \cdot \text{m}^3/\text{kg} \equiv \text{kJ/kg}$$
$$\text{bar} \cdot \text{m}^3 \equiv 100\ \text{kJ}$$
$$\text{MPa} \cdot \text{m}^3 \equiv 1000\ \text{kJ}$$

CamScanner الممسوحة ضوئيا بـ

24/10

Saturated Liquid and Saturated Vapor States

- **Table A–4**: Saturation properties of water under temperature.
- **Table A–5**: Saturation properties of water under pressure.

A partial list of Table A–4.

Temp. °C T	Sat. press. kPa P_{sat}	Specific volume m^3/kg Sat. liquid v_f	Sat. vapor v_g
85	57.868	0.001032	2.8261
90	70.183	0.001036	2.3593
95	84.609	0.001040	1.9808

Specific temperature

Corresponding saturation pressure

Specific volume of saturated liquid

Specific volume of saturated vapor

v_f = specific volume of saturated liquid

v_g = specific volume of saturated vapor

v_{fg} = difference between v_g and v_f (that is, $v_{fg} = v_g - v_f$)

Enthalpy of vaporization, h_{fg} (Latent heat of vaporization): The amount of energy needed to vaporize a unit mass of saturated liquid at a given temperature or pressure.

ask & believe & recieve
الممسوحة ضوئيا بـ CamScanner

Introduction and Basic Concepts

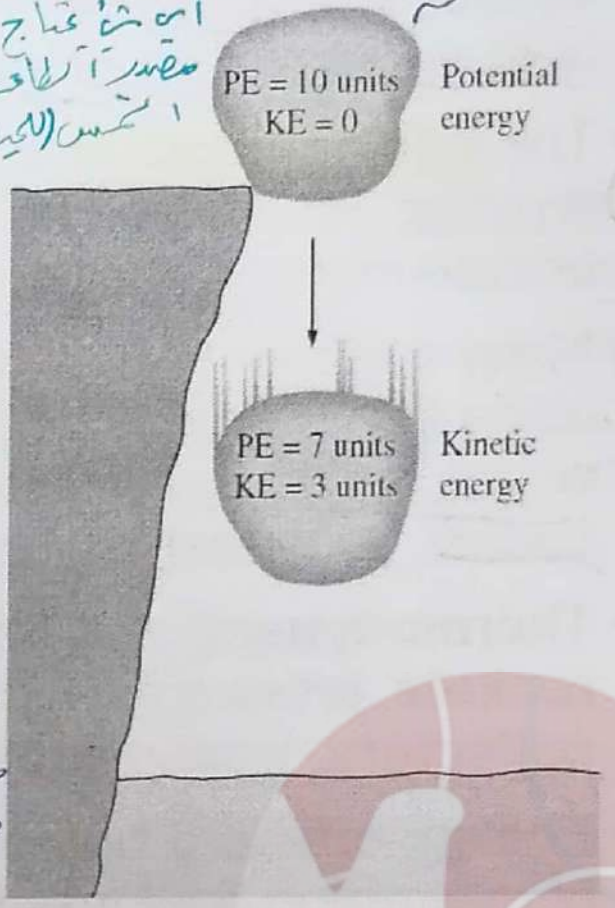
- One of the most fundamental laws of nature is the conservation of energy principle. It simply states that during an interaction, energy can change from one form to another, but the **total amount of energy** remains constant. That is, energy cannot be created or destroyed.
- A rock falling off a cliff, for example, picks up speed as a result of its potential energy being converted to kinetic energy.
- A person who has a greater energy input (food) than energy output (exercise) will gain weight (store energy in the form of fat), and a person who has a smaller energy input than output will lose weight.
- The change in the energy content of a body or any other system is equal to the difference between the energy input and the energy output, and the energy balance is expressed as:

$$E_{in} - E_{out} = \Delta E.$$

CamScanner الممسوحة ضوئيا بـ

THERMODYNAMICS AND ENERGY-1

- **Thermodynamics**: The science of *energy*.
- **Energy**: The ability to cause changes.
- The name *thermodynamics* stems from the Greek words *therme* (heat) and *dynamis* (power).
- **Conservation of energy principle**: During an interaction, *energy can change from one form to another*, but the total amount of energy remains constant.
- Energy cannot be created or destroyed.
- **The first law of thermodynamics**: An expression of the conservation of energy principle.
- The first law asserts that *energy* is a thermodynamic property.



Energy cannot be created or destroyed; it can only change forms (the first law).

الممسوحة ضوئيا بـ CamScanner

THERMODYNAMICS AND ENERGY-2

- **The second law of thermodynamics**: It asserts that energy has *quality* as well as *quantity*, and actual processes occur in the direction of decreasing quality of energy.



Heat flows in the direction of decreasing temperature.

Types of Thermodynamic Studies:

- **Classical thermodynamics**: A macroscopic approach to the study of thermodynamics that does not require a knowledge of the behavior of individual particles.
  - It provides a direct and easy way to the solution of engineering problems (used in this course).
- **Statistical thermodynamics**: A microscopic approach, based on the average behavior of large groups of individual particles (molecules).

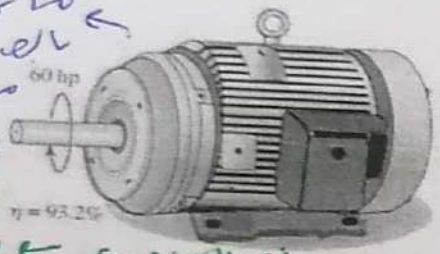
CamScanner الممسوحة ضوئيا بـ

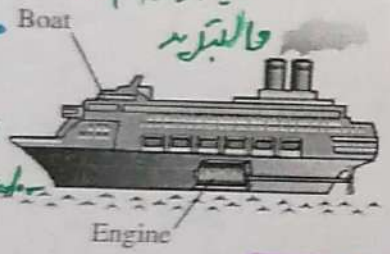
Applications of Thermodynamics

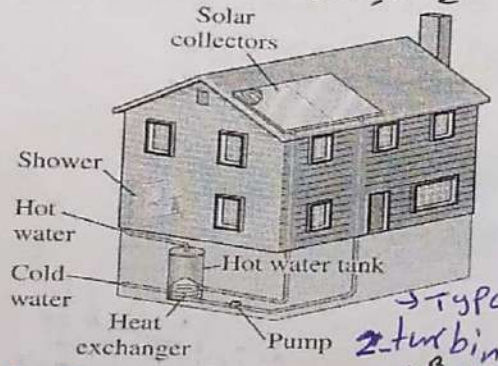
- **Thermodynamics** is encountered in many engineering systems and other aspects of life.
- The **heart** is constantly pumping blood to all parts of the human body, various energy conversions occur in trillions of body cells, and the body heat generated is constantly rejected to the environment.
- The **human comfort** is closely tied to the rate of this metabolic heat rejection (controlling heat transfer rate by adjusting clothing to environmental conditions).
- Many ordinary **household appliances** are designed, in whole or in part, by using the principles of **thermodynamics.** Some examples include electric or gas range, heating and air-conditioning systems, refrigerator, pressure cooker, water heater, computer, etc.
- **Thermodynamics** is basic in design and analysis of **automotive engines, rockets, jet engines, power plants, electrochemical cells, solar collectors, transportation vehicles from ordinary cars to airplanes.**
- **Energy-efficient home** that you may be living in is designed on the basis of minimizing heat loss in winter and heat gain in summer.
- Size, location, and power input of the **fan of your computer** is also selected after an analysis that involves **th**

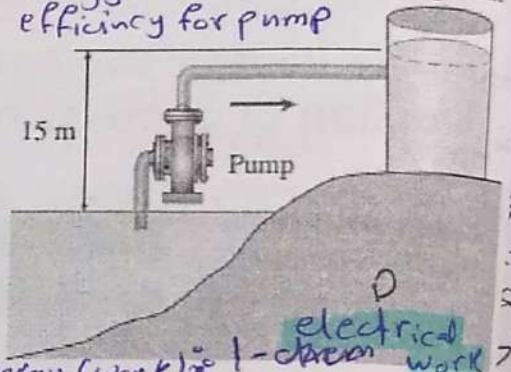
CamScanner الممسوحة ضوئيا بـ

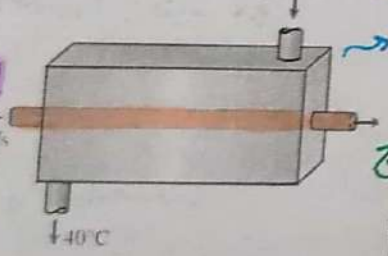
Applications of Thermodynamics



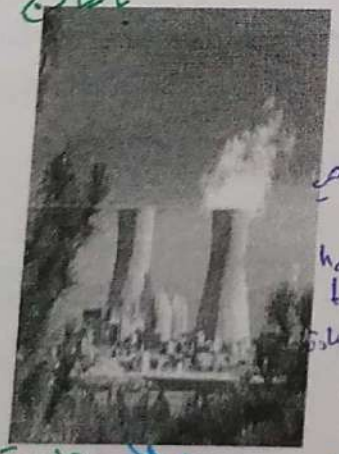


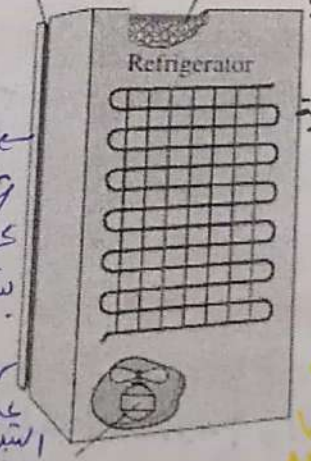


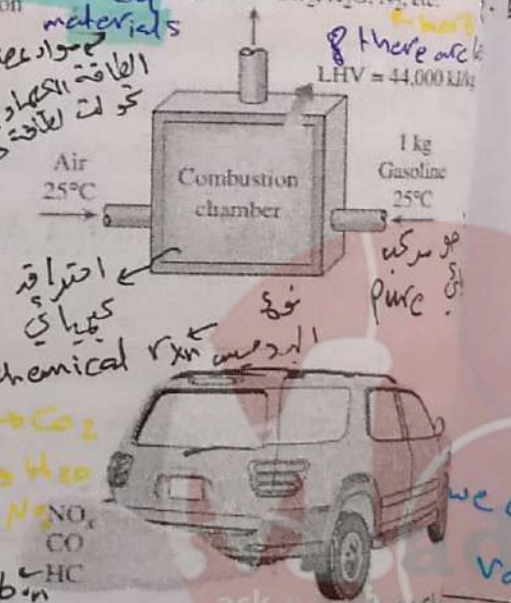












IMPORTANCE OF DIMENSIONS AND UNITS

Two types of units :-

- Any physical quantity can be characterized by **dimensions**.
- The magnitudes assigned to the dimensions are called **units**.
- Some basic dimensions such as **mass *m*, length *L*, time *t*, and temperature *T*** are selected as **primary** or **fundamental dimensions**.
- Others such as **velocity *V*, energy *E*, and volume *V*** are expressed in terms of the primary dimensions and are called **secondary dimensions**, or **derived dimensions**.

primary أي وحدة مشتقة من ال

TABLE 1–1

The seven fundamental (or primary) dimensions and their units in SI

Dimension	Unit
Length	meter (m)
Mass	kilogram (kg)
Time	second (s)
Temperature	kelvin (K)
Electric current	ampere (A)
Amount of light	candela (cd)
Amount of matter	mole (mol)

(kg · m · s)

TABLE 1–2

Standard prefixes in SI units

Multiple	Prefix
10^{12}	tera, T
10^{9}	giga, G
10^{6}	mega, M
10^{3}	kilo, k
10^{2}	hecto, h
10^{1}	deka, da
10^{-1}	deci, d
10^{-2}	centi, c
10^{-3}	milli, m
10^{-6}	micro, μ
10^{-9}	nano, n
10^{-12}	pico, p

ask & believe & recieve
CamScanner الممسوحة ضوئيا بـ

12/10/2023

SYSTEMS AND CONTROL VOLUMES

- **System**: A quantity of matter or a region in space chosen for study.
- **Surroundings**: The mass or region outside the system.
- **Boundary (Control Surface)**: The real or imaginary surface that separates the system from its surroundings.
- The boundary of a system can be *fixed* or *movable*.
- Systems may be considered to be *closed* or *open*.

Types of Systems

I) Closed (Control mass).

II) Open (Control volume).

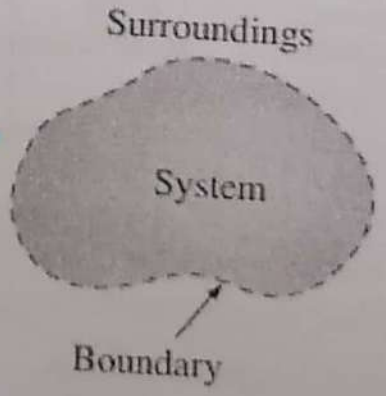


FIGURE 1–18
System, surroundings, and boundary.

Madar ask & believe & recieve
الممسوحة ضوئيا بـ CamScanner

* Closed Systems (Control Mass) *

* اذا ثبتت ال mass بغض النظر volume والعكس كذلك

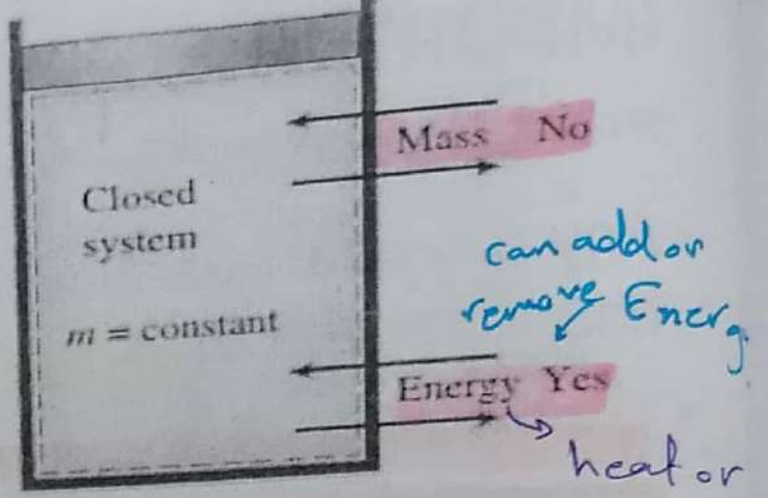


FIGURE 1–19
Mass cannot cross the boundaries of a closed system, but energy can.

- Energy, not Mass, crosses Closed System boundaries.

- **Example Applications:**

1) Piston-cylinder devices.
2) Batch reactor tank.
3) Refrigerator.
4) Air conditioner.
5) Small electric heater.

اذا حللت حرارة أو حللت ضغط بترتفع piston بتحرك

ماشيه ← عبر ثابتة الغاز

كمية الحارة فيه flow ثابتة

If we do mixing we add ing work

← مخانه الكهرباء العاديه في

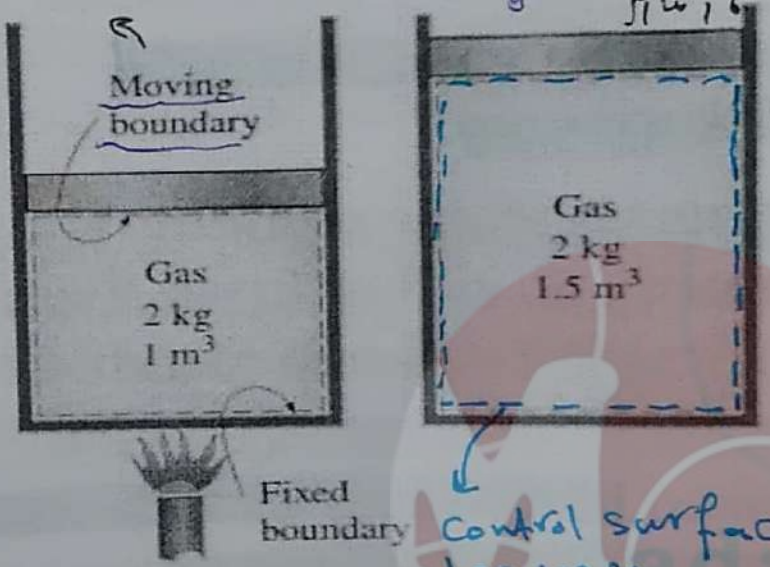


FIGURE 1–20
A closed system with a moving boundary.

لانه ال fixed sys بالتالي ما في ل طاقة ال kinetic و potential و heat و work بتضيف وبتوقف

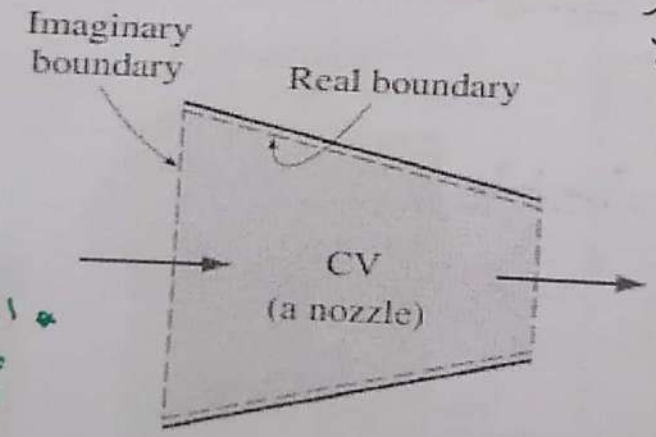
عند ال

CamScanner الممسوحة ضوئيا بـ

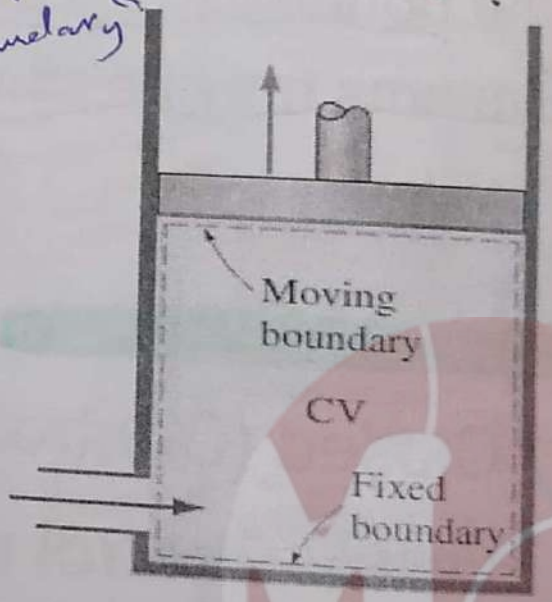
*Open Systems (Control Volume)

- Both Mass and Energy Cross Open System (Control Volume) Boundaries.
- Control surface: The boundaries of a control volume. It can be *real or imaginary.*
- **Example applications:**

1) Fluid flow in pipes, water pumps, air compressors, heat exchangers, etc.
2) Continuous-flow chemical reactors.
3) Automobile motor engines.
4) Power plant turbine systems.



(a) A control volume (CV) with real and imaginary boundaries



(b) A control volume (CV) with fixed and moving boundaries as well as real and imaginary boundaries

الممسوحة ضوئيا بـ CamScanner

PROPERTIES OF A SYSTEM

- **Property**: Any characteristic of a system.
- Some familiar properties are pressure P, temperature T, volume V, and mass m.
- Properties are considered to be either *intensive* or *extensive*.

❑ **Intensive properties**: Those that are *independent of the mass* of a system, such as temperature, pressure, and density.

❑ **Extensive properties**: Those whose values *depend on the size* (or extent) of the system.

- **Specific properties**: Extensive properties *per unit mass.*

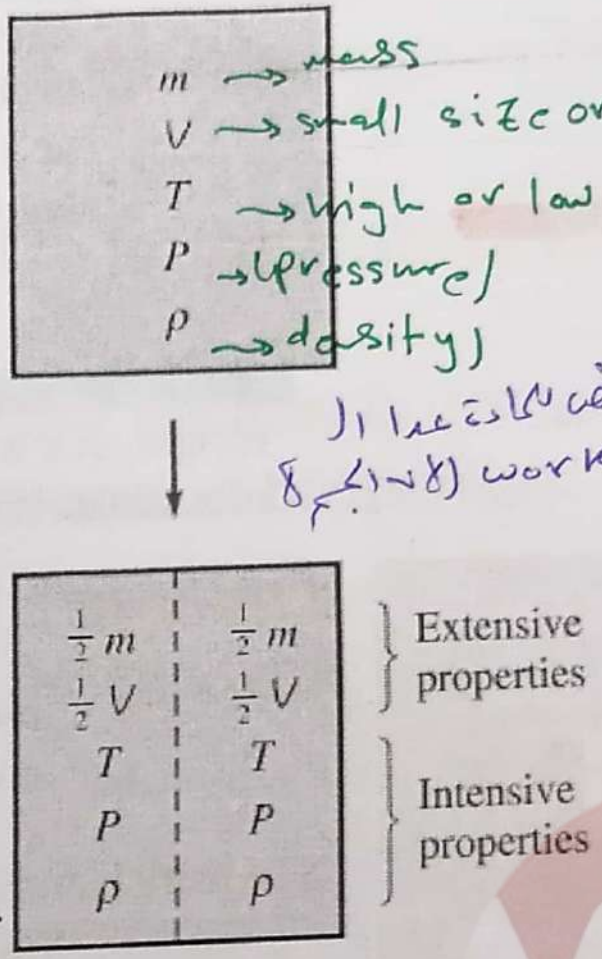


FIGURE 1–23
Criterion to differentiate intensive and extensive properties.

CamScanner الممسوحة ضوئيا بـ

properties *per unit mass.*

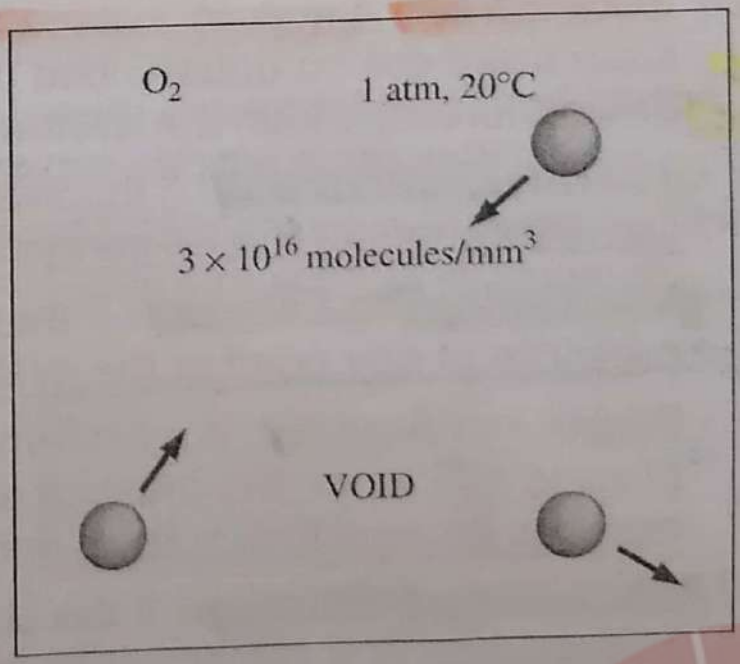
13

* الفرق بين Intensive properties و Extensive properties

* عكس الحجم النوعي specific volume (م³/كجم) المادة تتكون من molecules متفرقة (في الغازات) لكنه احنا بنتعاملها بنعتبره Continuous

Continuum

- Matter is made up of atoms that are widely spaced in the gas phase. Yet it is very convenient to disregard the atomic nature of a substance and view it as a *continuous, homogeneous matter* with no holes, that is, a ***continuum***.
- The continuum idealization allows us to treat properties as point functions and to assume the properties vary continually in space with no jump discontinuities.
- This idealization is valid as long as the size of the system we deal with is large relative to the space between the molecules.
- This is the case in practically all problems.
- In this text we will limit our consideration to substances that can be modeled as a ***continuum.***



Despite the large gaps between molecules, a substance can be treated as a *continuum* because of the very large number of molecules even in an extremely small volume.

14

Nadar ask & believe & recieve
الممسوحة ضوئيا بـ CamScanner

DENSITY AND SPECIFIC GRAVITY

Density

$$\rho = \frac{m}{V} \qquad (\text{kg/m}^3)$$

Specific volume

$$v = \frac{V}{m} = \frac{1}{\rho}$$

$V = 12\ \text{m}^3$
$m = 3\ \text{kg}$

$\rho = 0.25\ \text{kg/m}^3$

$v = \frac{1}{\rho} = 4\ \text{m}^3/\text{kg}$

Specific gravity: The ratio of the density of a substance to the density of some standard substance at a specified temperature (usually water at 4°C).

$$\text{SG} = \frac{\rho}{\rho_{H_2O}}$$

It is a ratio between ρ of any substance with ρ of water (dimentionless)

Specific weight: The weight of a unit volume of a substance.

$$\gamma_s = \rho g \qquad (\text{N/m}^3)$$

weight = mass * acc of gravity
$w = m * g$

→ Density is mass per unit volume;
→ specific volume is volume per unit mass.

TABLE 1–3

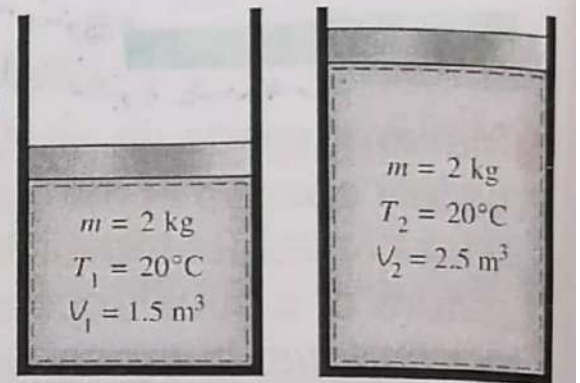
Specific gravities of some substances at 0°C

Substance	SG
Water	1.0
Blood	1.05
Seawater	1.025
Gasoline	0.7
Ethyl alcohol	0.79
Mercury	13.6
Wood	0.3–0.9
Gold	19.2
Bones	1.7–2.0
Ice	0.92
Air (at 1 atm)	0.0013

CamScanner الممسوحة ضوئيا بـ

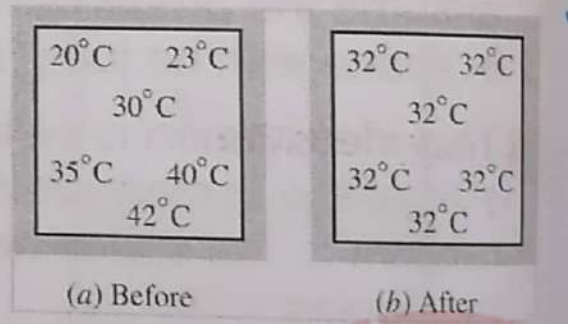
STATE AND EQUILIBRIUM

- Thermodynamics deals with ***equilibrium* states.**
- **Equilibrium:** A state of balance. In an equilibrium state there are no unbalanced potentials (or driving forces) within the system.
- **Thermal equilibrium:** If the temperature is the same throughout the entire system.
- **Mechanical equilibrium:** If there is no change in pressure at any point of the system with time.
- **Phase equilibrium:** If a system involves two phases and when the mass of each phase reaches an equilibrium level and stays there.
- **Chemical equilibrium:** If the chemical composition of a system does not change with time, that is, no chemical reactions occur.



(*a*) State 1 (*b*) State 2

A system at two different states



(*a*) Before (*b*) After

A closed system reaching thermal equilibrium.

❑ A system is said to be "in **thermodynamic equilibrium**" if it maintains:

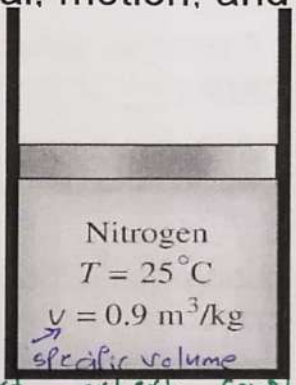
(1) thermal (uniform temp.), (2) mechanical (uniform pressure), (3) phase (mass of two phases, e.g., ice and liquid water, in equilibrium), and (4) chemical equilibrium (uniform composition).

الممسوحة ضوئيا بـ CamScanner

The State Postulate

- The state of a system is described by its properties.
- But, by experience not all properties must be known before the state is specified.
- The number of properties required to fix the state of a system is given by the **state postulate**:
  - *The state of a simple compressible system is completely specified by two independent, intensive properties.*
- **Simple compressible system:** If a system involves no electrical, magnetic, gravitational, motion, and surface tension effects.

The state of nitrogen is fixed by two independent, intensive properties.



equation of state : ideal gas law

$PV = nRT$

$P\hat{V} = RT$, $[v_m] = m^3/kmol$

molar volume (intensive) $[\hat{V}] = m^3/kg = \frac{v}{mass}$

PROCESSES AND CYCLES-1

Process: Any change that a system undergoes from one equilibrium state to another.

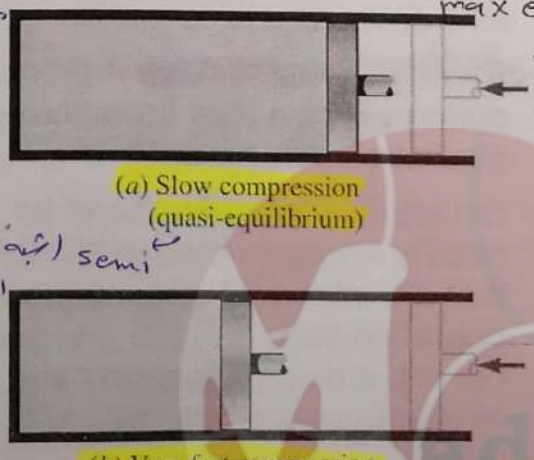
Path: The series of states through which a system passes during a process.

To describe a process completely, one should specify **the initial and final states**, as well as **the path** it follows, and the interactions with the surroundings.

Quasi-equilibrium process: When a process proceeds in such a manner that the system remains **infinitesimally close to an equilibrium** state at all times.

Characteristics:

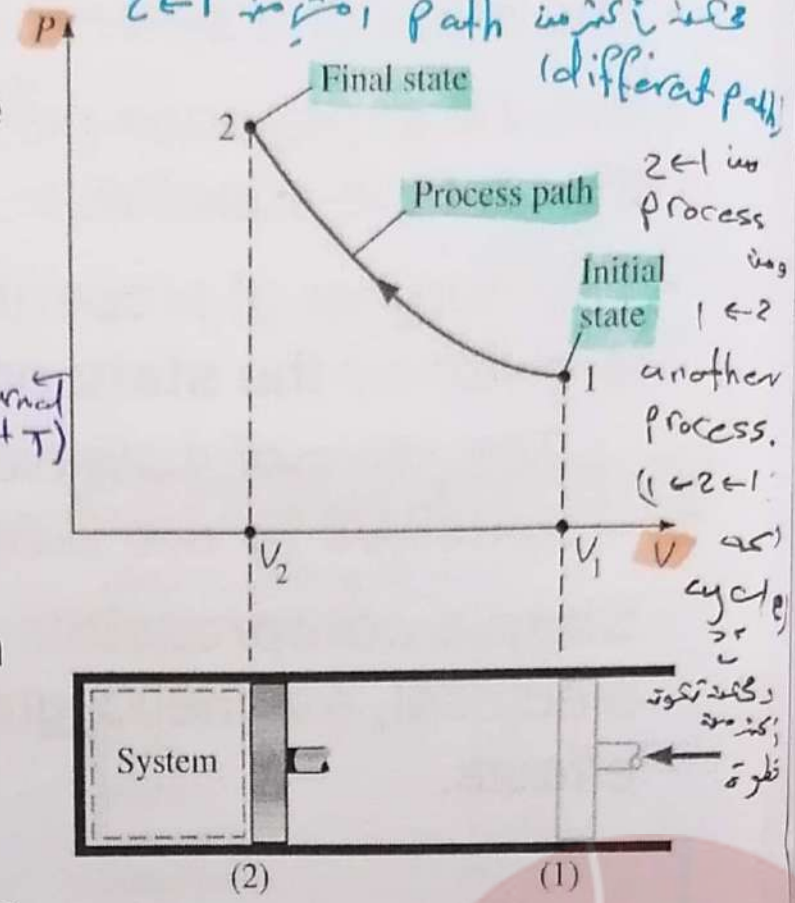
1) During a quasi-equilibrium (slow) process, the system remains practically at equilibrium at all times.
2) They are Easier to analyze (equations of state can apply).
3) Work-producing devices deliver the most work.
4) Work-consuming devices consume the least amount of work.



CamScanner الممسوحة ضوئيا بـ

PROCESSES AND CYCLES-2

- Process diagrams plotted by employing thermodynamic properties as coordinates are very useful in visualizing the processes.
- Some common properties that are used as coordinates are temperature T, pressure P, and volume V (or specific volume v).
- The prefix ***iso***- is often used to designate a process for which a particular property remains constant.
- **Isothermal process**: A process during which the temperature T remains constant.
- **Isobaric process**: A process during which the pressure P remains constant.
- **Isochoric (or isometric) process**: A process during which the specific volume v remains constant.
- **Cycle**: A process during which the initial and final states are identical.



The *P-V* diagram of a compression process.

The Steady-Flow Process

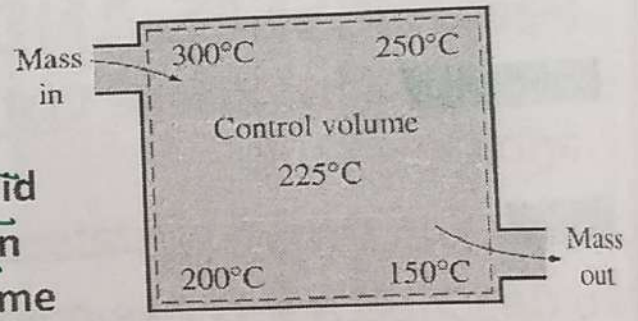
change with space → uniform

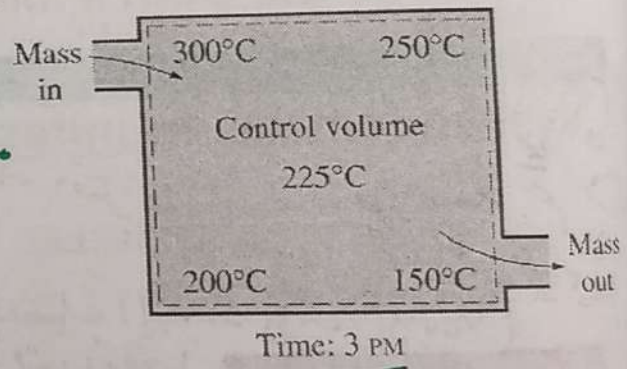
- The term *steady* implies *no change with time*. The opposite of steady is *unsteady*, or *transient*.
- A large number of engineering devices operate for long periods of time under the same conditions, and they are classified as *steady-flow devices*.
- **Steady-flow process**: A process during which a fluid flows through a control volume steadily.
- Steady-flow conditions can be closely approximated by devices that are intended for continuous operation such as turbines, pumps, boilers, condensers, and heat exchangers or power plants or refrigeration systems.

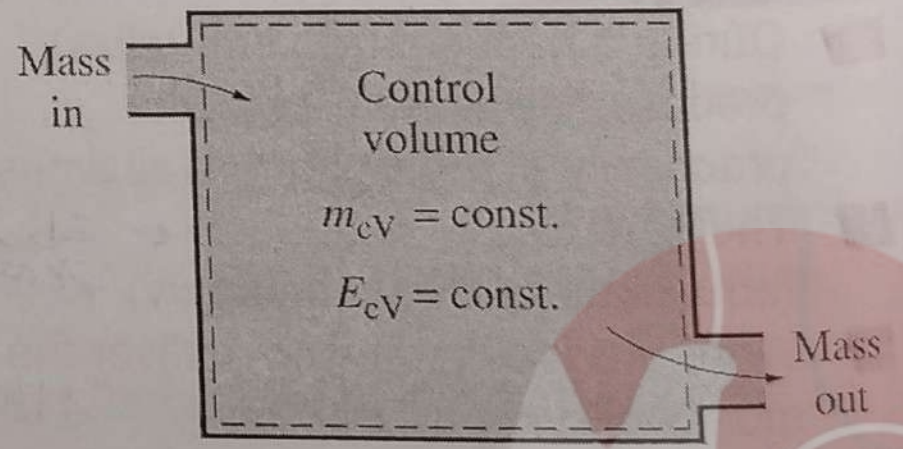
معظم اة اجهزة والمصانع تشتغل Steady state عند

During a steady-flow process, fluid properties within the control volume may change with position but not with time.

ما تتغير مع الزمن







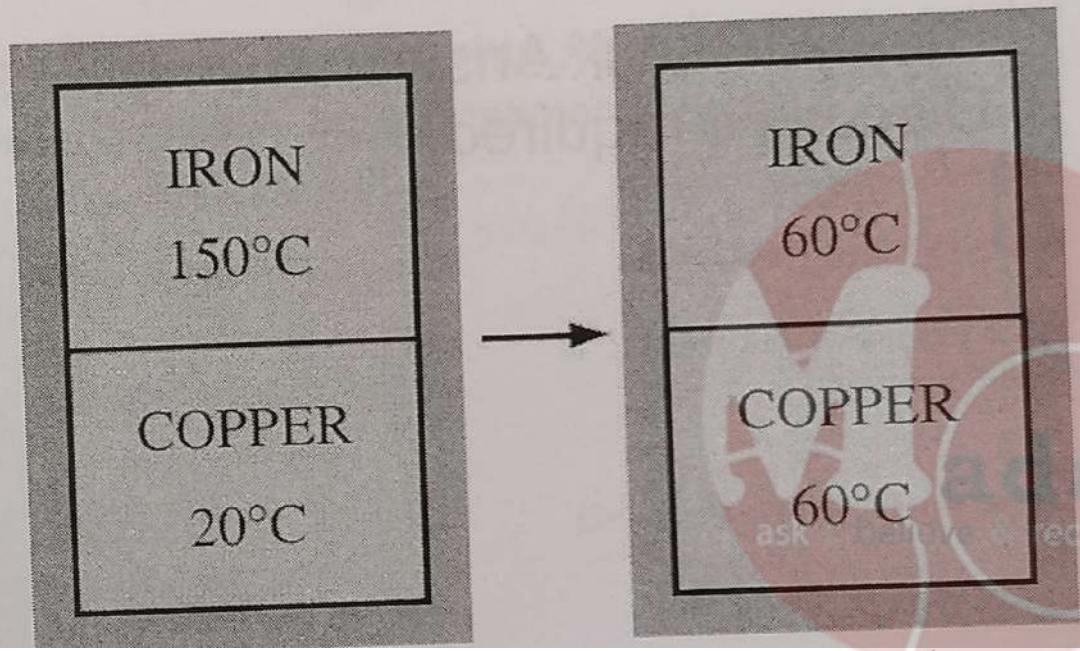
Under steady-flow conditions, the mass and energy contents of a control volume remain constant.

الممسوحة ضوئيا بـ CamScanner

TEMPERATURE AND THE ZEROTH LAW OF THERMODYNAMICS

thermal equilibrium نفس قانون ال

- **The zeroth law of thermodynamics**: If two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other.
- By replacing the third body with a thermometer, the zeroth law can be restated as *two bodies are in thermal equilibrium if both have the same temperature reading even if they are not in contact.*



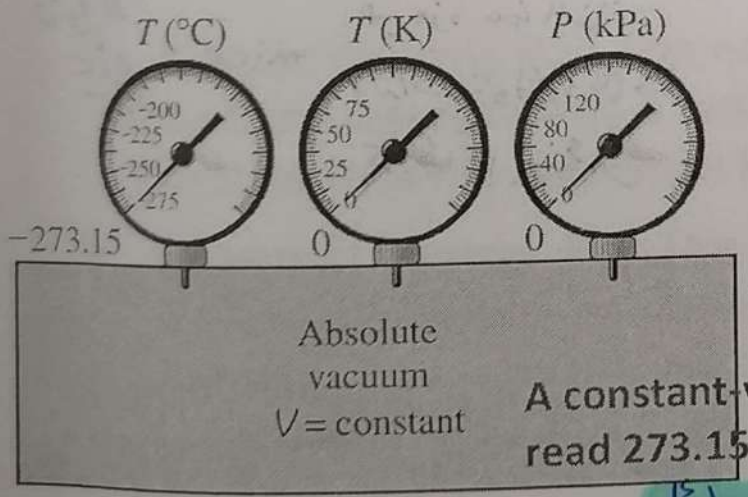
Two bodies reaching thermal equilibrium after being brought into contact in an isolated enclosure.

الممسوحة ضوئيا بـ CamScanner

absolute temp scale less relative temp scale

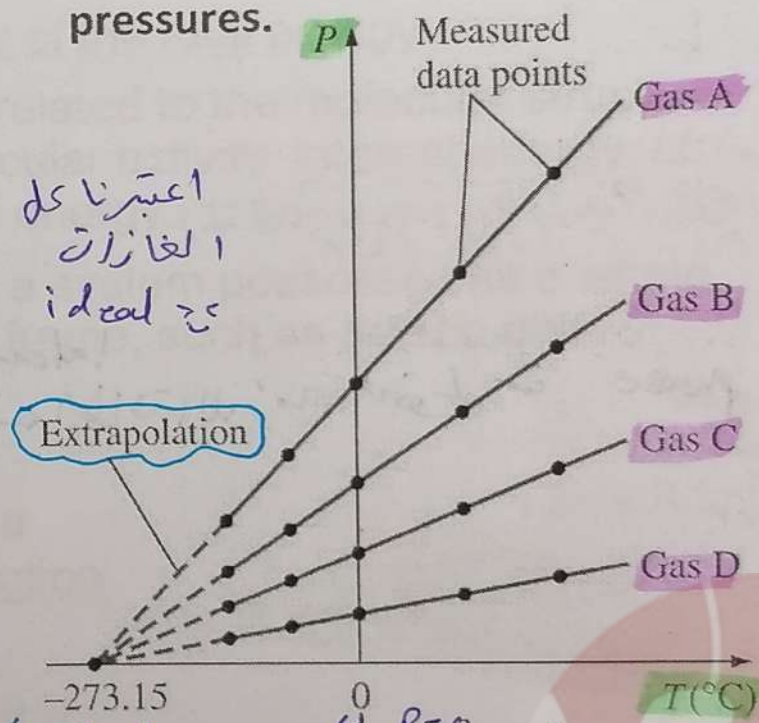
Temperature Scales

- All temperature scales are based on some easily reproducible states such as the freezing and boiling points of water: the *ice point* and the *steam point.*
- **Thermodynamic temperature scale**: A temperature scale that is independent of the properties of any substance.
- **Kelvin scale** (SI)
- A temperature scale nearly identical to the Kelvin scale is the **ideal-gas temperature scale**. The temperatures on this scale are measured using a constant-volume gas thermometer.



A constant-volume gas thermometer would read 273.15°C at absolute zero pressure.

P versus T plots of the experimental data obtained from a constant-volume gas thermometer using four different gases at different (but low) pressures.



CamScanner الممسوحة ضوئيا بـ

Forms of Energy

- Energy can exist in numerous forms such as thermal, mechanical, kinetic, potential, electric, magnetic, chemical, and nuclear, and their sum constitutes the total energy, E of a system.
- Thermodynamics deals with the *change* of the total energy.
- **Microscopic forms of energy**: Those related to the molecular structure of a system and the degree of the molecular activity. Internal energy, U: The sum of all the microscopic forms of energy.
- **Macroscopic forms of energy**: Those a system possesses as a whole with respect to some outside reference frame, such as *kinetic and potential energies*.

- **Kinetic energy, KE**: The energy that a system possesses as a result of its motion relative to some reference frame.
- **Potential energy, PE**: The energy that a system possesses as a result of its elevation in a gravitational field.

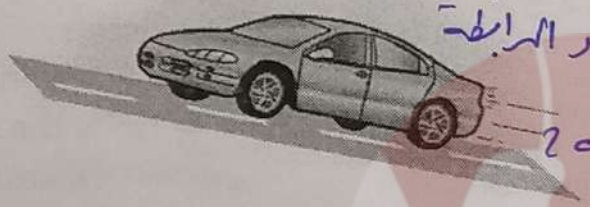


FIGURE 2–4
The macroscopic energy of an object changes with velocity and elevation.

CamScanner الممسوحة ضوئيا بـ

Energy ... numerous forms:

- Thermal
- Mechanical
- Kinetic
- Potential
- Electric
- Magnetic
- Chemical
- Nuclear

Their sum constitutes the total energy, E of a system

The total energy of a system on a unit mass:

$$e = \frac{E}{m} \quad (kJ/kg)$$

Those related to the molecular structure of a system and the degree of the molecular activity.

Internal energy, U

The sum of all the microscopic forms of energy.

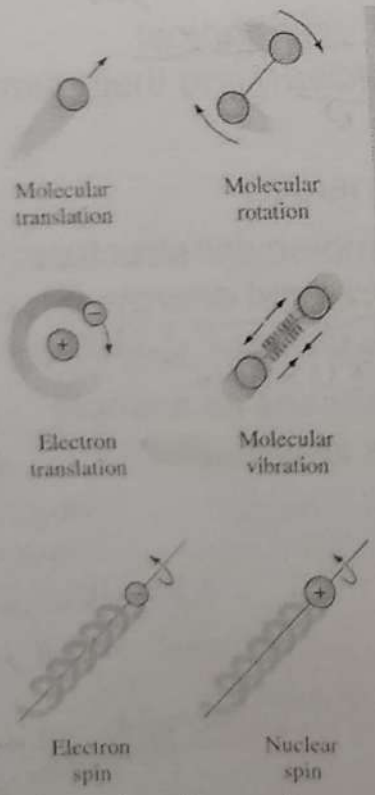
Kinetic energy, KE

The energy that a system possesses as a result of its motion relative to some reference frame.

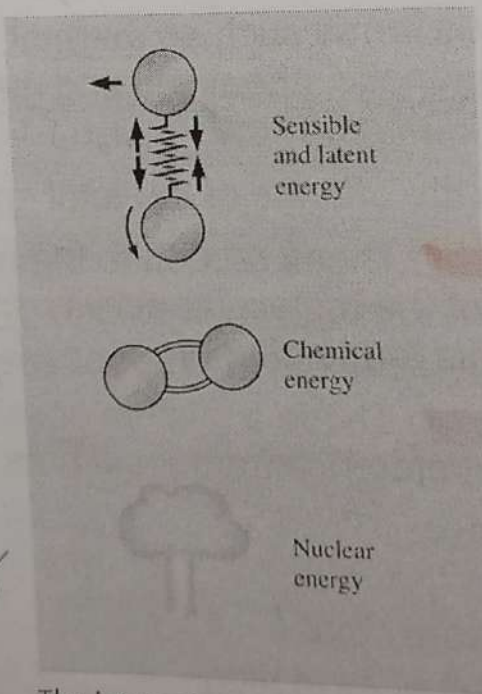
Potential energy, PE

The energy that a system possesses as a result of its elevation in a gravitational field.

Some Physical Insight to Internal Energy



The various forms of microscopic energies that make up ***sensible*** **energy.**



The internal energy of a system is the sum of all forms of the ***microscopic energies***.

Sensible energy: The portion of the internal energy of a system associated with the kinetic energies of the molecules.

Latent energy: The internal energy associated with the phase of a system.

Chemical energy: The internal energy associated with the atomi bonds in a molecule.

Nuclear energy: The tremendous amount of energy associated wit the strong bonds within the nucleus of the atom itself.

Thermal = Sensible + Latent

Internal = Sensible + Latent + Chemical + Nuclear

CamScanner الممسوحة ضوئيا بـ

* heat & work not properties for the sys (فقط process اثناء نظهر)

Energy of A System

*KE, PE & IE → are properties for the sys

1) The **total energy of a system**, can be *contained* or ***stored*** in a system, and thus can be viewed as the ***static* forms of energy**. like PE, KE, IE

2) The forms of energy ***not stored*** in a system can be viewed as the ***dynamic* forms of energy** or as ***energy interactions***. like heat & work

- ❑ The dynamic forms of energy are recognized at the system boundary as they cross it, and they represent the *energy gained or lost by a system during a process.* (عكزنه sys واثناء نظهرها boundary)
- ❑ The only two forms of energy interactions associated with a **closed system** are **heat transfer** and **work**.

3) The difference between **heat transfer** and **work:**

An energy interaction is heat transfer if its driving force is a temperature difference. Otherwise, it is work.

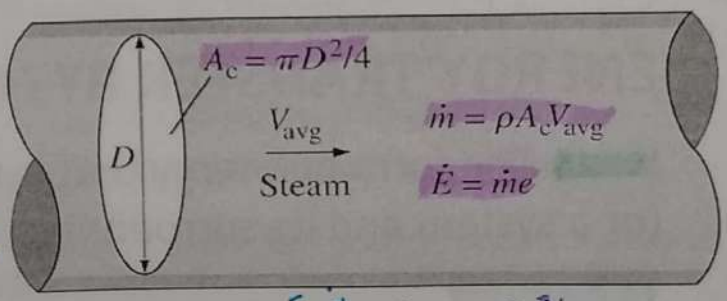
-: work اذا

1-piston rising (piston حركة)
2- rotation like mixers
3- wire passes through current

5

Energy of A System

(not energy balance)



Capital letter : tot energy
small : per unit mass

$$KE = m\frac{V^2}{2} \quad (kJ)$$ **Kinetic energy**

$$ke = \frac{V^2}{2} \quad (kJ/kg)$$ **Kinetic energy per unit mass**

$$PE = mgz \quad (kJ)$$ **Potential energy**

$$pe = gz \quad (kJ/kg)$$ **Potential energy per unit mass**

$$E = U + KE + PE = U + m\frac{V^2}{2} + mgz \quad (kJ)$$ **Total energy of a system**

Mass flow rate ← energy flow rate

$$\dot{m} = \rho\dot{V} = \rho A_c V_{avg} \quad (kg/s)$$

volume flow rate

Energy flow rate

$$\dot{E} = \dot{m}e \quad (kJ/s \text{ or } kW)$$

$A_c = \pi D^2/4$

$V_{avg} = \frac{\dot{V}}{A_c}$

الممسوحة ضوئيا بـ CamScanner

Energy of A System

(not energy balance)

Capital letter : tot energy
small " : per unit mass

$$KE = m\frac{V^2}{2} \quad (kJ)$$ Kinetic energy

$$ke = \frac{V^2}{2} \quad (kJ/kg)$$ Kinetic energy per unit mass

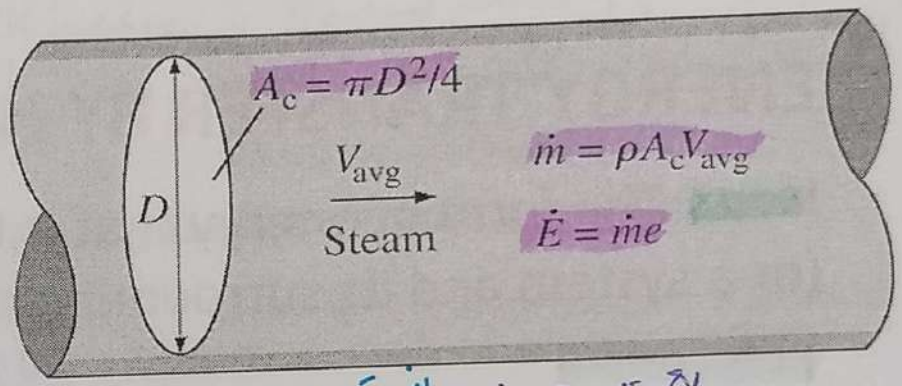
$$PE = mgz \quad (kJ)$$ Potential energy

$$pe = gz \quad (kJ/kg)$$ Potential energy per unit mass

$$E = U + KE + PE = U + m\frac{V^2}{2} + mgz \quad (kJ)$$ Total energy of a system

$$e = u + ke + pe = u + \frac{V^2}{2} + gz \quad (kJ/kg)$$ Energy of a system per unit mass

$$e = \frac{E}{m} \quad (kJ/kg)$$ Total energy per unit mass



Mass flow rate

$$\dot{m} = \rho\dot{V} = \rho A_c V_{avg} \quad (kg/s)$$

Energy flow rate

$$\dot{E} = \dot{m}e \quad (kJ/s \text{ or } kW)$$

ask : believe & recieve

الممسوحة ضوئيا بـ CamScanner

$$e = \frac{E}{m} \qquad (\text{kJ/kg})$$

Mechanical Energy

- **Mechanical energy:** The form of energy ***that can be converted to mechanical work completely*** and directly by an ideal mechanical device such as an ideal turbine.
- **Kinetic and potential energies:** The **familiar forms** of mechanical energy.

$$e_{\text{mech}} = \frac{P}{\rho} + \frac{V^2}{2} + gz$$

Mechanical energy of a flowing fluid per unit mass

$$\dot{E}_{\text{mech}} = \dot{m}e_{\text{mech}} = \dot{m}\left(\frac{P}{\rho} + \frac{V^2}{2} + gz\right)$$

Rate of mechanical energy of a flowing fluid

Mechanical energy change of a fluid during incompressible flow per unit mass

$$\Delta e_{\text{mech}} = \frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \qquad (\text{kJ/kg})$$

= rate of change

Rate of mechanical energy change of a fluid during incompressible flow

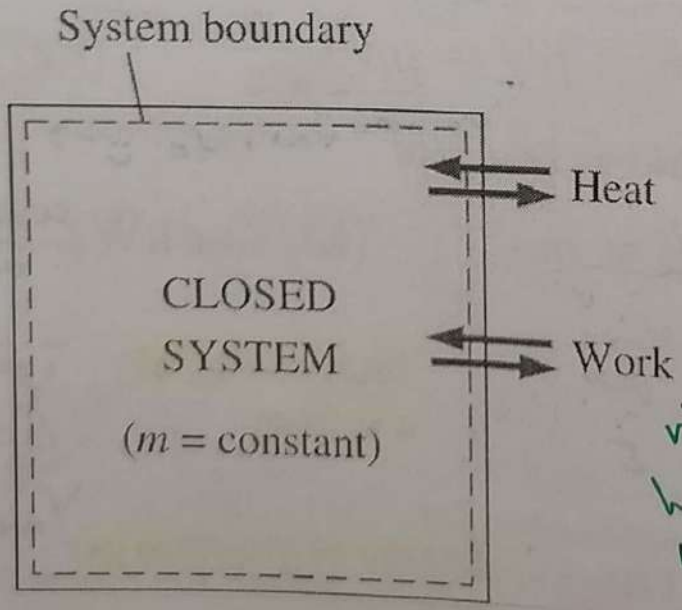
$$\Delta \dot{E}_{\text{mech}} = \dot{m}\Delta e_{\text{mech}} = \dot{m}\left(\frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right) \qquad (\text{kW})$$

(small P ∵) ≠ property of pressure

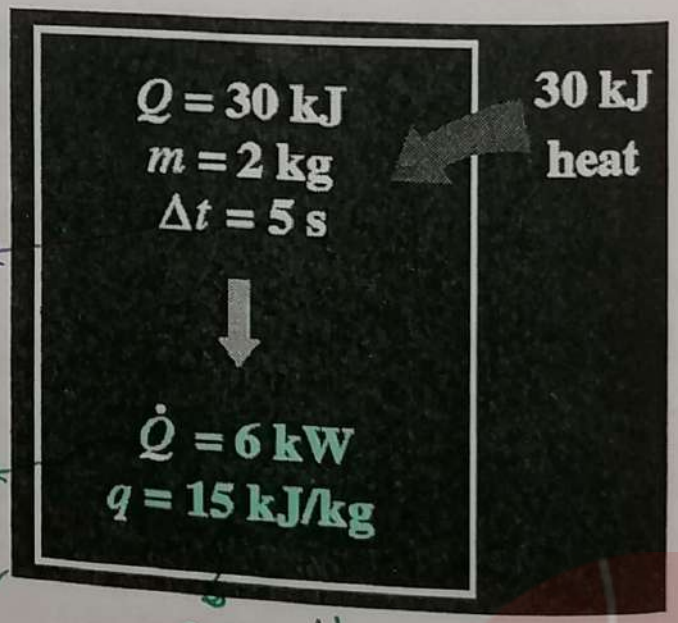
CamScanner الممسوحة ضوئيا بـ

ENERGY TRANSFER BY HEAT

Heat: The form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a *temperature difference.*



Energy can cross the boundaries of a closed system in the form of **heat** and **work.**



Heat transfer is expressed both:

- As time rate (kJ/s or KW), and
- As specific heat transfer, kJ/kg of system mass

heat & work can be express in two ways

ENERGY TRANSFER BY HEAT

$$q = \frac{Q}{m} \quad (\text{kJ/kg})$$

Heat transfer per unit mass

$$Q = \dot{Q}\,\Delta t \quad (\text{kJ})$$

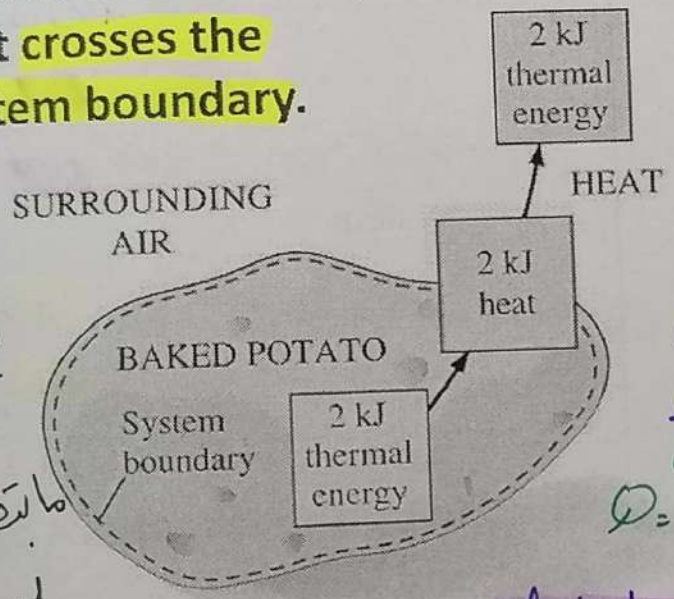
Amount of heat transfer when heat transfer rate is constant

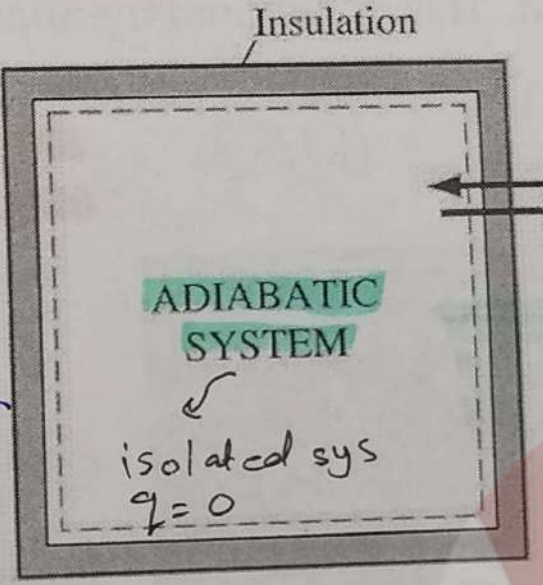
rate of heat transfer or specific heat

$$Q = \int_{t_1}^{t_2} \dot{Q}\,dt \quad (\text{kJ})$$

Amount of heat transfer when heat transfer rate changes with time

Energy is recognized as heat transfer only as it crosses the system boundary.





During an adiabatic process, a system exchanges no heat with its surroundings.

adiabatic = isentropic

CamScanner الممسوحة ضوئيا بـ

Kinetic & thermal energy مرتبطة
اذا كانت الحرارة قليلة في تفاعل

Historical Background on Heat

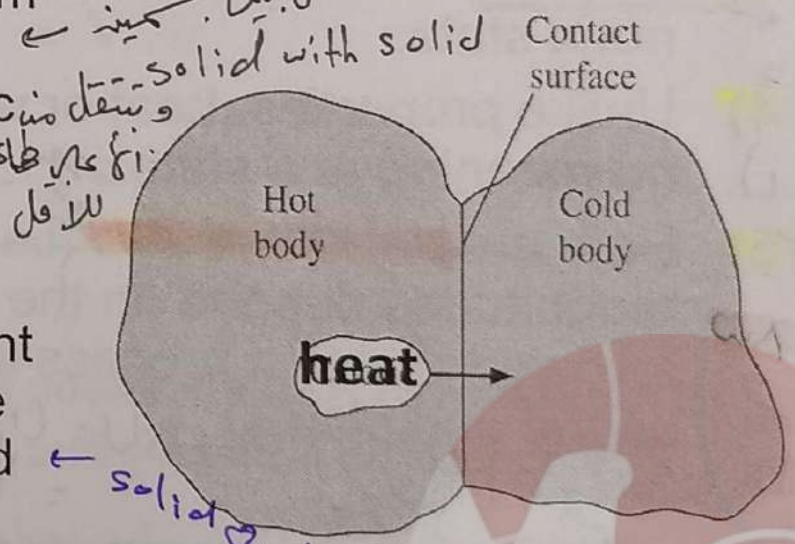
طاقة حركية
- **Kinetic theory**: Treats molecules as tiny balls that are in motion and thus possess kinetic energy.
  ال molecule
- **Heat**: The energy associated with the random motion of atoms and molecules.

كيف تنتقل الحرارة من ال sys لل surrounding والعكس!

Heat transfer mechanisms:

by 3 mechanisms :-

1. **Conduction**: The transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interaction between particles.
   انتقال بين جسمين ← solid with solid وتنتقل من الأعلى طاقة للأقل
2. **Convection**: The transfer of energy between a solid surface and the adjacent fluid that is in motion, and it involves the combined effects of conduction and fluid motion.
   الحمل الحرارة ← solid & liq phase
   فوتونات وانكاءات
3. **Radiation**: The transfer of energy due to the emission of electromagnetic waves (or photons). at high tem



(واحد بكون بارد وواحد بكون ساخن) السطح ساخن وننزل عليه بفلويد أو الفلويد ساخن بخلي السطح ساخن

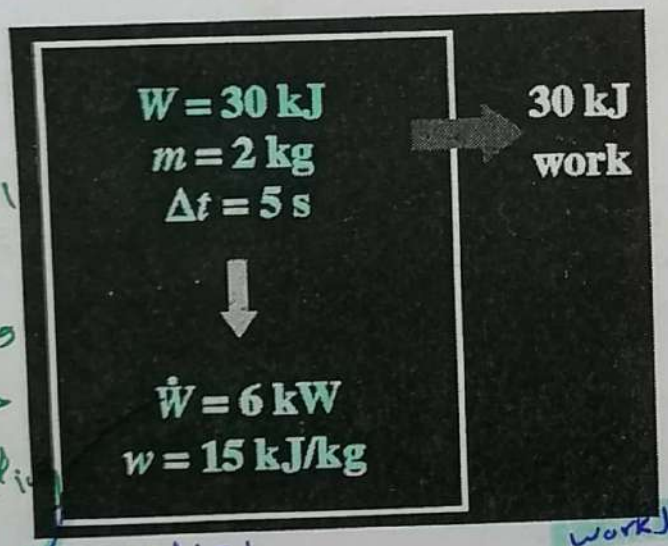
CamScanner الممسوحة ضوئيا بـ

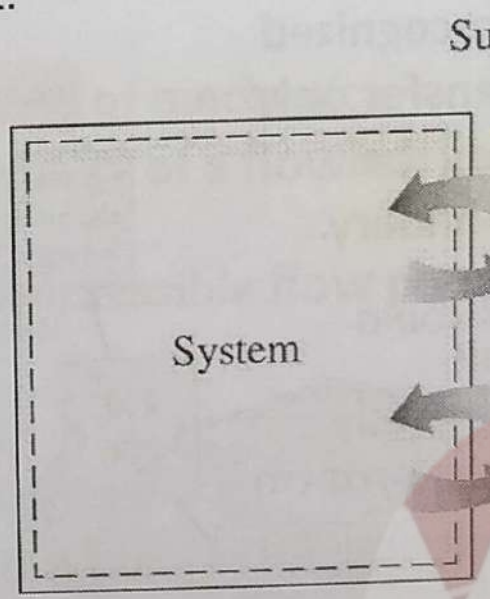
ENERGY TRANSFER BY WORK

- **Work:** The energy transfer associated with a force acting through a distance.
- **A rising piston, a rotating shaft, and an electric wire crossing the system boundaries** are all associated with work interactions
- **Formal sign convention**: *Heat transfer to a system and work done by a system are positive; heat transfer from a system and work done on a system are negative.*
- **Alternative to sign convention** is to use the subscripts ***in*** and ***out*** to indicate direction. This is the primary approach in this text.

$$w = \frac{W}{m} \qquad (\text{kJ/kg})$$

Work done per unit mass





Specifying the directions of heat and work.

Power is the work done per unit time (kW)

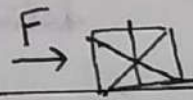
$$\dot{W} = \frac{\delta W}{\delta t}$$

$$\dot{W} = \frac{dW}{dt}$$

$$\dot{W} = F \cdot V$$

$$dW = F\,dL$$

$$W = \int F\,dL$$



heat and work.

rate of work transfer = power

$dW = F\,dL$ (function) — أول تعريف للـ work

$W = \int F\,dL$ (for solid)

Heat and Work مقارنة بينهم

1) Both are recognized at the boundaries of a system as they cross the boundaries. That is, both heat and work are *boundary* phenomena.

2) Systems possess energy, but **not** heat or work.

3) Both are associated with a *process*, not a state.

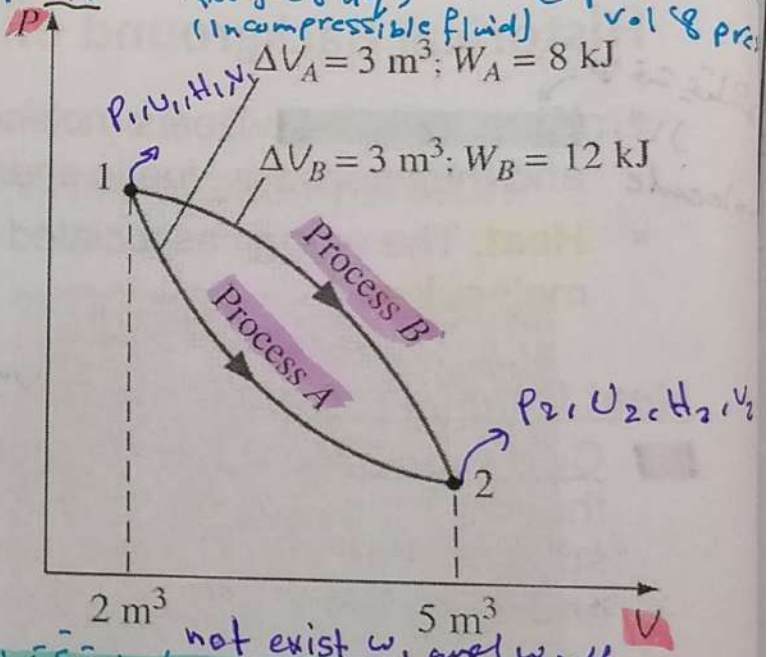
4) Unlike properties, heat or work has no meaning at a state.

5) Both are *path functions* (i.e., their magnitudes depend on the path followed during a process as well as the end states).

$dW = P(A\,dL)$

$W = \int P\,dV$ (for gas & liq) (incompressible fluid)

for gas we express it with vol & pressure



Properties are point functions; but heat and work are path functions (their magnitudes depend on the path followed).

not exist w_1 and w_2 — الـ work مش بالحالة دي

curve يتكون w_{12}

$\Delta U = U_2 - U_1 = \int_{P_1}^{P_2} dP$

w_1 & w_2 q_1 & q_2 ✗

$$\int_1^2 dV = V_2 - V_1 = \Delta V$$

تفاضل كامل

$$\int_1^2 \delta W = W_{12} \quad (not\ \Delta W)$$

inexact يعني تفاضل غير تامة

Properties are point functions; they have exact differentials (d)

Path functions have inexact differentials (δ)

الممسوحة ضوئيا بـ CamScanner

Forms of Work

❑ **Various forms of work are expressed as follows:**

› ***Electrical work:***
$$W_e = VI\Delta t \quad \textbf{(kJ)}$$

› ***Boundary work:*** or (flow work)
$$W_b = \int_1^2 P dV$$

› ***Gravitational work*** **(= ΔPE):**
$$W_g = mg(z_2 - z_1)$$

› ***Acceleration work*** **(= ΔKE):**
$$W_a = \frac{1}{2} m(\vec{V}_2^2 - \vec{V}_1^2)$$

› ***Shaft (stirring) work:***
$$W_{sh} = 2\pi n \tau$$

› ***Spring work:***
$$W_{spring} = \frac{1}{2} k(x_2^2 - x_1^2)$$

CamScanner الممسوحة ضوئيا بـ

قانون أوم: التيار يتناسب طردياً مع فرق الجهد أي يعني ← طاقة كهربائية

$V = IR$ ∴

Electrical Work

Electrical work — كمية الكهرباء

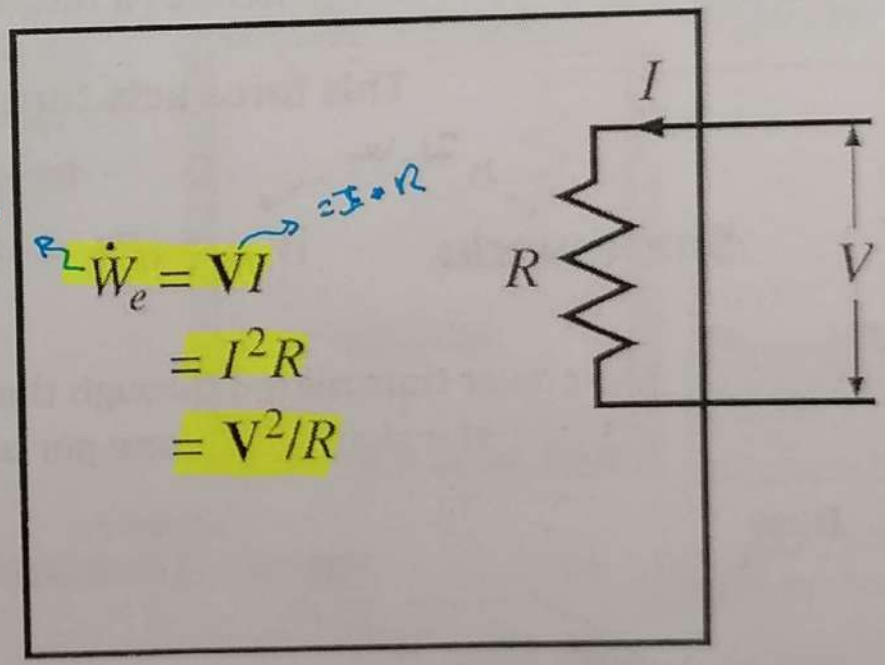
$$W_e = VN$$

V: voltage (volt)

Electrical power

$$\dot{W}_e = VI \quad (W)$$

I: current (A)



$\dot{W}_e = VI = I \cdot R$

$= I^2R$

$= V^2/R$

قسمنا على الزمن

When potential difference and current change with time

$$W_e = \int_1^2 VI\,dt \quad (kJ)$$

dt: In second

When potential difference and current remain constant

$$W_e = VI\,\Delta t \quad (kJ)$$

Electrical power in terms of resistance R, current I, and potential difference V.

→ N = coulombs of electrons move through a potential difference V

$N = I \cdot \Delta t$ ←

1 coulomb = 1 Ampere * 1 second

ohm's law: $V = I * R$

1 Joule = 1 Volt * 1 coulomb

قاس بالكولوم — قانون فاراداي: كمية الكهرباء = التيار * الزمن

$Q = I t$

[Colomb] = A * Sec

Qadar recieve

الممسوحة ضوئيا بـ CamScanner

MECHANICAL FORMS OF WORK

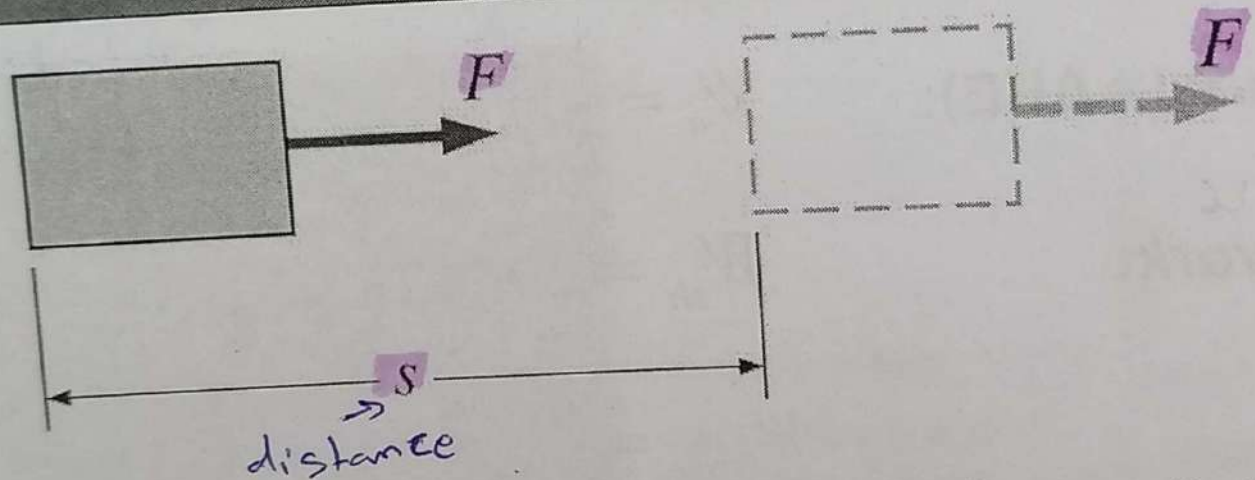
- There are two requirements for a work interaction between a system and its surroundings to exist:
  - there must be a ***force*** acting on the boundary.
  - the boundary must ***move***.

Work = Force × Distance

$$W = Fs \qquad \text{(kJ)}$$

When force is not constant

$$W = \int_1^2 F\, ds \qquad \text{(kJ)}$$



The work done is proportional to the force applied (*F*) and the distance traveled (*s*).

CamScanner الممسوحة ضوئيا بـ

قانون أوم: التيار يتناسب طردياً مع فرق الجهد أي يعني ← طاقة كهربائية

$V = IR$ ∴

Electrical Work

Electrical work — كمية الكهرباء

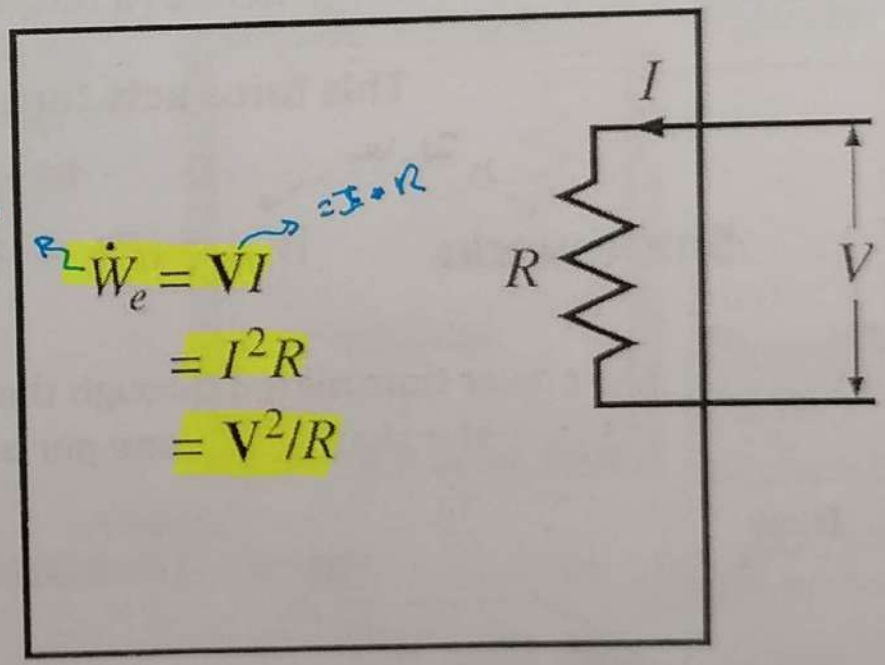
$$W_e = VN$$

V: voltage (volt)

Electrical power

$$\dot{W}_e = VI \quad (W)$$

I: current (A)



$\dot{W}_e = VI = I \cdot R$

$= I^2R$

$= V^2/R$

قسمنا على الزمن

When potential difference and current change with time

$$W_e = \int_1^2 VI\,dt \quad (kJ)$$

dt: In second

When potential difference and current remain constant

$$W_e = VI\,\Delta t \quad (kJ)$$

Electrical power in terms of resistance R, current I, and potential difference V.

→ N = coulombs of electrons move through a potential difference V

$N = I \cdot \Delta t$ ←

1 coulomb = 1 Ampere * 1 second

ohm's law: $V = I * R$

1 Joule = 1 Volt * 1 coulomb

قاس بالكولوم — قانون فاراداي: كمية الكهرباء = التيار * الزمن

$Q = I t$

[Colomb] = A * Sec

Qadar recieve

الممسوحة ضوئيا بـ CamScanner

Shaft Work

A force F acting through a moment arm r generates a torque T

$$T = Fr \quad \rightarrow \quad F = \frac{T}{r}$$

This force acts through a distance s

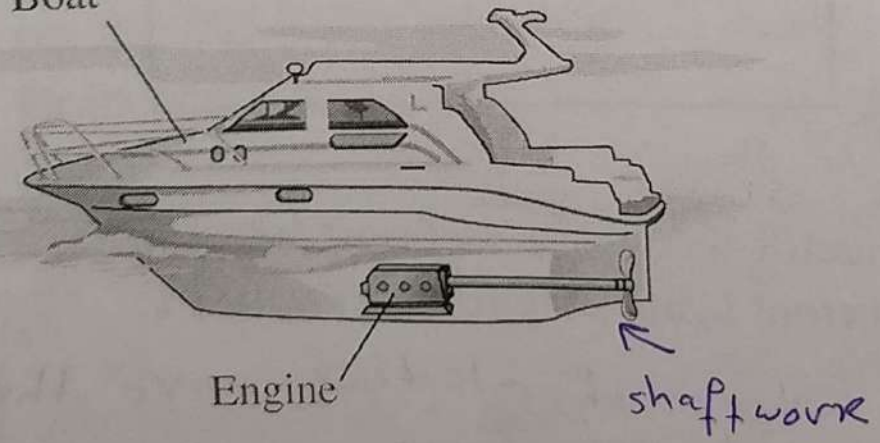
$$s = (2\pi r)n$$

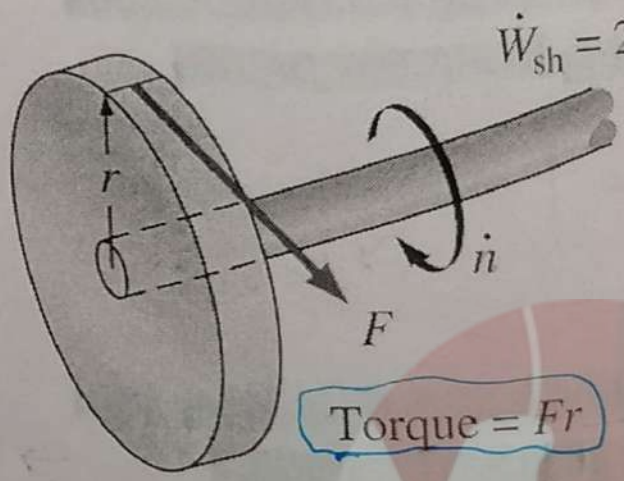
Shaft work:

$$W_{sh} = Fs = \left(\frac{T}{r}\right)(2\pi r n) = 2\pi n T \quad \text{(kJ)}$$

The power transmitted through the shaft is the shaft work done per unit time

$$\dot{W}_{sh} = 2\pi \dot{n} T \quad \text{(kW)}$$





Energy transmission through rotating shafts is commonly encountered in practice.

Shaft work is proportional to the torque applied and the number of revolutions of the shaft.

CamScanner الممسوحة ضوئيا بـ

THE FIRST LAW OF THERMODYNAMICS

- The *first law of thermodynamics* (***the conservation of energy principle***) provides a sound basis for studying the relationships among the various forms of energy and energy interactions.
- The first law states that ***energy can be neither created nor destroyed during a process; it can only change forms.***
- The *First Law*: For all adiabatic processes between two specified states of a closed system, the net work done is the same regardless of the nature of the closed system and the details of the process.

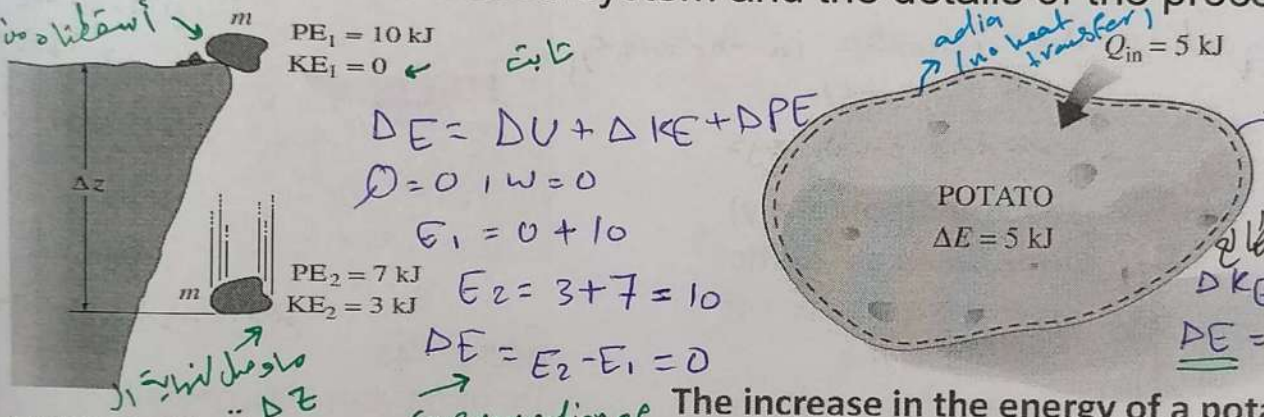
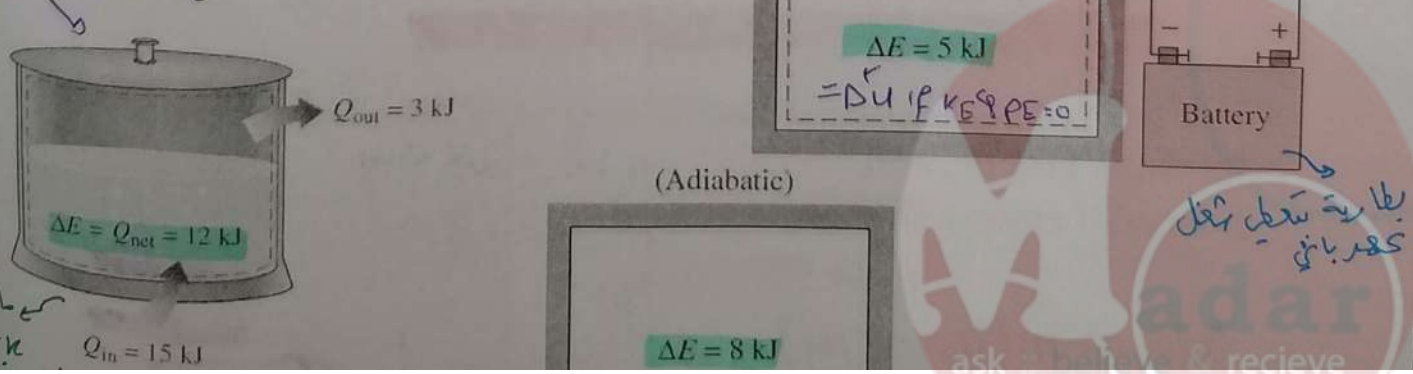


FIGURE 2–39
Energy cannot be created or destroyed; it can only change forms.

The increase in the energy of a potato in an oven is equal to the amount of heat transferred to it.

THE FIRST LAW OF THERMODYNAMICS

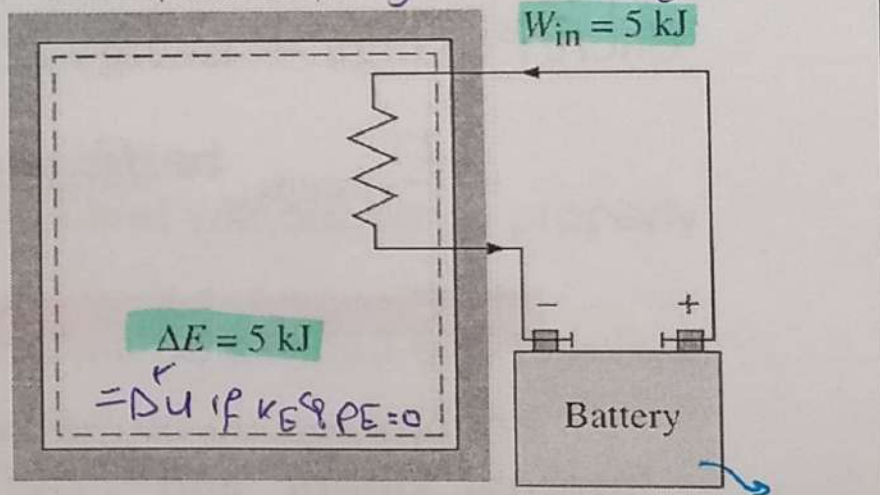
The work (electrical) done on an adiabatic system is equal to the increase in the energy of the system.



CamScanner الممسوحة ضوئيا بـ

THE FIRST LAW OF THERMODYNAMICS

The work (electrical) done on an adiabatic system is equal to the increase in the energy of the system.



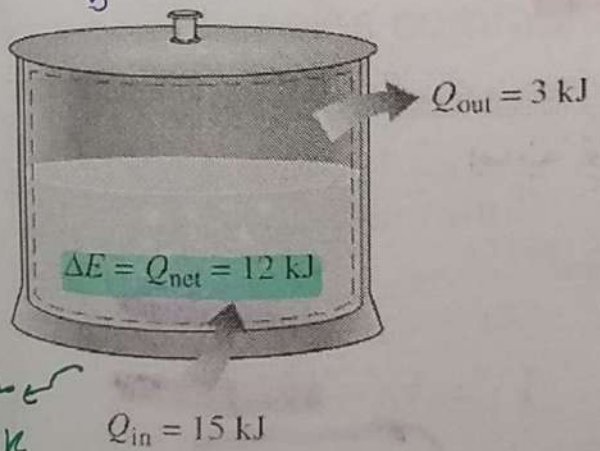
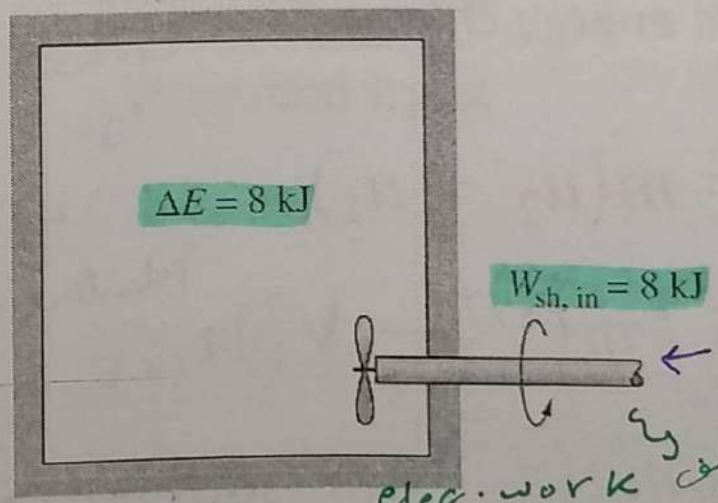


FIGURE 2–41
In the absence of any work interactions, the energy change of a system is equal to the net heat transfer.



The work (shaft) done on an adiabatic system is equal to the increase in the energy of the system.

CamScanner الممسوحة ضوئيا بـ

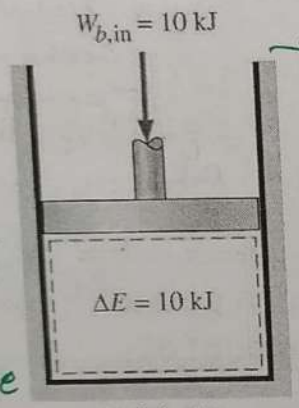
Energy Balance

*The net change (increase or decrease) in the **total energy** of the system during a process is equal to the difference between the total energy entering and the total energy leaving the system during that process.*

$$\begin{pmatrix}\text{Total energy}\\ \text{entering the system}\end{pmatrix} - \begin{pmatrix}\text{Total energy}\\ \text{leaving the system}\end{pmatrix} = \begin{pmatrix}\text{Change in the total}\\ \text{energy of the system}\end{pmatrix}$$

$$E_{in} - E_{out} = \Delta E_{system}$$

The boundary work done on an adiabatic sys is equal to the increase in the energy of the system



work done on the sys

The work (boundary) done on an adiabatic system is equal to the increase in the energy of the system.

$\Delta E = \Delta U = Q - W$

$0 - (-10) = 10$

OR: $\Delta E = \Delta U = W_{in} - W_{out}$

$= 10 - 0$

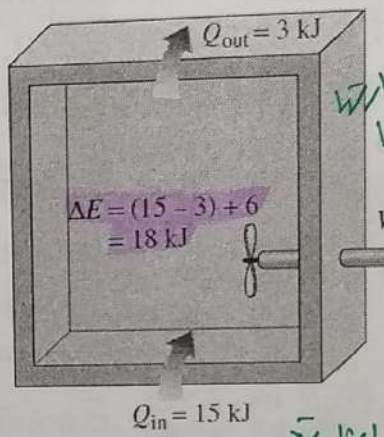


FIGURE 2–45
The energy change of a system during a process is equal to the *net* work and heat transfer between the system and its surroundings.

Energy Change of a System, ΔE_{system}

Energy change = Energy at final state − Energy at initial state

$$\Delta E_{system} = E_{final} - E_{initial} = E_2 - E_1$$

$$\Delta E = \Delta U + \Delta KE + \Delta PE$$

Internal, kinetic, and potential energy changes

$$\Delta U = m(u_2 - u_1)$$

$$\Delta KE = \frac{1}{2}m(V_2^2 - V_1^2)$$

Stationary Systems

$z_1 = z_2 \rightarrow \Delta PE = 0$

$V_1 = V_2 \rightarrow \Delta KE = 0$

$\Delta E = \Delta U$

ask recieve

الممسوحة ضوئيا بـ CamScanner

Energy Change of a System, ΔE_{system}

Energy change = Energy at final state − Energy at initial state

$$\Delta E_{system} = E_{final} - E_{initial} = E_2 - E_1$$

$$\Delta E = \Delta U + \Delta KE + \Delta PE$$

Internal, kinetic, and potential energy changes

$$\Delta U = m(u_2 - u_1)$$

$$\Delta KE = \frac{1}{2}m(V_2^2 - V_1^2)$$

$$\Delta PE = mg(z_2 - z_1)$$

Stationary Systems

$z_1 = z_2 \rightarrow \Delta PE = 0$

$V_1 = V_2 \rightarrow \Delta KE = 0$

$\Delta E = \Delta U$

Nadar ask & believe & recieve

الممسوحة ضوئيا بـ CamScanner

$\Delta = \text{In} - \text{out}$

energy balance

$\Delta T = T_2 - T_1$

$\Delta P = P_2 - P_1$

Mechanisms of Energy Transfer, E_{in} and E_{out}

$$E_{in} - E_{out} = (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass,in} - E_{mass,out}) = \Delta E_{system}$$

energy balance

1) Heat transfer
2) Work transfer
3) Mass flow

just for open sys

A closed mass involves only *heat transfer* and work.

$$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic, potential, etc., energies}} \quad \text{(kJ)}$$

الطاقة المخزنة بالجسم ونتاجة بسبب الحركة

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} \quad \text{(kW)}$$

$$Q = \dot{Q}\,\Delta t \ \text{(kJ)} \qquad W = \dot{W}\,\Delta t \qquad \Delta E = (dE/dt)\,\Delta t$$

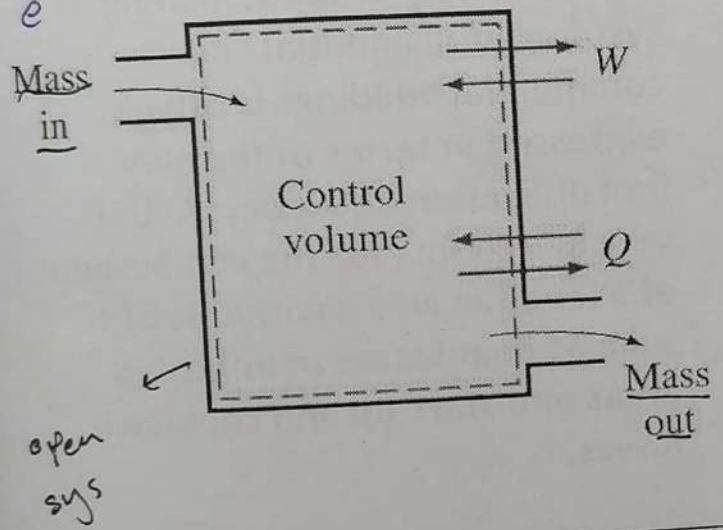
معدل تغير الـ energy

$$e_{in} - e_{out} = \Delta e_{system} \quad \text{(kJ/kg)}$$

energy per unit mass

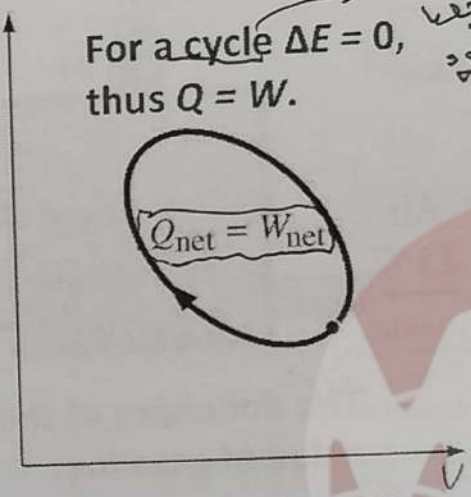
$$\delta E_{in} - \delta E_{out} = dE_{system} \qquad \delta e_{in} - \delta e_{out} = de_{system}$$

$$\dot{W}_{net,out} = \dot{Q}_{net,in} \quad \text{(for a cycle)}$$



open sys

The energy content of a control volume can be changed by mass flow as well as heat and work interactions.



For a cycle $\Delta E = 0$, thus $Q = W$.

كنا عند نقطة درجة عندما ...

ask recieve
CamScanner الممسوحة ضوئيا بـ

ENERGY CONVERSION EFFICIENCIES

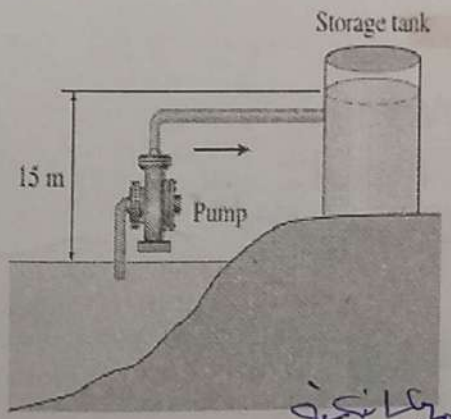
- *Efficiency* is one of the most frequently used terms in thermo-dynamics, and it indicates how well an energy conversion or transfer process is accomplished.
- *Efficiency* is also one of the most frequently misused terms in thermodynamics, because it is often used without being properly defined first.
- Some efficiencies commonly used in practice will be defined and clarified.
- *Efficiency* can be expressed in terms of the desired output and the required input as:

(In general equation) →

$$\text{Efficiency} = \frac{\text{Desired output}}{\text{Required input}}$$

← عم حطت مقارنة بالي حطيتيه

Example:



← رفعت الي من مكان لمكان عن طريق طاقة ميكانيكية

$$\eta_{\text{pump}} = \frac{\Delta \dot{E}_{\text{mech,fluid}}}{\dot{W}_{\text{shaft,in}}} = \frac{\dot{W}_{\text{pump},u}}{\dot{W}_{\text{pump}}}$$

useful

الـ shaftwork تحولت إلى طاقة ميكانيكية مخزنة بالي

ask & believe & recieve
الممسوحة ضوئيا بـ CamScanner

losses

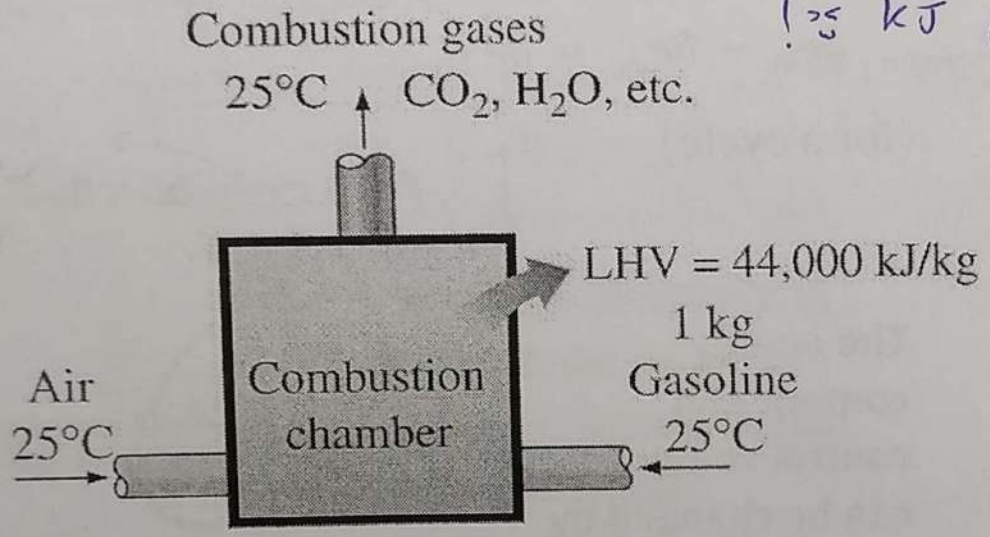
Combustion

$$\eta_{combustion} = \frac{Q}{HV} = \frac{\text{Amount of heat released during combustion}}{\text{Heating value of the fuel burned}}$$

Heating value of the fuel: The amount of heat released when a unit amount of fuel at room temperature is completely burned, and the combustion products are cooled to the room temperature.

Lower heating value (LHV): When the water leaves as a vapor.

Higher heating value (HHV): When the water in the combustion gases is completely condensed and thus the heat of vaporization is also recovered.

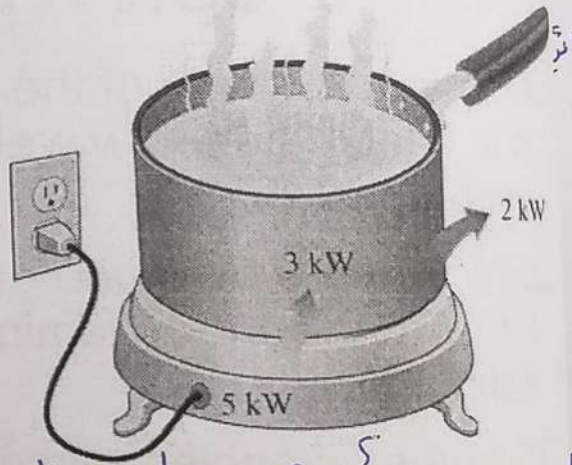


The definition of the heating value of gasoline.

The efficiency of space heating systems of residential and commercial buildings is usually expressed in terms of the annual fuel utilization efficiency (AFUE), which accounts for the combustion efficiency as well as other losses such as heat losses to unheated areas and start-up and cooldown losses.

CamScanner الممسوحة ضوئيا بـ

The efficiency of a **cooking appliance** represents the fraction of the energy supplied to the appliance that is transferred to the food.



$$\text{Efficiency} = \frac{\text{Energy utilized}}{\text{Energy supplied to appliance}}$$

$$= \frac{3\ \text{kWh}}{5\ \text{kWh}} = 0.60$$

Power Plants

- **Generator:** A device that converts mechanical energy to electrical energy.
- **Generator efficiency:** The ratio of the electrical power output to the mechanical power input.
- **Thermal efficiency of a power plant:**

  The ratio of the net electrical power output to the rate of fuel energy input:

$$\eta_{overall} = \eta_{combustion}\,\eta_{thermal}\,\eta_{generator} = \frac{\dot{W}_{net,electric}}{HHV \times \dot{m}_{fuel}}$$

$$\dot{W}_{net,mech} \times \frac{\dot{W}_{net,elect}}{\dot{W}_{net,mech}} =$$

CamScanner المسوحة ضوئيا بـ

Efficiencies of Mechanical and Electrical Devices

Mechanical efficiency

$$\eta_{mech} = \frac{\text{Mechanical energy output}}{\text{Mechanical energy input}} = \frac{E_{mech,out}}{E_{mech,in}} = 1 - \frac{E_{mech,loss}}{E_{mech,in}}$$

The effectiveness of the conversion process between the mechanical work supplied or extracted and the mechanical energy of the fluid is expressed by the pump efficiency and turbine efficiency:

$$\eta_{pump} = \frac{\text{Mechanical energy increase of the fluid}}{\text{Mechanical energy input}} = \frac{\Delta \dot{E}_{mech,fluid}}{\dot{W}_{shaft,in}} = \frac{\dot{W}_{pump,u}}{\dot{W}_{pump}}$$

$$\Delta \dot{E}_{mech,fluid} = \dot{E}_{mech,out} - \dot{E}_{mech,in}$$

$$\eta_{turbine} = \frac{\text{Mechanical energy output}}{\text{Mechanical energy decrease of the fluid}} = \frac{\dot{W}_{shaft,out}}{|\Delta \dot{E}_{mech,fluid}|} = \frac{\dot{W}_{turbine}}{\dot{W}_{turbine,e}}$$

$$|\Delta \dot{E}_{mech,fluid}| = \dot{E}_{mech,in} - \dot{E}_{mech,out}$$

$$\eta_{motor} = \frac{\text{Mechanical power output}}{\text{Electric power input}} = \frac{\dot{W}_{shaft,out}}{\dot{W}_{elect,in}}$$

Pump efficiency

$$\eta_{pump} = \frac{\dot{W}_{pump,u}}{\dot{W}_{shaft,in}} = \frac{\Delta \dot{E}_{mech,fluid}}{\dot{W}_{shaft,in}}$$

Generator efficiency

$$\eta_{generator} = \frac{\text{Electric power output}}{\text{Mechanical power input}} = \frac{\dot{W}_{elect,out}}{\dot{W}_{shaft,in}}$$

Pump-Motor overall efficiency

$$\eta_{pump-motor} = \eta_{pump}\eta_{motor} = \frac{\dot{W}_{pump,u}}{\dot{W}_{elect,in}} = \frac{\Delta \dot{E}_{mech,fluid}}{\dot{W}_{elect,in}}$$

Turbine-Generator overall efficiency

$$\eta_{turbine-gen} = \eta_{turbine}\eta_{generator} = \frac{\dot{W}_{elect,out}}{\dot{W}_{turbine,e}} = \frac{\dot{W}_{elect,out}}{|\Delta \dot{E}_{mech,fluid}|}$$

$\eta_{turbine} = 0.75 \quad \eta_{generator} = 0.97$

الممسوحة ضوئيا بـ CamScanner

$|\Delta E_{\text{mech,fluid}}|$ $E_{\text{mech,in}}$ $E_{\text{mech,out}}$

generator

useful work وبستفيد منه ... مش كل الـ shaft بعطينا

Motor efficiency

$$\eta_{\text{motor}} = \frac{\text{Mechanical power output}}{\text{Electric power input}} = \frac{\dot{W}_{\text{shaft,out}}}{\dot{W}_{\text{elect,in}}}$$

Pump efficiency

$$\eta_{\text{pump}} = \frac{\Delta \dot{E}_{\text{mech,fluid}}}{\dot{W}_{\text{shaft}}}$$

Generator efficiency

$$\eta_{\text{generator}} = \frac{\text{Electric power output}}{\text{Mechanical power input}} = \frac{\dot{W}_{\text{elect,out}}}{\dot{W}_{\text{shaft,in}}}$$

Pump-Motor overall efficiency

$$\eta_{\text{pump-motor}} = \eta_{\text{pump}}\eta_{\text{motor}} = \frac{\dot{W}_{\text{pump},u}}{\dot{W}_{\text{elect,in}}} = \frac{\Delta \dot{E}_{\text{mech,fluid}}}{\dot{W}_{\text{elect,in}}}$$

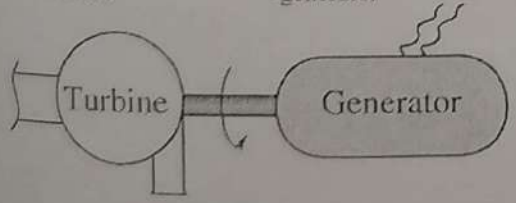
this is the system

Turbine-Generator overall efficiency

$$\eta_{\text{turbine-gen}} = \eta_{\text{turbine}}\eta_{\text{generator}} = \frac{\dot{W}_{\text{elect,out}}}{\dot{W}_{\text{turbine},e}} = \frac{\dot{W}_{\text{elect,out}}}{|\Delta \dot{E}_{\text{mech,fluid}}|}$$

flowrate — heat

$\eta_{\text{turbine}} = 0.75$ $\eta_{\text{generator}} = 0.97$



$$\eta_{\text{turbine-gen}} = \eta_{\text{turbine}}\eta_{\text{generator}} = 0.75 \times 0.97 = 0.73$$

The overall efficiency of a turbine–generator is **the product of** the efficiency of the turbine and the efficiency of the generator and represents the fraction of the mechanical energy of the fluid converted to electric energy.

working fluid ... steam

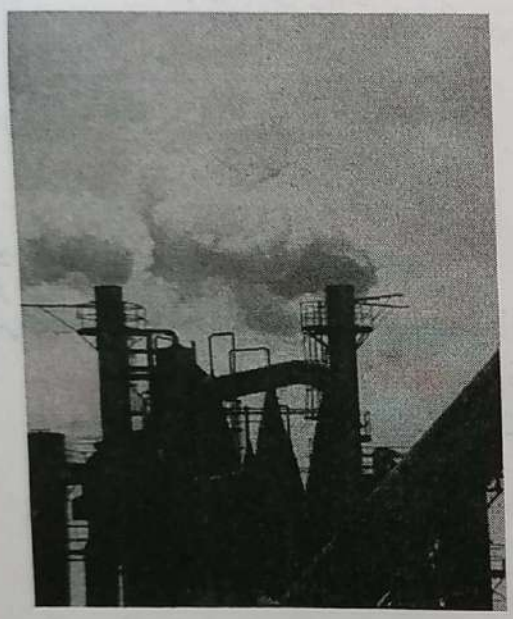
(working fluid) ما في إنتاج طاقة إلا فيه فلويد

Qadar ask · believe & recieve
الممسوحة ضوئيا بـ CamScanner

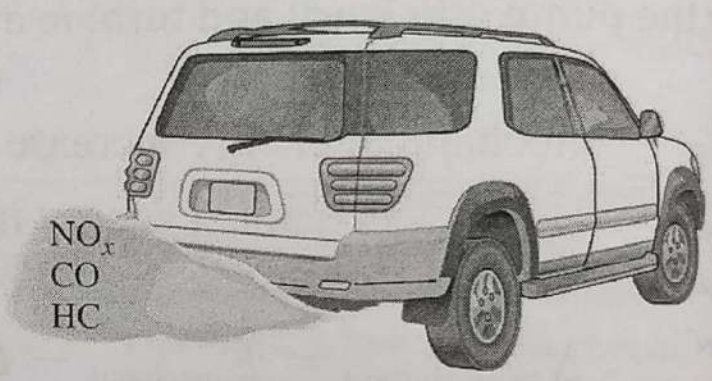
ENERGY AND ENVIRONMENT

Reading

- The conversion of energy from one form to another often affects the environment and the air we breathe in many ways, and thus the study of energy is not complete without considering its impact on the environment.
- Pollutants emitted during the combustion of fossil fuels are responsible for **smog**, **acid rain**, and **global warming**.
- The environmental pollution has reached such high levels that it became a serious threat to **vegetation**, **wildlife**, and **human health**.



Energy conversion processes are often accompanied by environmental pollution.



Motor vehicles are the largest source of air pollution.

EXAMPLE 2–2 **Wind Energy**

A site evaluated for a wind farm is observed to have steady winds at a speed of 8.5 m/s (Fig. 2–13). Determine the wind energy (*a*) per unit mass, (*b*) for a mass of 10 kg, and (*c*) for a flow rate of 1154 kg/s for air.

SOLUTION A site with a specified wind speed is considered. Wind energy per unit mass, for a specified mass, and for a given mass flow rate of air are to be determined.

Assumptions Wind flows steadily at the specified speed.

Analysis The only harvestable form of energy of atmospheric air is the kinetic energy, which is captured by a wind turbine.

(a) Wind energy per unit mass of air is

$$e = \text{ke} = \frac{V^2}{2} = \frac{(8.5\ \text{m/s})^2}{2}\left(\frac{1\ \text{J/kg}}{1\ \text{m}^2/\text{s}^2}\right) = 36.1\ \text{J/kg}$$

(b) Wind energy for an air mass of 10 kg is

الممسوحة ضوئيا بـ CamScanner

EXAMPLE 2–2 **Wind Energy**

A site evaluated for a wind farm is observed to have steady winds at a speed of 8.5 m/s (Fig. 2–13). Determine the wind energy (*a*) per unit mass, (*b*) for a mass of 10 kg, and (*c*) for a flow rate of 1154 kg/s for air.

SOLUTION A site with a specified wind speed is considered. Wind energy per unit mass, for a specified mass, and for a given mass flow rate of air are to be determined.

Assumptions Wind flows steadily at the specified speed.

Analysis The only harvestable form of energy of atmospheric air is the kinetic energy, which is captured by a wind turbine.

(a) Wind energy per unit mass of air is

$$e = \text{ke} = \frac{V^2}{2} = \frac{(8.5\ \text{m/s})^2}{2}\left(\frac{1\ \text{J/kg}}{1\ \text{m}^2/\text{s}^2}\right) = 36.1\ \text{J/kg}$$

(b) Wind energy for an air mass of 10 kg is

$$E = me = (10\ \text{kg})(36.1\ \text{J/kg}) = 361\ \text{J}$$

(c) Wind energy for a mass flow rate of 1154 kg/s is

$$\dot{E} = \dot{m}e = (1154\ \text{kg/s})(36.1\ \text{J/kg})\left(\frac{1\ \text{kW}}{1000\ \text{J/s}}\right) = 41.7\ \text{kW}$$



CamScanner الممسوحة ضوئيا بـ

EXAMPLE 2–10 Cooling of a Hot Fluid in a Tank

A rigid tank contains a hot fluid that is cooled while being stirred by a paddle wheel. Initially, the internal energy of the fluid is 800 kJ. During the cooling process, the fluid loses 500 kJ of heat, and the paddle wheel does 100 kJ of work on the fluid. Determine the final internal energy of the fluid. Neglect the energy stored in the paddle wheel.

SOLUTION A fluid in a rigid tank looses heat while being stirred. The final internal energy of the fluid is to be determined.

Assumptions 1 The tank is stationary and thus the kinetic and potential energy changes are zero, $\Delta KE = \Delta PE = 0$. Therefore, $\Delta E = \Delta U$ and internal energy is the only form of the system's energy that may change during this process. 2 Energy stored in the paddle wheel is negligible.

Analysis Take the contents of the tank as the system (Fig. 2–49). This is a *closed system* since no mass crosses the boundary during the process.

We observe that the volume of a rigid tank is constant, and thus there is no moving boundary work. Also, heat is lost from the system and shaft work is done on the system. Applying the energy balance on the system gives

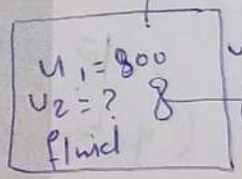
$$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic, potential, etc., energies}}$$

$$W_{sh,in} - Q_{out} = \Delta U = U_2 - U_1$$

$$100 \text{ kJ} - 500 \text{ kJ} = U_2 - 800 \text{ kJ}$$

$$U_2 = 400 \text{ kJ}$$

Therefore, the final internal energy of the system is 400 kJ.



EXAMPLE 2–15 Power Generation from a Hydroelectric Plant

Electric power is to be generated by installing a hydraulic turbine–generator at a site 70 m below the free surface of a large water reservoir that can supply water at a rate of 1500 kg/s steadily (Fig. 2–60). If the mechanical power output of the turbine is 800 kW and the electric power generation is 750 kW, determine the turbine efficiency and the combined turbine–generator efficiency of this plant. Neglect losses in the pipes.

SOLUTION A hydraulic turbine-generator installed at a large reservoir is to generate electricity. The combined turbine–generator efficiency and the turbine efficiency are to be determined.

Assumptions 1 The water elevation in the reservoir remains constant. 2 The mechanical energy of water at the turbine exit is negligible.

Analysis We take the free surface of water in the reservoir to be point 1

CamScanner الممسوحة ضوئيا بـ

EXAMPLE 2–15 Power Generation from a Hydroelectric Plant

Electric power is to be generated by installing a hydraulic turbine–generator at a site 70 m below the free surface of a large water reservoir that can supply water at a rate of 1500 kg/s steadily (Fig. 2–60). If the mechanical power output of the turbine is 800 kW and the electric power generation is 750 kW, determine the turbine efficiency and the combined turbine–generator efficiency of this plant. Neglect losses in the pipes.

SOLUTION A hydraulic turbine-generator installed at a large reservoir is to generate electricity. The combined turbine–generator efficiency and the turbine efficiency are to be determined.

Assumptions 1 The water elevation in the reservoir remains constant. 2 The mechanical energy of water at the turbine exit is negligible.

Analysis We take the free surface of water in the reservoir to be point 1 and the turbine exit to be point 2. We also take the turbine exit as the reference level ($z_2 = 0$) so that the potential energies at 1 and 2 are $pe_1 = gz_1$ and $pe_2 = 0$. The flow energy P/ρ at both points is zero since both 1 and 2 are open to the atmosphere ($P_1 = P_2 = P_{atm}$). Further, the kinetic energy at both points is zero ($ke_1 = ke_2 = 0$) since the water at point 1 is essentially motionless, and the kinetic energy of water at turbine exit is assumed to be negligible. The potential energy of water at point 1 is

adar ask · believe & recieve
الممسوحة ضوئيا بـ CamScanner

$$pe_1 = gz_1 = (9.81\ \text{m/s}^2)(70\ \text{m})\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = 0.687\ \text{kJ/kg}$$

Then the rate at which the mechanical energy of water is supplied to the turbine becomes

$$|\Delta \dot{E}_{\text{mech, fluid}}| = \dot{m}(e_{\text{mech, in}} - e_{\text{mech, out}}) = \dot{m}(pe_1 - 0) = \dot{m}pe_1$$
$$= (1500\ \text{kg/s})(0.687\ \text{kJ/kg})$$
$$= 1031\ \text{kW}$$

The combined turbine–generator and the turbine efficiency are determined from their definitions to be

$$\eta_{\text{turbine-gen}} = \frac{\dot{W}_{\text{elect, out}}}{|\Delta \dot{E}_{\text{mech, fluid}}|} = \frac{750\ \text{kW}}{1031\ \text{kW}} = 0.727 \text{ or } 72.7\%$$

$$\eta_{\text{turbine}} = \frac{\dot{W}_{\text{elect, out}}}{|\dot{E}_{\text{mech, fluid}}|} = \frac{800\text{kW}}{1031\text{kW}} = 0.776 \text{ or } 77.6\%$$

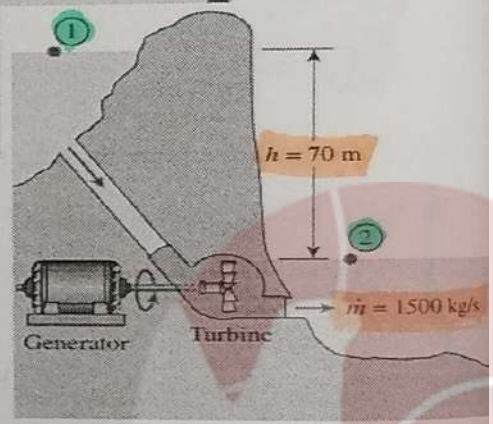


FIGURE 2-60
Schematic for Example 2-15

Mazar
ask & believe & recieve

الممسوحة ضوئيا بـ CamScanner



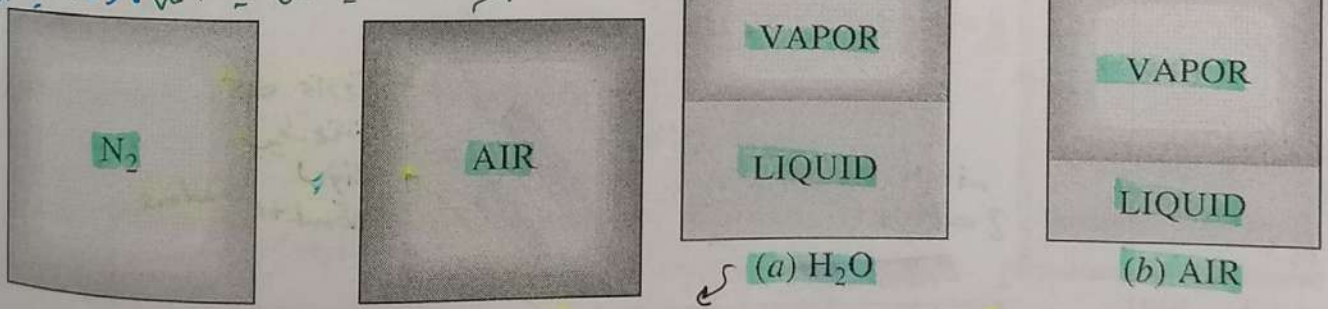
SUBSTANCES

Thermodynamics: An Engineering Approach
Yunus A. Cengel, Michael A. Boles, Mehmet Kanoglu
McGraw-Hill

Dr. Ahmad M. AbuYaghi
October 2023

PURE SUBSTANCE

- **Pure substance**: A substance that has a fixed chemical composition throughout.
- Air is a mixture of several gases, but it is considered to be a pure substance.

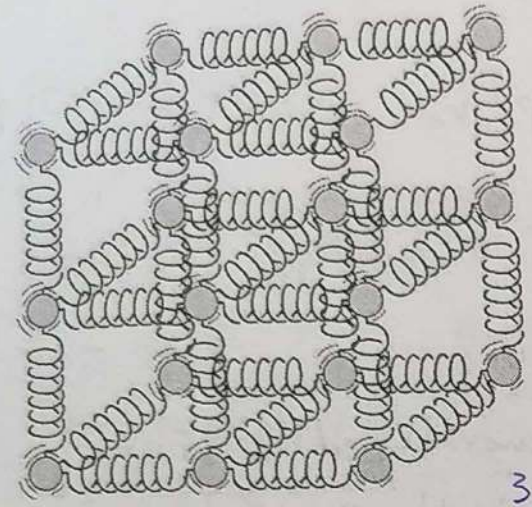


Nitrogen and gaseous air are pure substances.

A mixture of liquid and gaseous water is a pure substance, but a mixture of liquid and gaseous air is not.

* PHASES OF A PURE SUBSTANCE *

Inter & Intra molecular



The molecules in a solid are kept at their positions by the large springlike inter-molecular forces.



→ If we break it will get :-

Intramolecular $H_2O \rightarrow H_2 + \frac{1}{2} O_2$

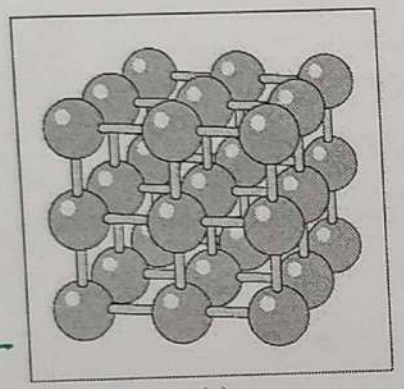
$H_2O - H_2O$ → If we break it will get s → L → g

Intermolecular

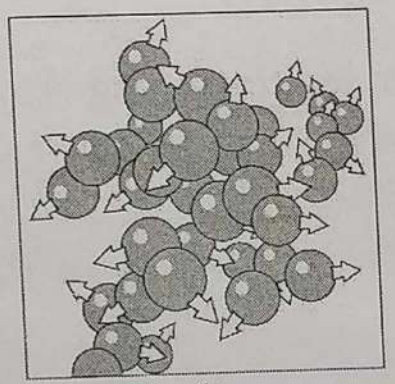
3 Types of substance :-

(3 phase change)

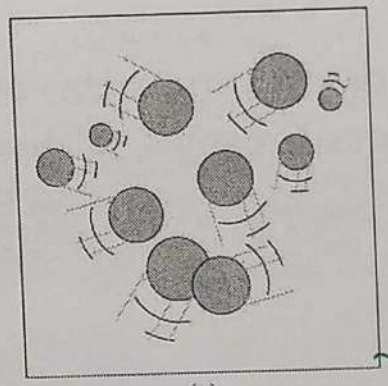
In a solid, the attractive and repulsive forces between the molecules tend to maintain them at relatively constant distances from each other.



Solid (a)



(b) liq



(c) gas

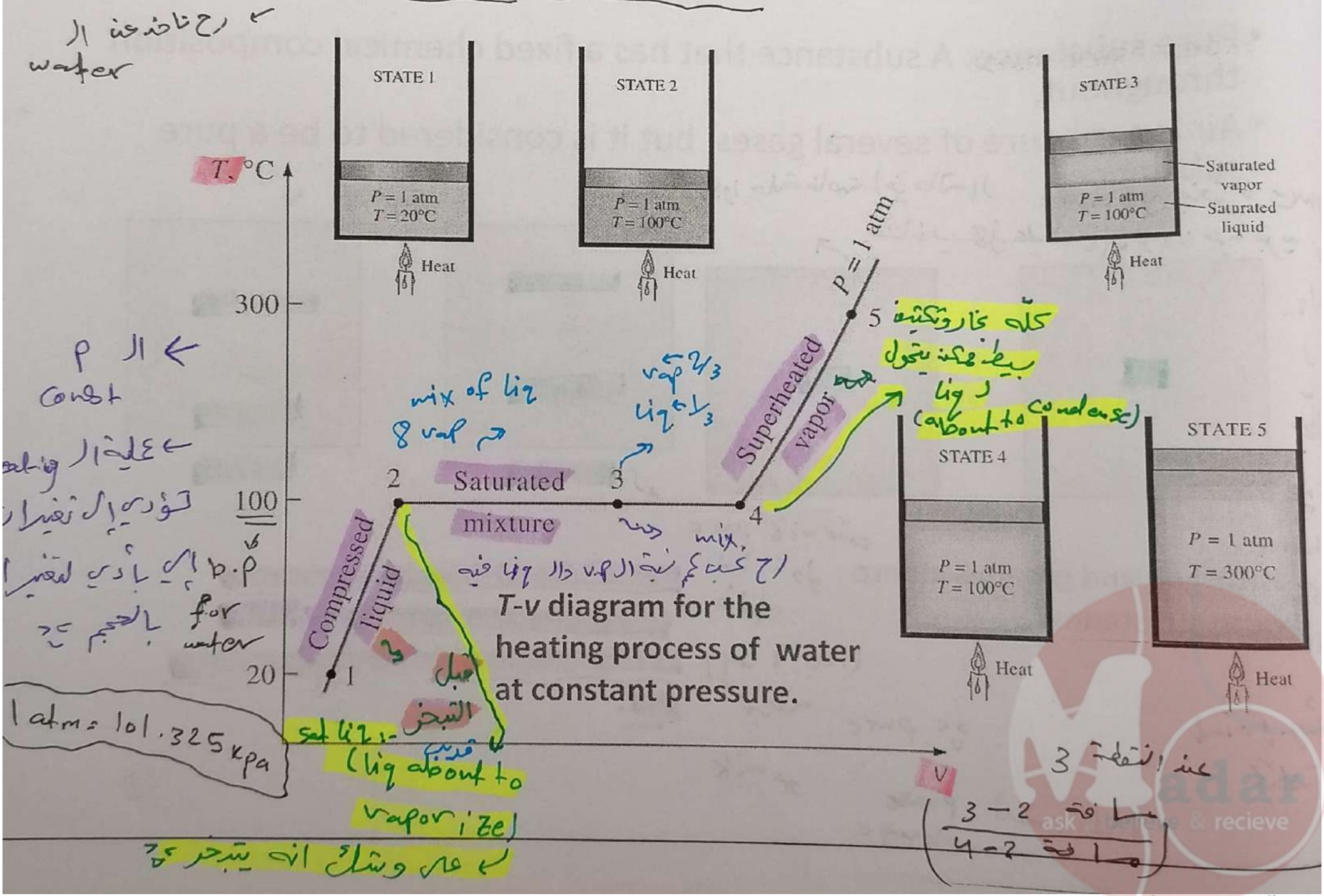
كل ما نعطي حرارة للمادة كل molecule بياخدها طاقة حركة ف بتبعد عن بعض وبتكسر الـ Intermolecular forces وبتتحول لـ liq وبعدين لـ gas

The arrangement of atoms in different phases: (*a*) molecules are at relatively fixed positions in a solid, (*b*) groups of molecules move about each other in the liquid phase, and (*c*) molecules move about at random in the gas phase.

Madar ask & believe & recieve

الممسوحة ضوئيا بـ CamScanner

PHASE-CHANGE PROCESSES OF PURE SUBSTANCES

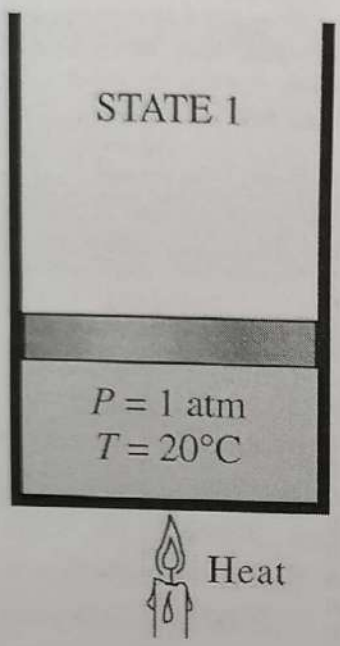


T-v diagram for the heating process of water at constant pressure.

Scanned with CamScanner
الممسوحة ضوئيا بـ CamScanner

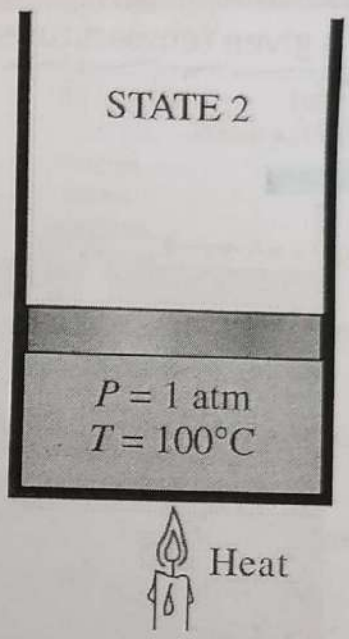
PHASE-CHANGE PROCESSES OF PURE SUBSTANCES

- **Compressed liquid (subcooled liquid)**: A substance that it is *not about to vaporize.*
- **Saturated liquid**: A liquid that is *about to vaporize.*

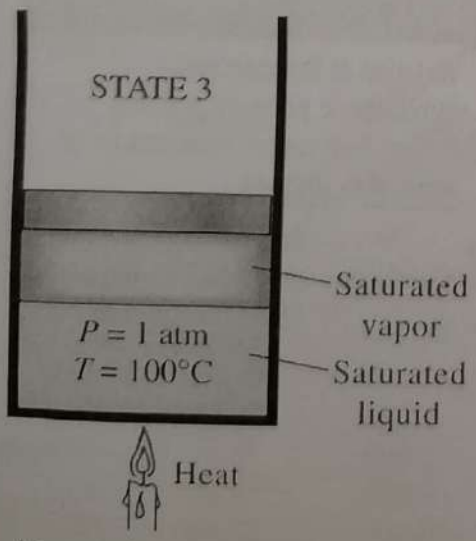


At 1 atm and 20°C, water exists in the liquid phase (***compressed liquid***).

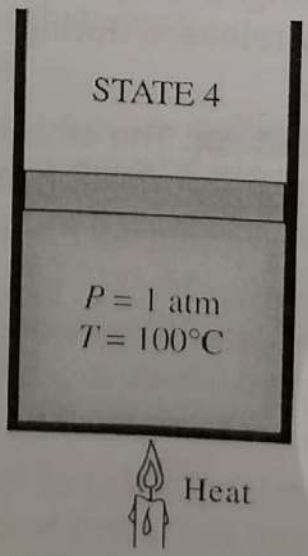
At 1 atm pressure and 100°C, water exists as a liquid that is ready to vaporize (***saturated liquid***).



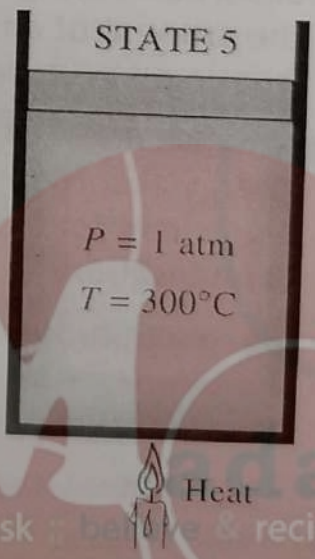
- **Saturated vapor**: A vapor that is *about to condense.*
- **Saturated liquid–vapor mixture**: The state at which the *liquid and vapor phases coexist* in equilibrium.
- **Superheated vapor**: A vapor that is *not about to condense* (i.e., not a saturated vapor).



As more heat is transferred, part of the saturated liquid vaporizes



At 1 atm pressure, the temperature remains constant

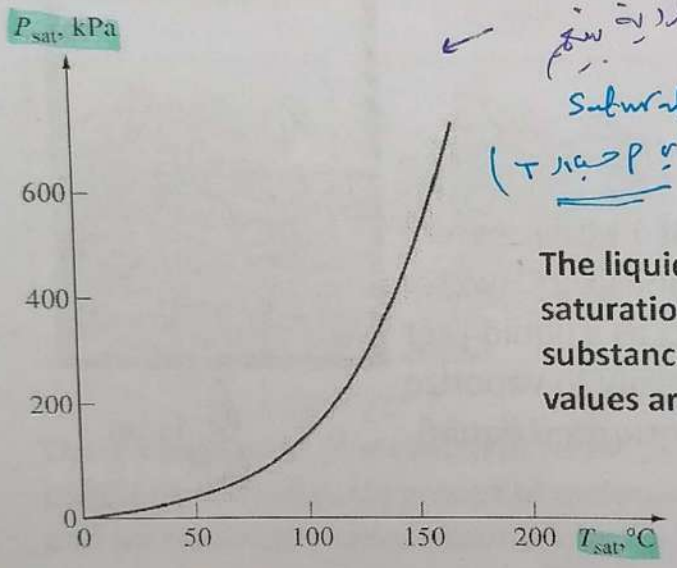


As more heat is transferred, the

ask & believe & recieve
CamScanner الممسوحة ضوئيا بـ

Saturation Temperature and Saturation Pressure

- The temperature at which water starts boiling depends on the pressure; therefore, if the pressure is fixed, so is the boiling temperature.
- Water boils at 100°C at 1 atm pressure.
- **Saturation temperature T_{sat}**: The temperature at which a pure substance changes phase at a given pressure.
- **Saturation pressure P_{sat}**: The pressure at which a pure substance changes phase at a given temperature.



The liquid–vapor saturation curve of a pure substance (numerical values are for water).

TABLE 3–1

Saturation (boiling) pressure of water at various temperatures

Temperature, T, °C	Saturation pressure, P_{sat}, kPa
−10	0.26
−5	0.40
0	0.61
5	0.87
10	1.23
15	1.71
20	2.34
25	3.17
30	4.25
40	7.39
50	12.35
100	101.4
150	476.2
200	1555
250	3976
300	8588

- **Latent heat**: The amount of energy absorbed or released during a phase-change process.
- **Latent heat of fusion**: The amount of energy absorbed during melting. It is equivalent to the amount of energy released during freezing.
- **Latent heat of vaporization**: The amount of energy absorbed during vaporization, and it is equivalent to the energy released during condensation.
- The magnitudes of the latent heats depend on the temperature or pressure at which the phase change occurs.
- At 1 atm pressure, the latent heat of fusion of water is 333.7 kJ/kg and the latent

TABLE 3–2

Variation of the standard atmospheric pressure and the boiling (saturation) temperature of water with altitude

Elevation, m	Atmospheric pressure, kPa	Boiling temperature, °C
0	101.33	100.0
1,000	89.55	96.5
2,000		

CamScanner الممسوحة ضوئيا بـ

- **Latent heat**: The amount of energy absorbed or released during a phase-change process.
- **Latent heat of fusion**: The amount of energy absorbed during melting. It is equivalent to the amount of energy released during freezing.
- **Latent heat of vaporization**: The amount of energy absorbed during vaporization, and it is equivalent to the energy released during condensation.
- The magnitudes of the latent heats depend on the temperature or pressure at which the phase change occurs.
- At 1 atm pressure, the latent heat of fusion of water is 333.7 kJ/kg and the latent heat of vaporization is 2256.5 kJ/kg.
- The atmospheric pressure, and thus the boiling temperature of water, decreases with elevation.

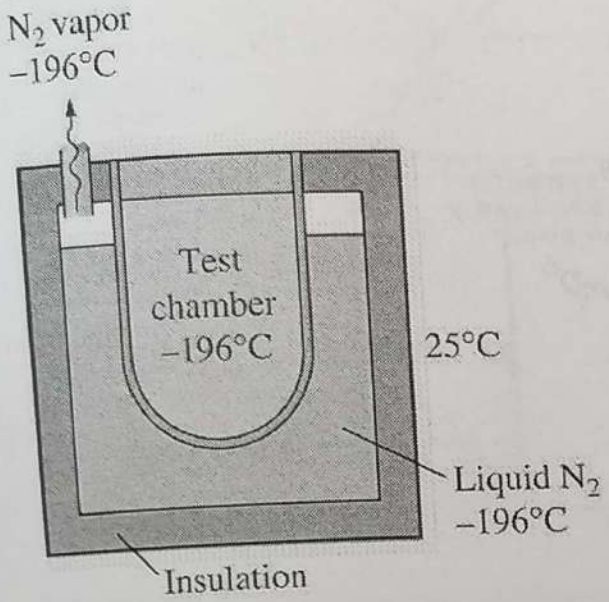
TABLE 3–2

Variation of the standard atmospheric pressure and the boiling (saturation) temperature of water with altitude

Elevation, m	Atmospheric pressure, kPa	Boiling temperature, °C
0	101.33	100.0
1,000	89.55	96.5
2,000	79.50	93.3
5,000	54.05	83.3
10,000	26.50	66.3
20,000	5.53	34.7

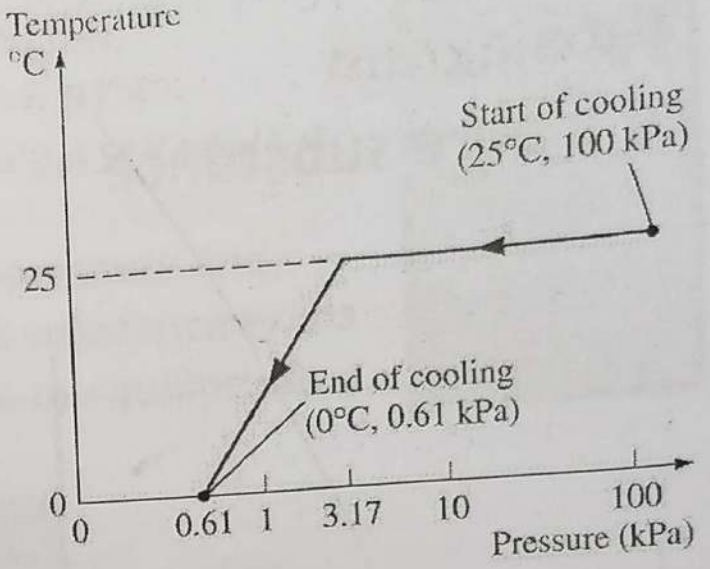
CamScanner الممسوحة ضوئيا بـ

Some Consequences of T_{sat} and P_{sat} Dependence

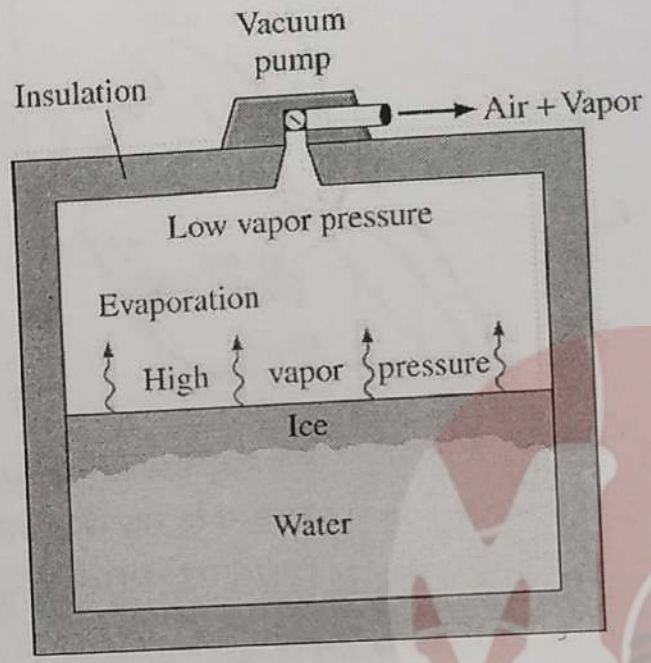


The temperature of liquid nitrogen exposed to the atmosphere remains constant at 196°C, and thus it maintains the test chamber at 196°C.

The variation of the temperature of fruits and vegetables with pressure during vacuum cooling from 25°C to 0°C.



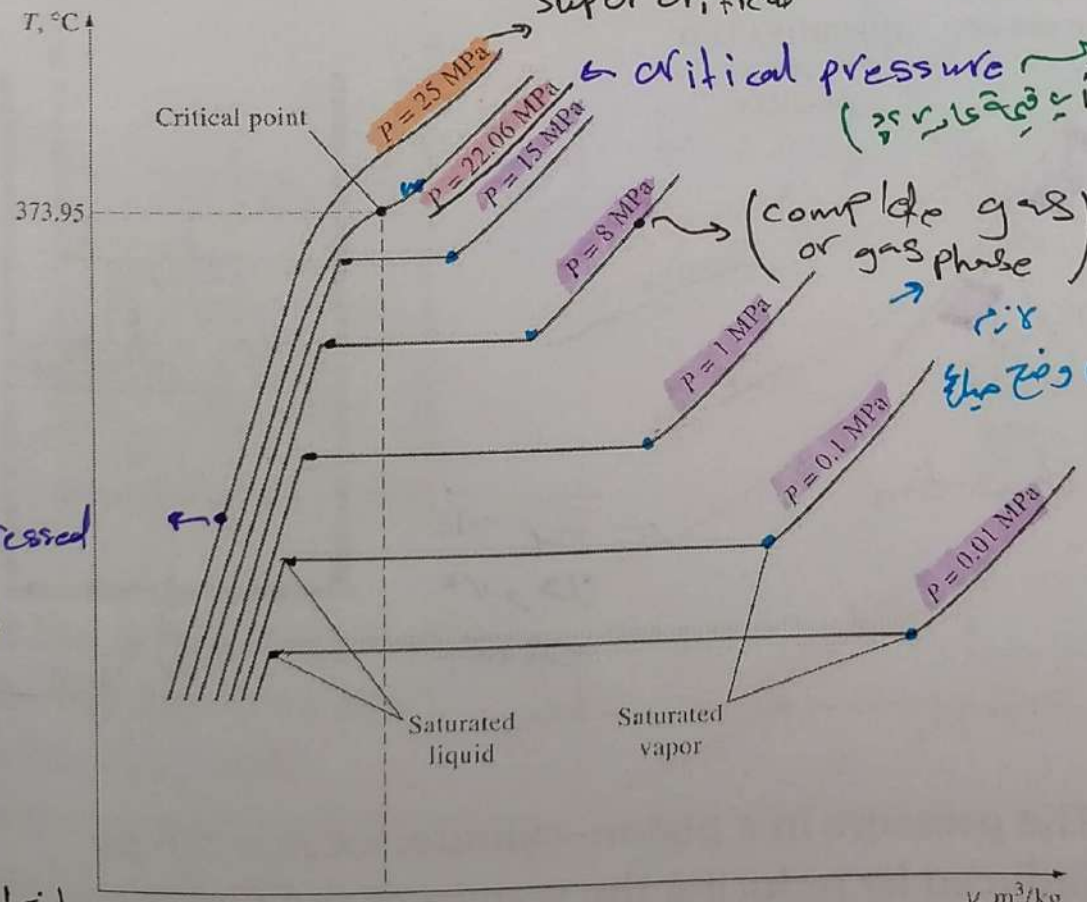
In 1775, ice was made by evacuating the air space in a water tank.



CamScanner الممسوحة ضوئيا بـ

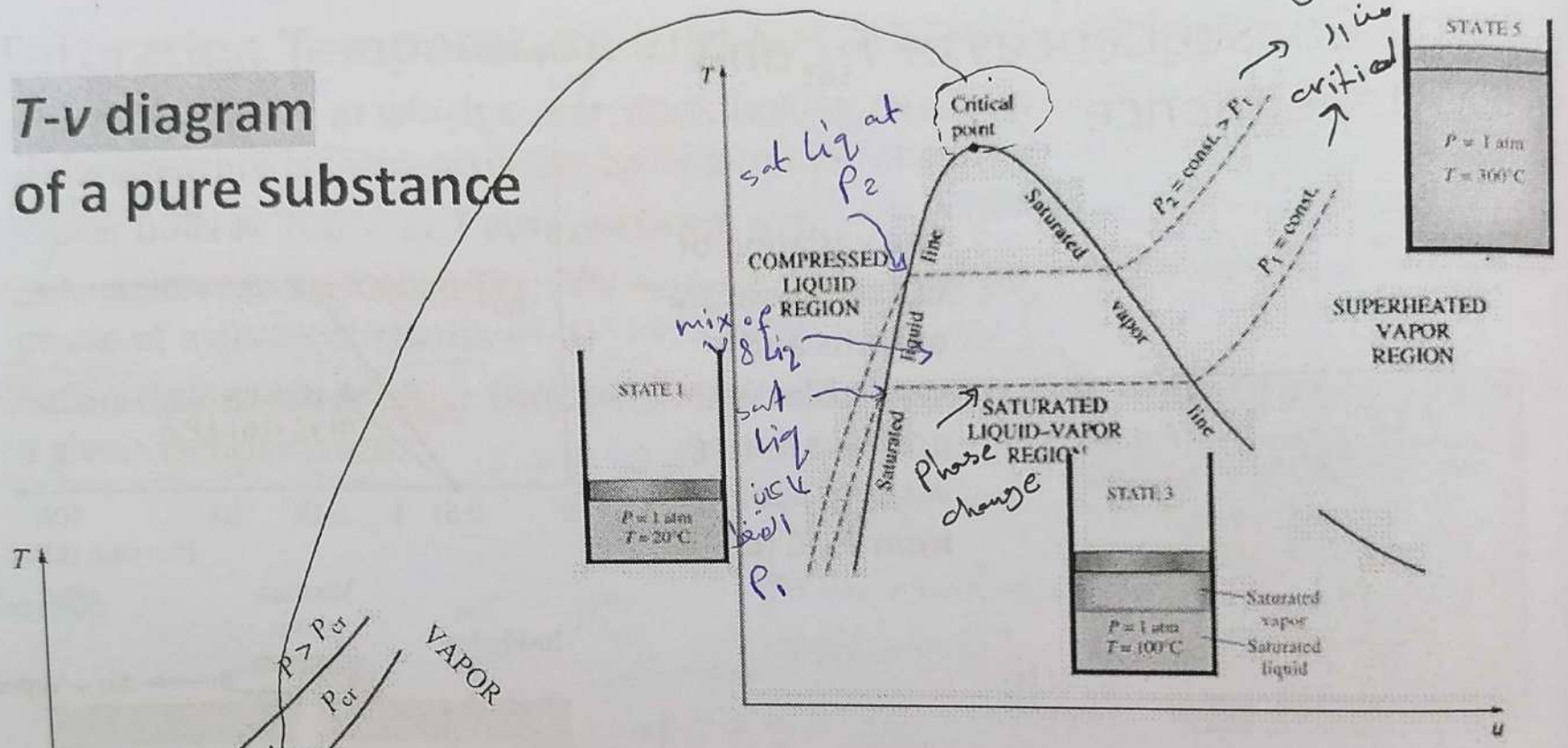
PROPERTY DIAGRAMS FOR PHASE-CHANGE PROCESSES

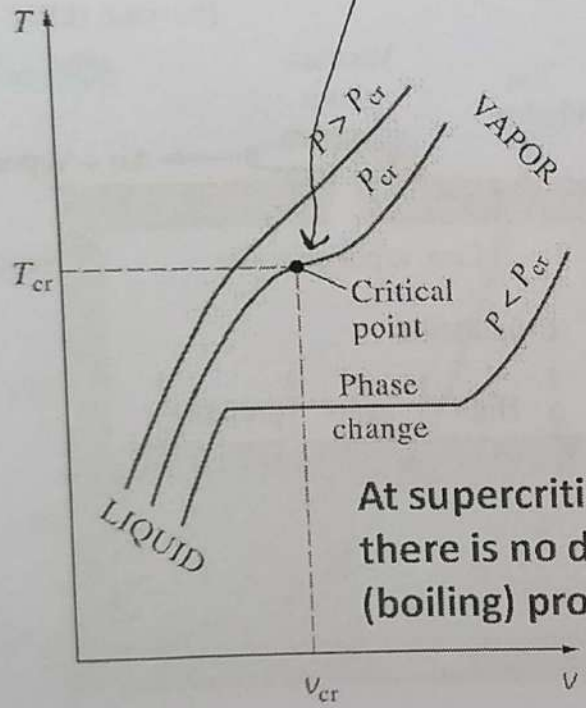
- The variations of properties during phase-change processes are best studied and understood with the help of property diagrams such as the ***T-v*, *P-v*, and *P-T* diagrams** for pure substances.



T-v diagram of constant-pressure phase-change processes of a pure substance at various pressures (numerical values are for water).

T-v diagram of a pure substance





At supercritical pressures ($P > P_{cr}$), there is no distinct phase-change (boiling) process.

Critical point: The point at which the saturated liquid and saturated vapor states are identical.

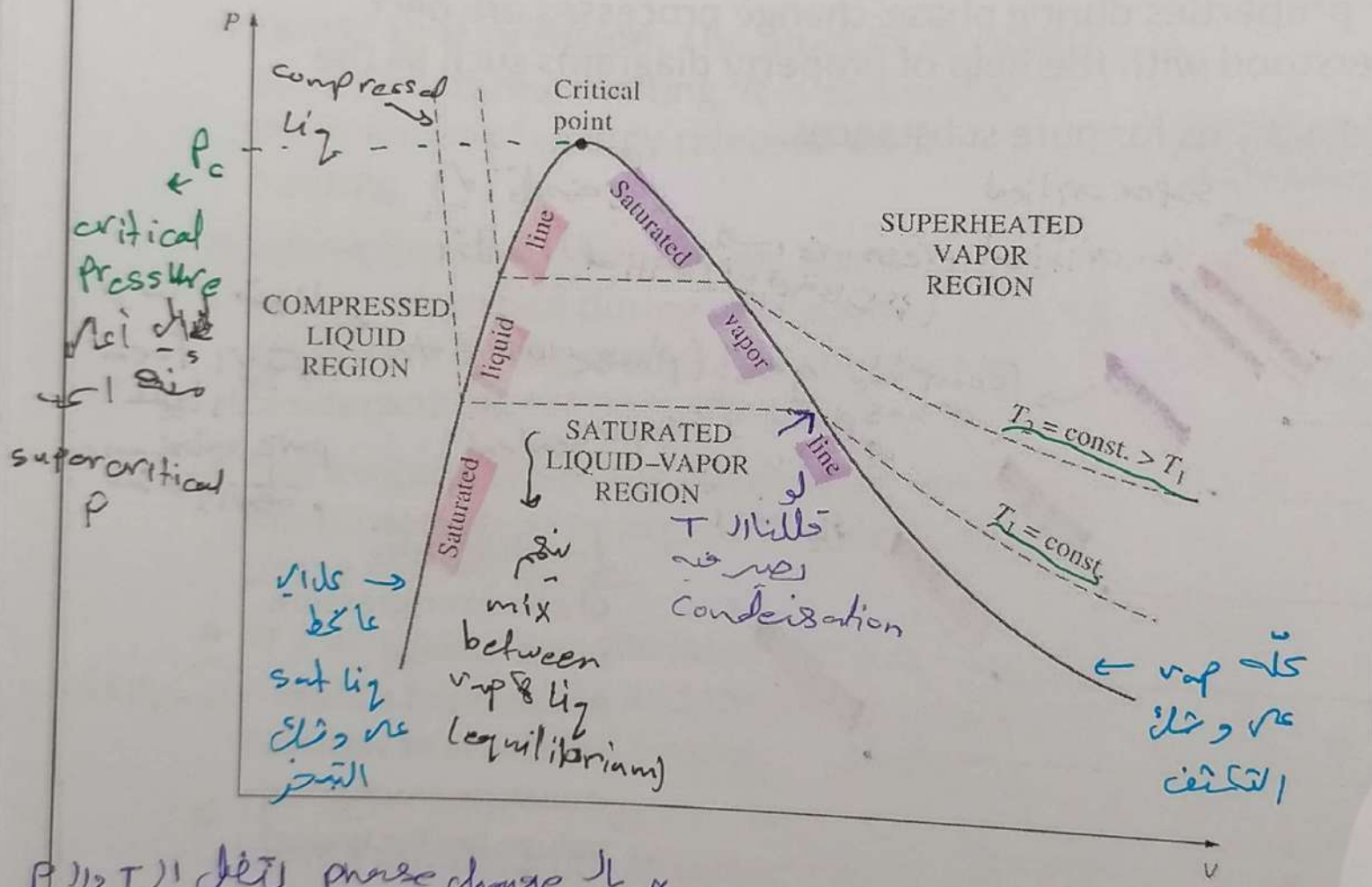
For water

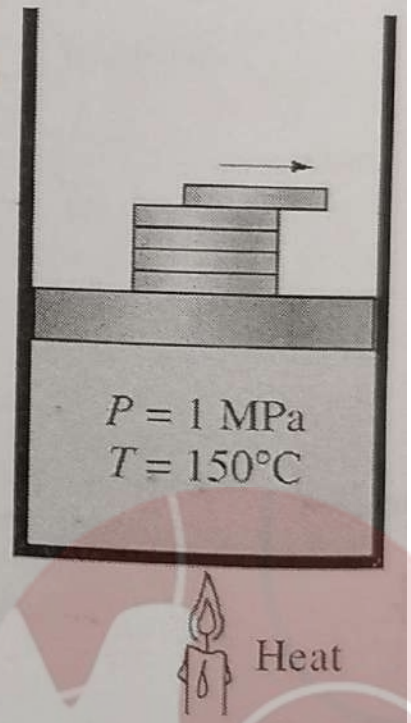
$T_c = 374\ c^\circ$

$P_c = 22.06\ MPa \simeq 22000\ KPa$

الممسوحة ضوئيا بـ CamScanner

P-v diagram of a pure substance.



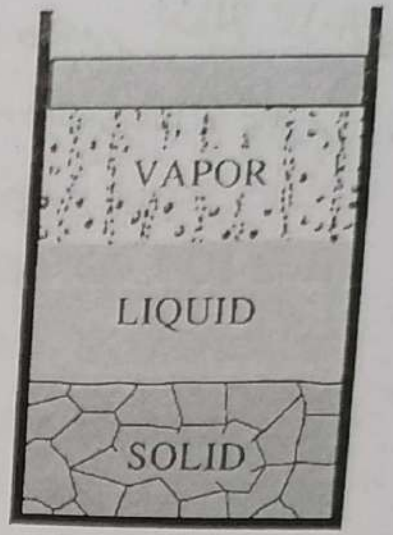


The pressure in a piston–cylinder device can be reduced by reducing the weight of the piston.

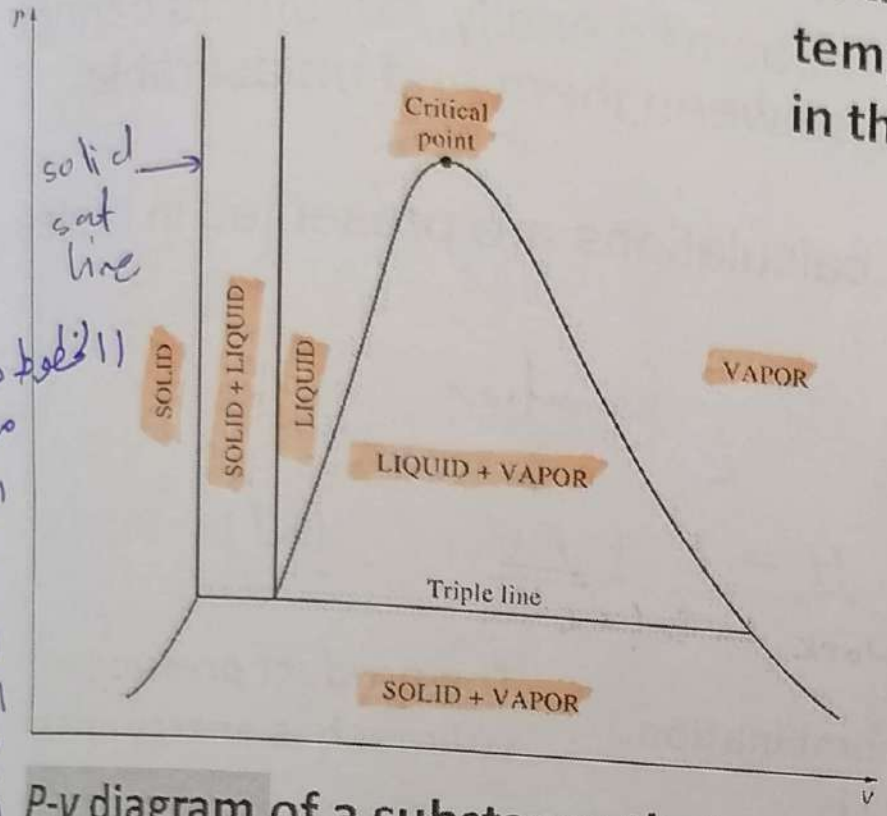
CamScanner الممسوحة ضوئيا بـ

Extending Diagrams to Include Solid Phase

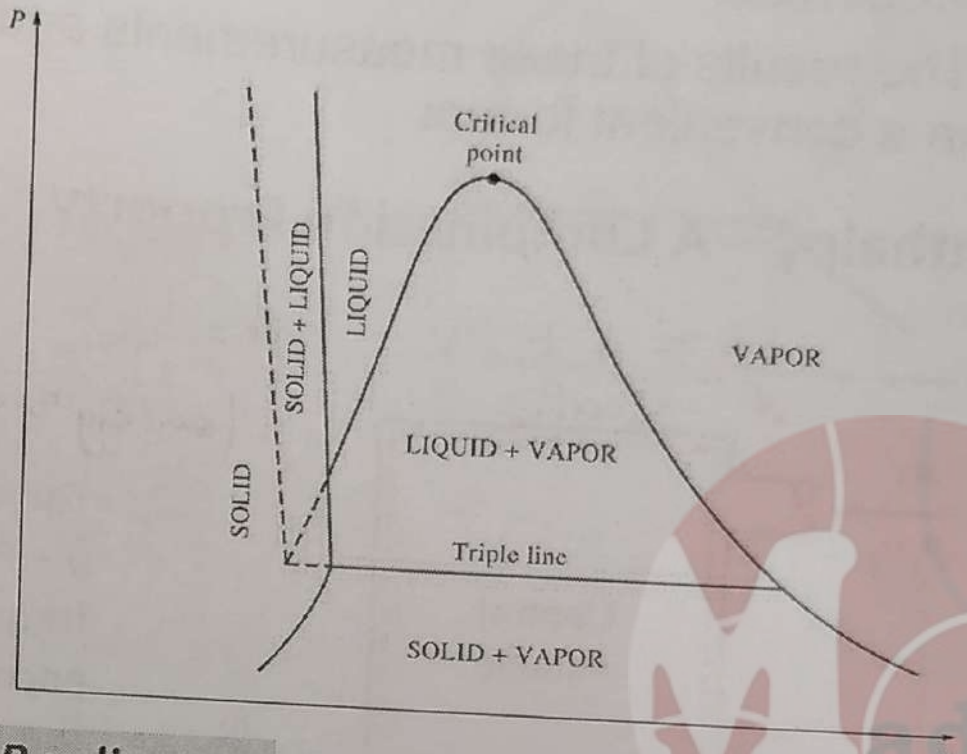
For water,
$T_{tp} = 0.01°C$
$P_{tp} = 0.6117$ kPa



At triple-point pressure and temperature, a substance exists in three phases in equilibrium.



P-v diagram of a substance that contracts on freezing.

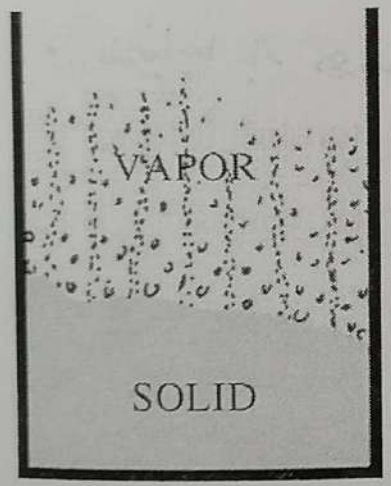


P-v diagram of a substance that expands on freezing (such as water).

CamScanner الممسوحة ضوئيا بـ

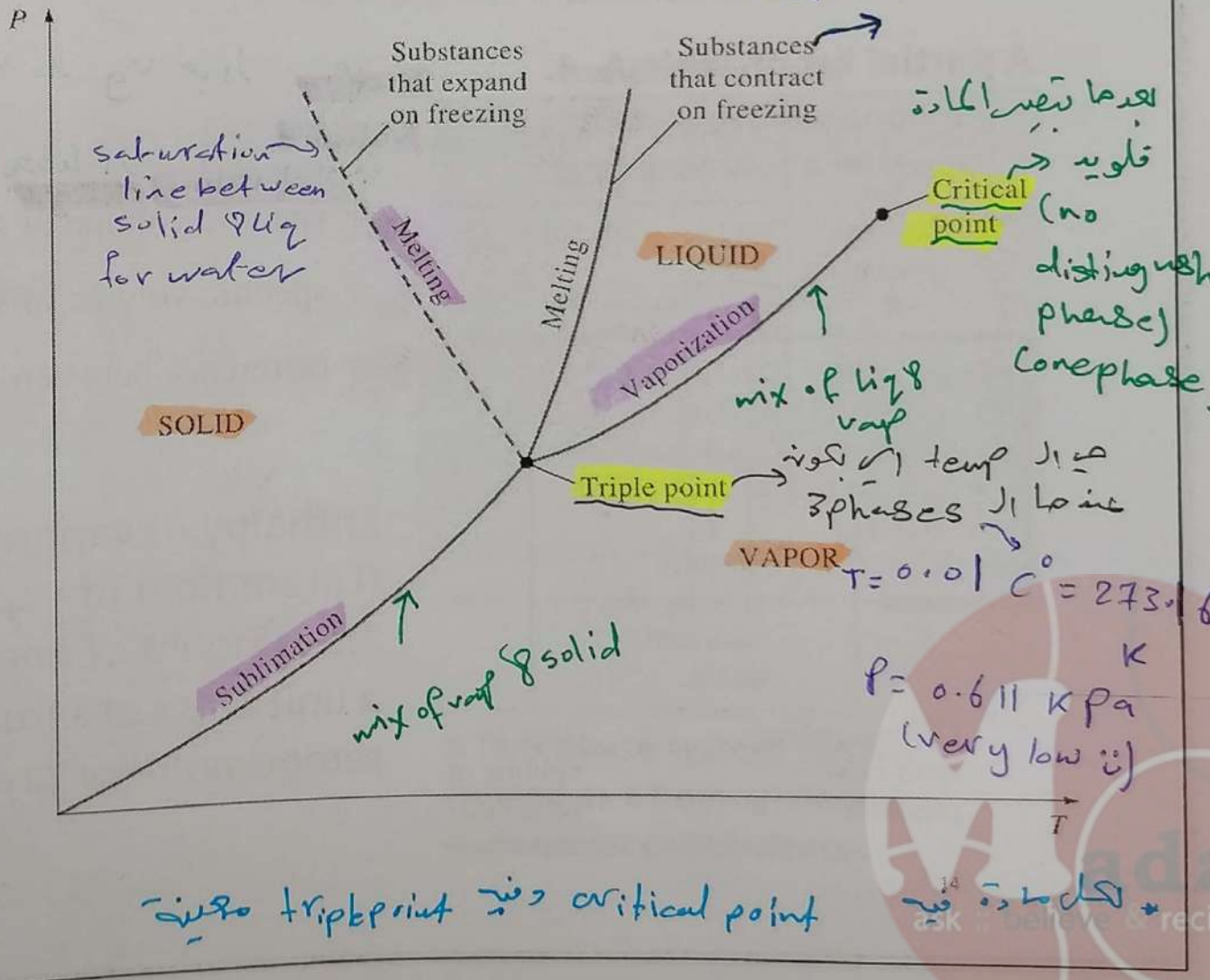
the first graph for study

Sublimation:
Passing from the solid phase directly into the vapor phase.



At low pressures (**below the triple-point value**), solids evaporate without melting first (*sublimation*).

P-T diagram of pure substances



هاد الخط لمعظم المواد ما عدا الـ H_2O

saturation line between solid & liq for water

بعدها بتصير المادة غازية (no distinguish phase/ one phase)

mix of liq & vap

عند هاد الـ temp بتكون 3 phases

$T = 0.01\ C^\circ = 273.16\ K$

$P = 0.611\ kPa$ (very low)

mix of vap & solid

* لكل مادة triple point و critical point معينة

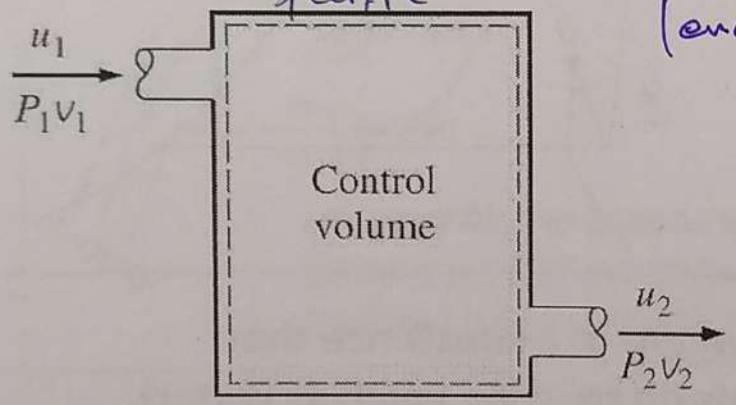
CamScanner الممسوحة ضوئيا بـ

PROPERTY TABLES

- For most substances, the relationships among thermodynamic properties are too complex to be expressed by simple equations.
- Therefore, properties are frequently presented in the form of tables.
- Some thermodynamic properties can be measured easily, but others cannot and are calculated by using the relations between them and measurable properties.
- The results of these measurements and calculations are presented in tables in a convenient format.

Enthalpy—A Combination Property

$$h = u + Pv \quad (\text{kJ/kg}) \qquad H = U + PV \quad (\text{kJ})$$



The combination *u + Pv* is frequently encountered in the analysis of control volumes.

The product *pressure* × *volume* has energy units.

$$\text{kPa} \cdot \text{m}^3 \equiv \text{kJ}$$
$$\text{kPa} \cdot \text{m}^3/\text{kg} \equiv \text{kJ/kg}$$
$$\text{bar} \cdot \text{m}^3 \equiv 100\ \text{kJ}$$
$$\text{MPa} \cdot \text{m}^3 \equiv 1000\ \text{kJ}$$

CamScanner الممسوحة ضوئيا بـ

24/10

Saturated Liquid and Saturated Vapor States

- **Table A–4**: Saturation properties of water under temperature.
- **Table A–5**: Saturation properties of water under pressure.

A partial list of Table A–4.

Temp. °C T	Sat. press. kPa P_{sat}	Specific volume m^3/kg Sat. liquid v_f	Sat. vapor v_g
85	57.868	0.001032	2.8261
90	70.183	0.001036	2.3593
95	84.609	0.001040	1.9808

Specific temperature

Corresponding saturation pressure

Specific volume of saturated liquid

Specific volume of saturated vapor

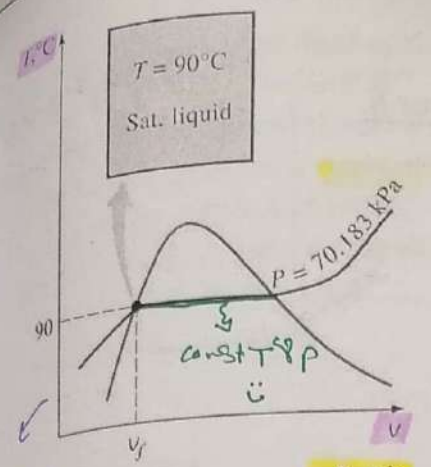
v_f = specific volume of saturated liquid

v_g = specific volume of saturated vapor

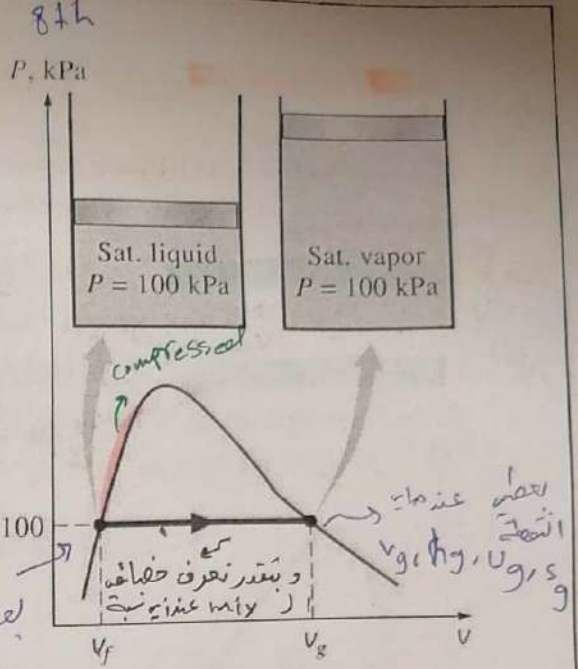
v_{fg} = difference between v_g and v_f (that is, $v_{fg} = v_g - v_f$)

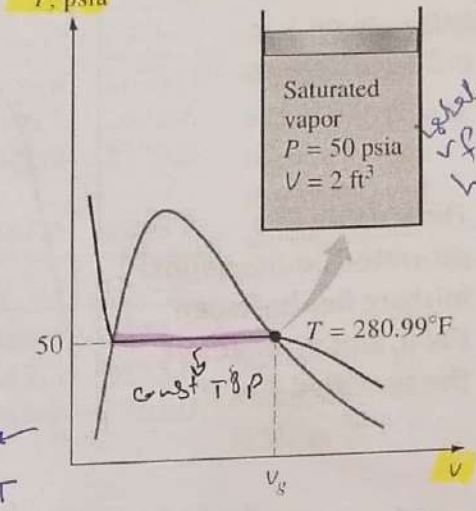
Enthalpy of vaporization, h_{fg} (Latent heat of vaporization): The amount of energy needed to vaporize a unit mass of saturated liquid at a given temperature or pressure.

ask & believe & recieve
الممسوحة ضوئيا بـ CamScanner



Examples: Saturated liquid and saturated vapor states of water on *T*-*v* and *P*-*v* diagrams.





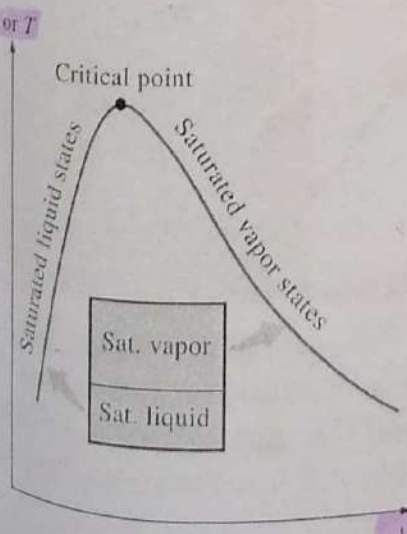
Saturated Liquid–Vapor Mixture

Quality, *x* : The ratio of the mass of vapor to the total mass of the mixture. Quality is between 0 and 1 **0: sat. liquid, 1: sat. vapor.**

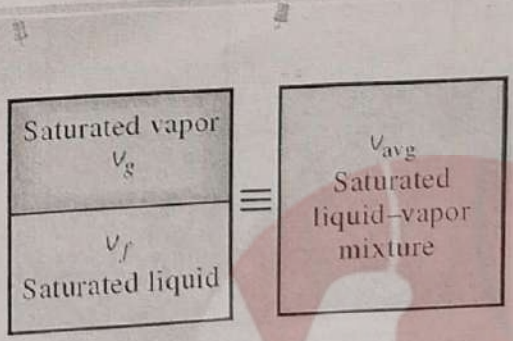
The properties of the saturated liquid are the same whether it exists alone or in a mixture with saturated vapor.

$$x = \frac{m_{\text{vapor}}}{m_{\text{total}}} \qquad m_{\text{total}} = m_{\text{liquid}} + m_{\text{vapor}} = m_f + m_g$$

Temperature and pressure are dependent properties for a mixture.



The relative amounts of liquid and vapor phases in a saturated mixture are specified by the *quality x*.



A two-phase system can be treated as a homogeneous mixture for convenience.

CamScanner الممسوحة ضوئيا بـ

$$v_{avg} = v_f + x v_{fg} \quad (m^3/kg)$$

$$x = m_g/m_t \qquad x = \frac{v_{avg} - v_f}{v_{fg}}$$

fraction of vap

$$u_{avg} = u_f + x u_{fg} \quad (kJ/kg)$$

$$h_{avg} = h_f + x h_{fg} \quad (kJ/kg)$$

combe

$y \rightarrow v, u, \text{or } h.$

$$y_{avg} = y_f + x y_{fg}$$

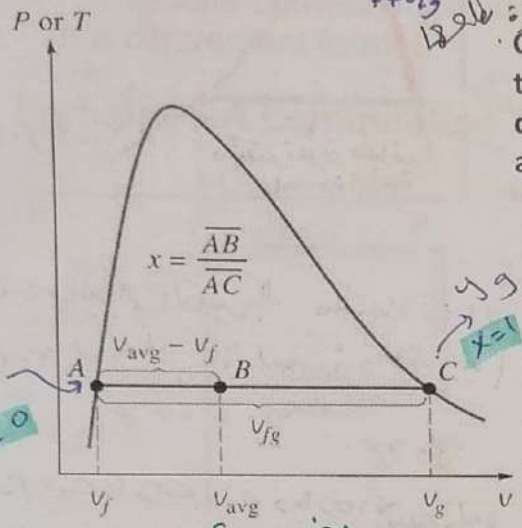
$$y_f \le y_{avg} \le y_g$$

من الجدول

If $x = 0 \rightarrow$ sat liq

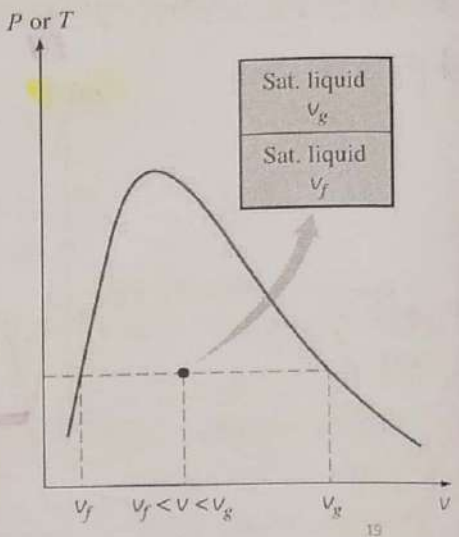
If $x = 1 \rightarrow$ sat vap

$0 < x < 1$



Quality is related to the horizontal distances on *P-v* and *T-v* diagrams.

The *v* value of a saturated liquid–vapor mixture lies between the v_f and v_g values at the specified *T* or *P*.

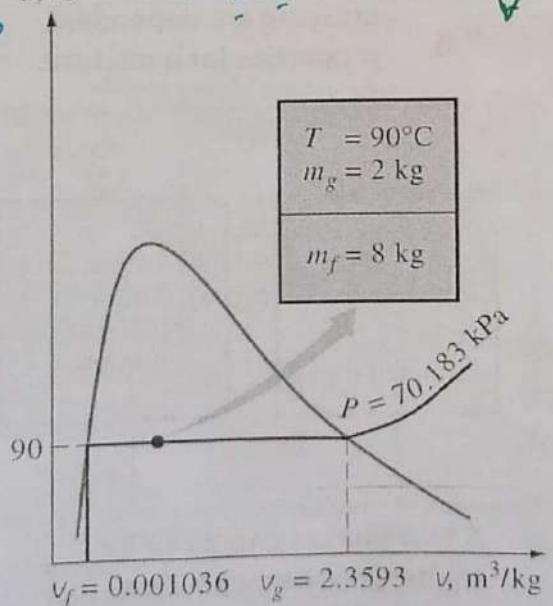


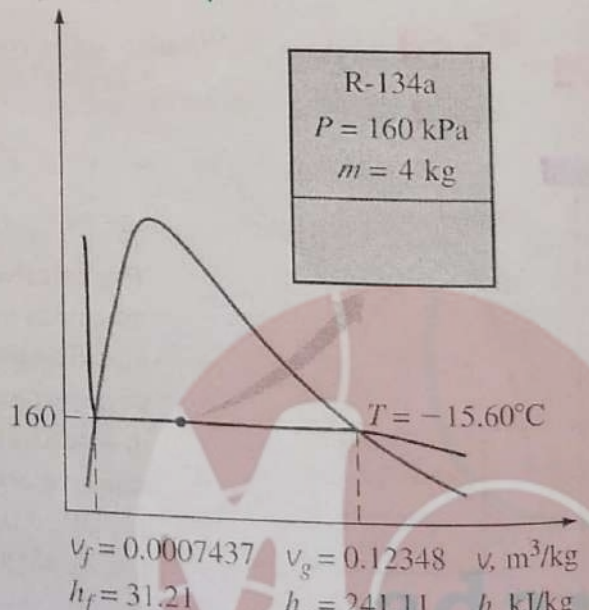
$v_{fg} = v_g - v_f$

$u_{fg} = u_g - u_f$

Examples:

Saturated liquid-vapor mixture states on *T-v* and *P-v* diagrams.





ask : believe & recieve
CamScanner الممسوحة ضوئيا بـ

Superheated Vapor

In the region to the right of the saturated vapor line and at temperatures above the critical point temperature, a substance exists as superheated vapor. In this region, temperature and pressure are independent properties.

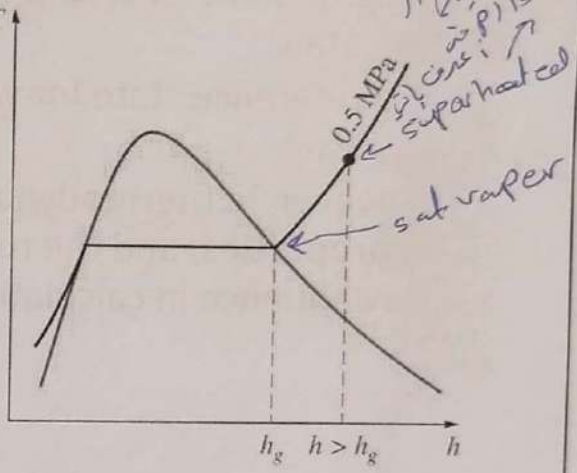
Compared to saturated vapor, superheated vapor is characterized by

- Lower pressures ($P < P_{sat}$ at a given T)
- Higher tempreatures ($T > T_{sat}$ at a given P)
- Higher specific volumes ($v > v_g$ at a given P or T)
- Higher internal energies ($u > u_g$ at a given P or T)
- Higher enthalpies ($h > h_g$ at a given P or T)

T, °C	v m³/kg	u kJ/kg	h kJ/kg
	$P = 0.1$ MPa (99.61°C)		
Sat.	1.6941	2505.6	2675.0
100	1.6959	2506.2	2675.8
150	1.9367	2582.9	2776.6
⋮	⋮	⋮	⋮
1300	7.2605	4687.2	5413.3
	$P = 0.5$ MPa (151.83°C)		
Sat.	0.37483	2560.7	2748.1
200	0.42503	2643.3	2855.8
250	0.47443	2723.8	2961.0

A partial listing of Table A–6.

At a specified P, superheated vapor exists at a higher h than the saturated vapor.



Compressed Liquid

The compressed liquid properties depend on temperature much more strongly than they do on pressure.

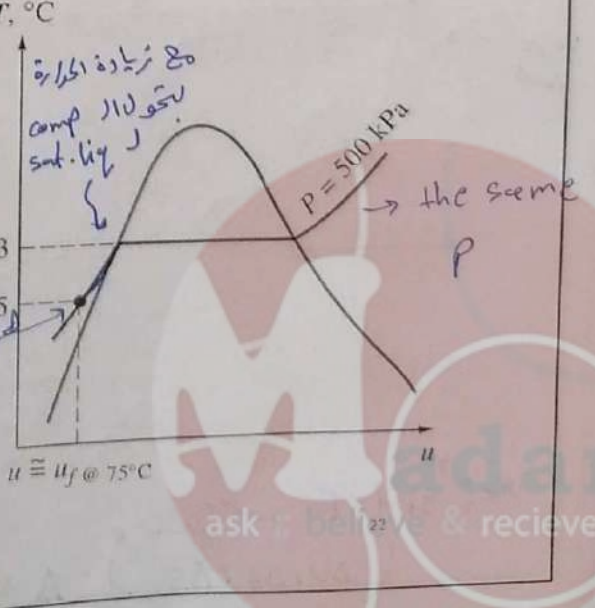
$y \cong y_{f\,@\,T}$ $\quad y \rightarrow v, u,$ or h

A more accurate relation for h

$$h \cong h_{f\,@\,T} + v_{f\,@\,T}(P - P_{sat\,@\,T})$$

Compressed liquid is characterized by

Higher pressures ($P > P_{sat}$ at a given T)
Lower tempreatures ($T < T_{sat}$ at a given P)
Lower specific volumes ($v < v_f$ at a given P or T)
Lower internal energies ($u < u_f$ at a given P or T)
Lower enthalpies ($h < h_f$ at a given P or T)



Given: P and T

$v \cong v_{f\,@T}$
$u \cong u_{f\,@T}$
$h \cong h_{f\,@T}$

A compressed liquid may be approximated as a saturated liquid at the given temperature.

At a given P and T, a pure substance will exist as a compressed liquid if $T < T_{sat\,@\,P}$

CamScanner الممسوحة ضوئيا بـ

13th

Reference State and Reference Values

- The values of ***u***, ***h***, and ***s*** cannot be measured directly, and they are calculated from measurable properties using the relations between properties.
- Those relations give the ***changes* in properties**, not the values of properties at specified states.
- Therefore, we need to choose a convenient ***reference state*** and assign a value of ***zero*** for a convenient property or properties at that state.
- The reference state for water is 0.01°C and for R-134a is -40°C in tables.
- However, In thermodynamics we are concerned with the ***changes* in properties,** and the reference state chosen is of no consequence in calculations.

14th

Reference State and Reference Values

Saturated water—Temperature table

Temp., T °C	Sat. press., P_{sat} kPa	Specific volume, m³/kg: Sat. liquid, v_f	Specific volume, m³/kg: Sat. vapor, v_g	Internal energy, kJ/kg: Sat. liquid, u_f	Internal energy, kJ/kg: Evap., u_{fg}	Internal energy, kJ/kg: Sat. vapor, u_g	Enthalpy, kJ/kg: Sat. liquid, h_f	Enthalpy, kJ/kg: Evap., h_{fg}	Enthalpy, kJ/kg: Sat. vapor, h_g	Entropy, kJ/kg · K: Sat. liquid, s_f	Entropy, kJ/kg · K: Evap., s_{fg}	Entropy, kJ/kg · K: Sat. vapor, s_g
0.01	0.6117	0.001000	206.00	0.000	2374.9	2374.9	0.001	2500.9	2500.9	0.0000	9.1556	9.1556
5	0.8725	0.001000	147.03	21.019	2360.8	2381.8	21.020	2489.1	2510.1	0.0763	8.9487	9.0249

triple point

Saturated refrigerant-134a—Temperature table

Temp., T °C	Sat. press., P_{sat} kPa	Specific volume, m³/kg: Sat. liquid, v_f	Specific volume, m³/kg: Sat. vapor, v_g	Internal energy, kJ/kg: Sat. liquid, u_f	Internal energy, kJ/kg: Evap., u_{fg}	Internal energy, kJ/kg: Sat. vapor, u_g	Enthalpy, kJ/kg: Sat. liquid, h_f	Enthalpy, kJ/kg: Evap., h_{fg}	Enthalpy, kJ/kg: Sat. vapor, h_g	Entropy, kJ/kg · K: Sat. liquid, s_f	Entropy, kJ/kg · K: Evap., s_{fg}	Entropy, kJ/kg · K: Sat. vapor, s_g
−40	51.25	0.0007054	0.36081	−0.036	207.40	207.37	0.000	225.86	225.86	0.00000	0.96866	0.96866

Ref state for reffrence

(ΔU، ΔH، ΔS) Δ وحتى لو ما كانة فيه reff نعتبرها الدلتا بالنيرو state

CamScanner الممسوحة ضوئيا بـ

THE IDEAL-GAS EQUATION OF STATE

- Equation of state: Any equation that relates the pressure, temperature, and specific volume of a substance.
- The simplest and best-known equation of state for substances in the gas phase is the ideal-gas equation of state. This equation predicts the *P-v-T* behavior of a gas quite accurately within some properly selected region.

$$P = R\left(\frac{T}{v}\right) \quad Pv = RT$$

Ideal gas equation of state

$$R = \frac{R_u}{M} \qquad (\text{kJ/kg} \cdot \text{K or kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})$$

R: gas constant
M: molar mass (kg/kmol)
R_u: universal gas constant

$R_u =$
- 8.31447 kJ/kmol · K
- 8.31447 kPa · m³/kmol · K
- 0.0831447 bar · m³/kmol · K
- 1.98588 Btu/lbmol · R
- 10.7316 psia · ft³/lbmol · R
- 1545.37 ft · lbf/lbmol · R

Substance	R, kJ/kg·K
Air	0.2870
Helium	2.0769
Argon	0.2081
Nitrogen	0.2968

Different substances have different gas constants.

$$w = \int_{v_1}^{v_2} P\,dv$$

Mass = Molar mass × Mole number

$$m = MN \quad (\text{kg})$$

$$V = mv \longrightarrow \boxed{PV = mRT}$$

$$mR = (MN)R = NR_u \longrightarrow PV = NR_uT$$

$$V = N\bar{v} \longrightarrow P\bar{v} = R_uT$$

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

Ideal gas equation at two states for a fixed mass

Various expressions of ideal gas equation

Per unit mass	Per unit mole
v, m³/kg	$\bar{v}$, m³/kmol
u, kJ/kg	$\bar{u}$, kJ/kmol
h, kJ/kg	$\bar{h}$, kJ/kmol

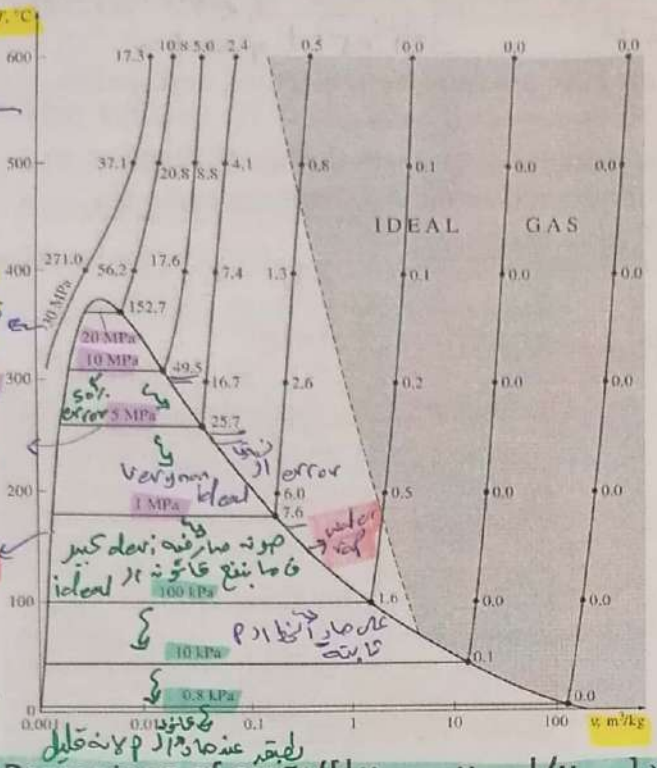
Properties per unit mole are denoted with a bar on the top.

- Real gases behave as an ideal gas at low densities (i.e., low pressure, high temperature).
- The ideal-gas relation often is not applicable to real gases; thus, care should be exercised when using it.

CamScanner الممسوحة ضوئيا بـ

17th

Is Water Vapor an Ideal Gas?



- At pressures below 10 kPa, water vapor can be treated as an ideal gas, regardless of its temperature, with negligible error (less than 0.1 percent).
- At higher pressures, however, the ideal gas assumption yields unacceptable errors, particularly in the vicinity of the critical point and the saturated vapor line.
- In air-conditioning applications, the water vapor in the air can be treated as an ideal gas. Why?
- In steam power plant applications, however, the pressures involved are usually very high; therefore, ideal-gas relations should not be used.

Percentage of error ($[|v_{table} - v_{ideal}|/v_{table}] \times 100$) involved in assuming steam to be an ideal gas, and the region where steam can be treated as an ideal gas with less than 1 percent error.

27

18th

COMPRESSIBILITY FACTOR—A MEASURE OF DEVIATION FROM IDEAL-GAS BEHAVIOR

Compressibility factor Z A factor that accounts for the deviation of real gases from ideal-gas behavior at a given temperature and pressure.

$$Pv = ZRT$$

$$Z = \frac{Pv}{RT} \qquad Z = \frac{V_{actual}}{V_{ideal}}$$

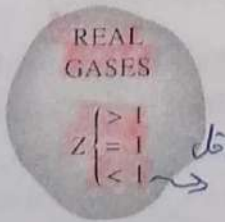
The farther away Z is from unity, the more the gas deviates from ideal-gas behavior.

Gases behave as an ideal gas at low densities (i.e., low pressure, high temperature).

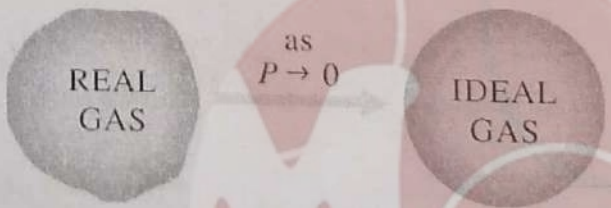
Question: **What is the criteria for low pressure and high temperature?**

Answer: **The pressure or temperature of a gas is high or low relative to its critical temperature or pressure.**





The compressibility factor is unity for ideal gases.



At very low pressures, all gases approach ideal-gas behavior (regardless of their temperature).

28

CamScanner الممسوحة ضوئيا بـ

Reduced Properties

Reduced pressure

$$P_R = \frac{P}{P_{cr}}$$

P_{cr} ← critical point pressure

Reduced temperature

$$T_R = \frac{T}{T_{cr}}$$

T ← actual condition point

T_{cr} ← critical point temp

Pseudo-reduced specific volume

$$v_R = \frac{v_{actual}}{RT_{cr}/P_{cr}}$$

- The Z factor is approximately the same for all gases at the same reduced temperature and reduced pressure, which are defined as

$$T_R = \frac{T}{T_{cr}} \quad \text{and} \quad P_R = \frac{P}{P_{cr}}$$

where P_{cr} and T_{cr} are the critical pressure and temperature, respectively.

- This is known as the *principle of corresponding states*.

Compressibility factor

The pvT properties of a component are expressed in terms of compressibility factor (Z) and Z can be related to p, T, and v (or V) as below:

$$Z = \frac{pV}{nRT} \qquad Z = \frac{pv}{RT} \quad (n = 1)$$

For ideal gas: $Z = 1.0$

For liquids: $Z = 0.01$ to 0.2 [9]

Z at the critical point is usually in the range of 0.27 to 0.29. For most substances, Z_c is 0.27.

$$\left.\begin{aligned} P_R &= \frac{P}{P_{cr}} \\ v_R &= \frac{v}{RT_{cr}/P_{cr}} \end{aligned}\right\} Z = \ldots \text{ (Fig. A–15)}$$

Z can also be determined from a knowledge of P_R and v_R.

Comparison of Z Factors for Various Gases

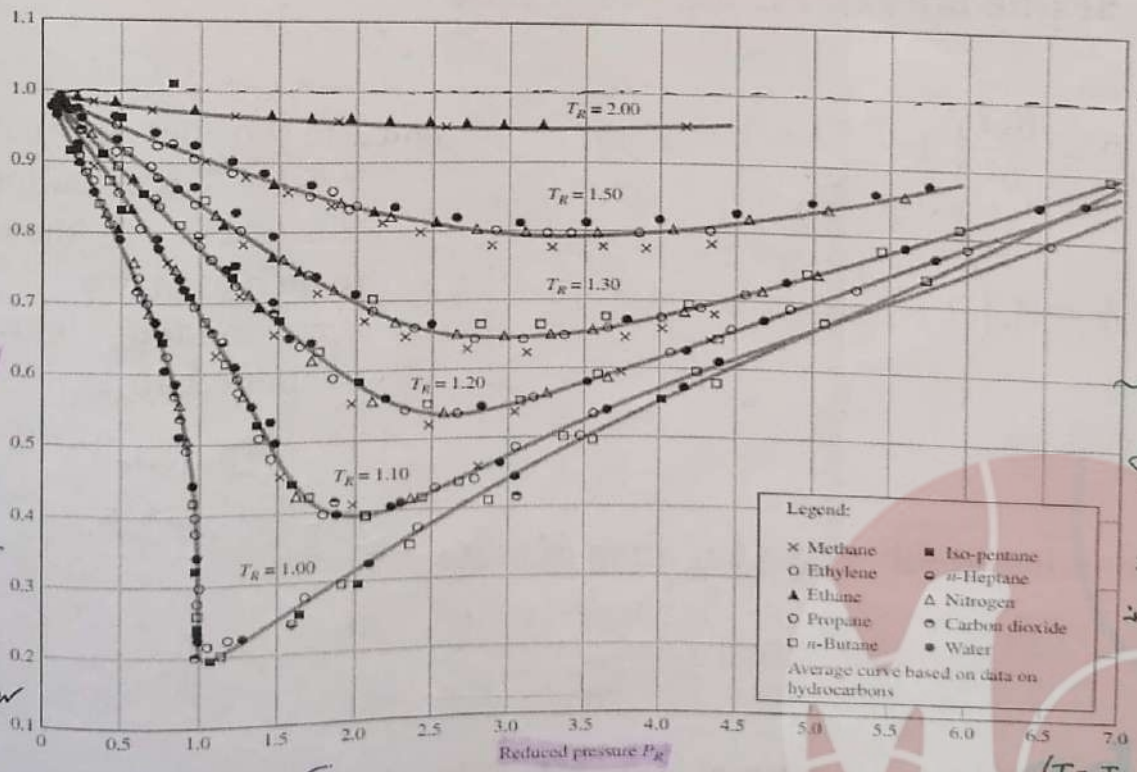


FIGURE 3–47
Comparison of Z factors for various gases.
Source: Gour-Jen Su, "Modified Law of Corresponding States," Ind. Eng. Chem. (International ed.) 38 (1946), p. 803.

CamScanner الممسوحة ضوئيا بـ

OTHER EQUATIONS OF STATE

Several equations have been proposed to represent the ***P-v-T*** behavior of substances accurately over a larger region with no limitations.

van der Waals
Berthelet
Redlich-Kwang
Beattie-Bridgeman
Benedict-Webb-Rubin
Strobridge
Virial

Van der Waals Equation of State

$$\left(P + \frac{a}{v^2}\right)(v - b) = RT$$

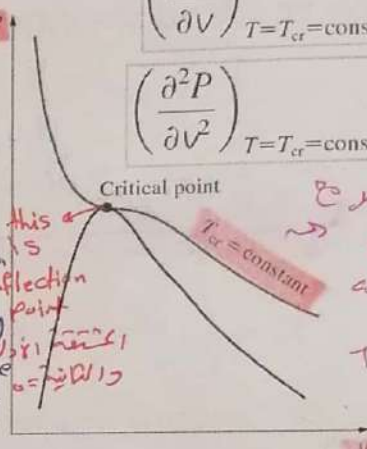
$$a = \frac{27R^2T_{cr}^2}{64P_{cr}} \qquad b = \frac{RT_{cr}}{8P_{cr}}$$

This model includes two effects not considered in the ideal-gas model: the *intermolecular attraction forces* and the *volume occupied by the molecules themselves*. The accuracy of the van der Waals equation of state is often inadequate.

Critical isotherm of a pure substance has an inflection point at the critical state.

$$\left(\frac{\partial P}{\partial v}\right)_{T=T_{cr}=\text{const}} = 0$$

$$\left(\frac{\partial^2 P}{\partial v^2}\right)_{T=T_{cr}=\text{const}} = 0$$



Beattie-Bridgeman Equation of State

$$P = \frac{R_u T}{\bar{v}^2}\left(1 - \frac{c}{\bar{v}T^3}\right)(\bar{v} + B) - \frac{A}{\bar{v}^2}$$

$$A = A_0\left(1 - \frac{a}{\bar{v}}\right) \qquad B = B_0\left(1 - \frac{b}{\bar{v}}\right)$$

The constants are given in Table 3–4 for various substances. It is known to be reasonably accurate for densities up to about $0.8\rho_{cr}$.

Benedict-Webb-Rubin Equation of State

$$P = \frac{R_u T}{\bar{v}} + \left(B_0 R_u T - A_0 - \frac{C_0}{T^2}\right)\frac{1}{\bar{v}^2} + \frac{bR_u T - a}{\bar{v}^3} + \frac{a\alpha}{\bar{v}^6} + \frac{c}{\bar{v}^3 T^2}\left(1 + \frac{\gamma}{\bar{v}^2}\right)e^{-\gamma/\bar{v}^2}$$

The constants are given in Table 3–4. This equation can handle substances at densities up to about 2.5 ρ_{cr}.

ask & believe & recieve
CamScanner الممسوحة ضوئيا بـ

Examples

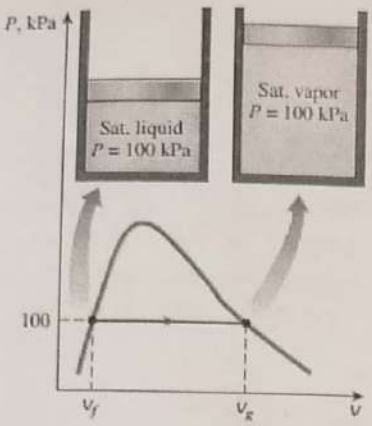


FIGURE 3–30
Schematic and *P-v* diagram for Example 3–3.

EXAMPLE 3–3 Volume and Energy Change during Evaporation

A mass of 200 g of saturated liquid water is completely vaporized at a constant pressure of 100 kPa. Determine (*a*) the volume change and (*b*) the amount of energy transferred to the water.

SOLUTION Saturated liquid water is vaporized at constant pressure. The volume change and the energy transferred are to be determined.

Analysis (*a*) The process described is illustrated on a *P-v* diagram in Fig. 3–30. The volume change per unit mass during a vaporization process is v_{fg}, which is the difference between v_g and v_f. Reading these values from Table A–5 at 100 kPa and substituting yield

$$v_{fg} = v_g - v_f = 1.6941 - 0.001043 = 1.6931 \text{ m}^3/\text{kg}$$

Thus,

$$\Delta V = mv_{fg} = (0.2 \text{ kg})(1.6931 \text{ m}^3/\text{kg}) = 0.3386 \text{ m}^3$$

(*b*) The amount of energy needed to vaporize a unit mass of a substance at a given pressure is the enthalpy of vaporization at that pressure, which is h_{fg} = 2257.5 kJ/kg for water at 100 kPa. Thus, the amount of energy transferred is

$$mh_{fg} = (0.2 \text{ kg})(2257.5 \text{ kJ/kg}) = 451.5 \text{ kJ}$$

Discussion Note that we have considered the first four decimal digits of v_{fg} and disregarded the rest. This is because v_g has significant numbers to the first four decimal places only, and we do not know the numbers in the other decimal places. Copying all the digits from the calculator would mean that we are assuming v_g = 1.694100, which is not necessarily the case. It could very well be that v_g = 1.694138 since this number, too, would truncate to 1.6941. All the digits in our result (1.6931) are significant. But if we did not truncate the result, we would obtain v_{fg} = 1.693057, which falsely implies that our result is accurate to the sixth decimal place.

EXAMPLE 3–4 Pressure and Volume of a Saturated Mixture

A rigid tank contains 10 kg of water at 90°C. If 8 kg of the water is in the liquid form and the rest is in the vapor form, determine (*a*) the pressure in the tank and (*b*) the volume of the tank.

SOLUTION A rigid tank contains saturated mixture. The pressure and the volume of the tank are to be determined.

Analysis (*a*) The state of the saturated liquid–vapor mixture is shown in Fig. 3–35. Since the two phases coexist in equilibrium, we have a saturated mixture, and the pressure must be the saturation pressure at the given temperature:

$$P = P_{\text{sat @ 90°C}} = 70.183 \text{ kPa} \qquad \text{(Table A–4)}$$

(*b*) At 90°C, we have v_f = 0.001036 m³/kg and v_g = 2.3593 m³/kg (Table A–4). One way of finding the volume of the tank is to determine the volume occupied by each phase and then add them:

$$V = V_f + V_g = m_f v_f + m_g v_g$$
$$= (8 \text{ kg})(0.001036 \text{ m}^3/\text{kg}) + (2 \text{ kg})(2.3593 \text{ m}^3/\text{kg})$$
$$= 4.73 \text{ m}^3$$

Another way is to first determine the quality *x*, then the average specific volume *v*, and finally the total volume:

$$x = \frac{m_g}{m_t} = \frac{2 \text{ kg}}{10 \text{ kg}} = 0.2$$

$$v = v_f + xv_{fg}$$
$$= 0.001036 \text{ m}^3/\text{kg} + (0.2)[(2.3593 - 0.001036) \text{ m}^3/\text{kg}]$$
$$= 0.473 \text{ m}^3/\text{kg}$$

and

$$V = mv = (10 \text{ kg})(0.473 \text{ m}^3/\text{kg}) = 4.73 \text{ m}^3$$

Discussion The first method appears to be easier in this case since the masses of each phase are given. In most cases, however, the masses of each phase are not available, and the second method becomes more convenient.

CamScanner الممسوحة ضوئيا بـ

EXAMPLE 3–5 **Properties of Saturated Liquid–Vapor Mixture**

An 80-L vessel contains 4 kg of refrigerant-134a at a pressure of 160 kPa. Determine (*a*) the temperature, (*b*) the quality, (*c*) the enthalpy of the refrigerant, and (*d*) the volume occupied by the vapor phase.

SOLUTION A vessel is filled with refrigerant-134a. Some properties of the refrigerant are to be determined.

Analysis (*a*) The state of the saturated liquid–vapor mixture is shown in Fig. 3–36. At this point we do not know whether the refrigerant is in the compressed liquid, superheated vapor, or saturated mixture region. This can be determined by comparing a suitable property to the saturated liquid and saturated vapor values. From the information given, we can determine the specific volume:

$$v = \frac{V}{m} = \frac{0.080\ \text{m}^3}{4\ \text{kg}} = 0.02\ \text{m}^3/\text{kg}$$

At 160 kPa, we read

$$v_f = 0.0007435\ \text{m}^3/\text{kg}$$
$$v_g = 0.12355\ \text{m}^3/\text{kg} \qquad \text{(Table A–12)}$$

Obviously, $v_f < v < v_g$, and, the refrigerant is in the saturated mixture region. Thus, the temperature must be the saturation temperature at the specified pressure:

$$T = T_{\text{sat @ 160 kPa}} = -15.60°\text{C}$$

(*b*) Quality can be determined from

$$x = \frac{v - v_f}{v_{fg}} = \frac{0.02 - 0.0007435}{0.12355 - 0.0007435} = 0.157$$

(*c*) At 160 kPa, we also read from Table A–12 that $h_f = 31.18$ kJ/kg and $h_{fg} = 209.96$ kJ/kg. Then,

$$h = h_f + xh_{fg}$$
$$= 31.18\ \text{kJ/kg} + (0.157)(209.96\ \text{kJ/kg})$$
$$= 64.1\ \text{kJ/kg}$$

(*d*) The mass of the vapor is

$$m_g = xm_t = (0.157)(4\ \text{kg}) = 0.628\ \text{kg}$$

and the volume occupied by the vapor phase is

$$V_g = m_g v_g = (0.628\ \text{kg})(0.12355\ \text{m}^3/\text{kg}) = 0.0776\ \text{m}^3\ (\text{or } 77.6\ \text{L})$$

The rest of the volume (2.4 L) is occupied by the liquid.

CamScanner الممسوحة ضوئيا بـ

EXAMPLE 3–11 The Use of Generalized Charts

Determine the specific volume of refrigerant-134a at 1 MPa and 50°C, using (a) the ideal-gas equation of state and (b) the generalized compressibility chart. Compare the values obtained to the actual value of 0.021796 m^3/kg and determine the error involved in each case.

SOLUTION The specific volume of refrigerant-134a is to be determined assuming ideal- and nonideal-gas behavior.

Analysis The gas constant, the critical pressure, and the critical temperature of refrigerant-134a are determined from Table A–1 to be

$$R = 0.0815 \text{ kPa·m}^3/\text{kg·K}$$
$$P_{cr} = 4.059 \text{ MPa}$$
$$T_{cr} = 374.2 \text{ K}$$

(a) The specific volume of refrigerant-134a under the ideal-gas assumption is

$$v = \frac{RT}{P} = \frac{(0.0815 \text{ kPa·m}^3/\text{kg·K})(323 \text{ K})}{1000 \text{ kPa}} = 0.026325 \text{ m}^3/\text{kg}$$

Therefore, treating the refrigerant-134a vapor as an ideal gas would result in an error of (0.026325 − 0.021796)/0.021796 = 0.208, or 20.8 percent in this case.

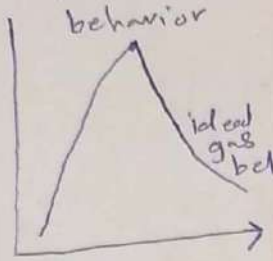
(b) To determine the correction factor Z from the compressibility chart, we first need to calculate the reduced pressure and temperature:

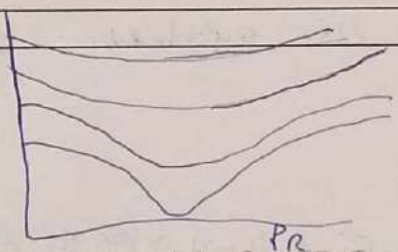
$$P_R = \frac{P}{P_{cr}} = \frac{1 \text{ MPa}}{4.059 \text{ MPa}} = 0.246$$
$$T_R = \frac{T}{T_{cr}} = \frac{323 \text{ K}}{374.2 \text{ K}} = 0.863$$
$$\Rightarrow Z = 0.84$$

Thus

$$v = Zv_{ideal} = (0.84)(0.026325 \text{ m}^3/\text{kg}) = 0.022113 \text{ m}^3/\text{kg}$$

Discussion The error in this result is less than 2 percent. Therefore, in the absence of tabulated data, the generalized compressibility chart can be used with confidence.





Exercises

3–23 Complete this table for H_2O:

T, °C	P, kPa	v, m³/kg	Phase description
140		0.05	
	550		Saturated liquid
125	750		
500		0.140	

3–26 Complete this table for refrigerant-134a:

T, °C	P, kPa	v, m³/kg	Phase description
−4	320		
10		0.0065	
	850		Saturated vapor
90	600		

CamScanner الممسوحة ضوئيا بـ

31 + 36 + 37 + 38 + 39 + 40 + 41 + 43

T(°C)	P(kPa)	U(kJ/kg)	phase composition
143.61	400	1450	Sat mix (because $U_f < U < U_g$)
220	2319.6	2801.3	Sat. vap
190	2500	805.05	compressed liq
466.2	4000	3040	superheated

* إذا أعطاني P لحال ← طلع الـ T (إذا كانت sat) والعكس (لأنه فيه dependency)
(في حالة الـ sat)

* أما إذا أعطاني (T و P) مع بعض في حال ← sat يكون
(يعني حالة one phase) ↳ Sup or compressed
(مش حالة mix)

← بالنسبة للحالة اللي جاية ندور إما على الـ super أو الـ compressed.

بنروح على A-6 عند الـ superheated عند الـ 190 والـ 2.5 ← بناءً على انه الحرارة أكبر من الـ 190 و الـ P أكبر من 2.5 MPa
(so not applicable)

← بنروح على A-7 ← بناءً على انه الـ P أكبر من 2.5 بنلاقي فعلاً (لأنه تقريباً) الـ compressed الـ P مش كتير بتأثر على الـ T (بتأثر بشكل كبير)

we interpolate in 3rd one

Radar
ask : believe & recieve
الممسوحة ضوئيا بـ CamScanner



Chapter 4

ENERGY ANALYSIS OF CLOSED SYSTEMS (Control Mass)

Thermodynamics: An Engineering Approach
Yunus A. Cengel, Michael A. Boles, Mehmet Kanoglu
McGraw-Hill

شو الفرق بين الـ E_{in} والـ E_{out} والـ ΔE !

Dr. Ahmad M. AbuYaghi
October 2023

MOVING BOUNDARY WORK

صوأ حدأ نواعي الـ work المرتبط بالحركة (moving boundary) زي الغاز لما يتمدد (كل ذرة بتضغط عالذرة اللي جنبها ت)

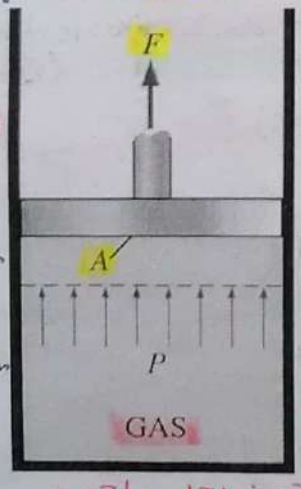
Moving boundary work (*P dV* work):
The expansion and compression work in a piston-cylinder device.

Quasi-equilibrium process:
A process during which the system remains nearly in equilibrium at all times.

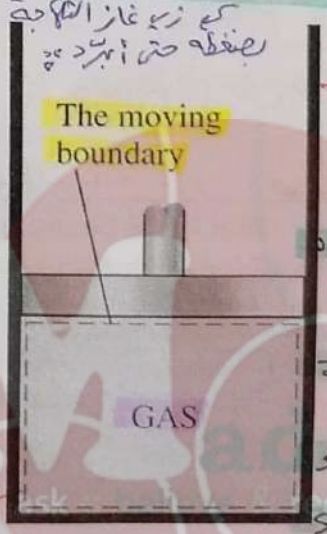
$$\delta W_b = F\,ds = PA\,ds = P\,dV$$

$$W_b = \int_1^2 P\,dV \quad (\text{kJ})$$

W_b is positive → for expansion
W_b is negative → for compression

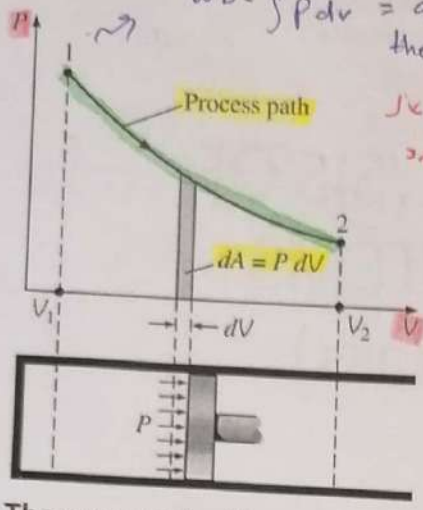


A gas does a differential amount of work δW_b as it forces the piston to move by a differential amount *ds*.



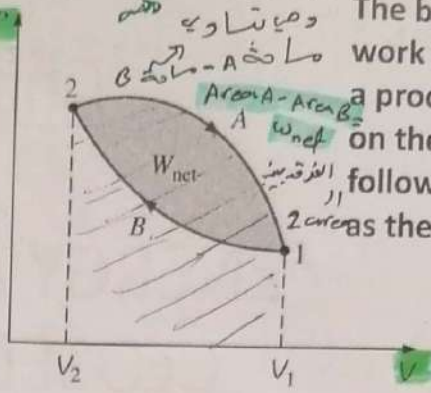
The work associated with a moving boundary is called *boundary work*.

الممسوحة ضوئيا بـ CamScanner

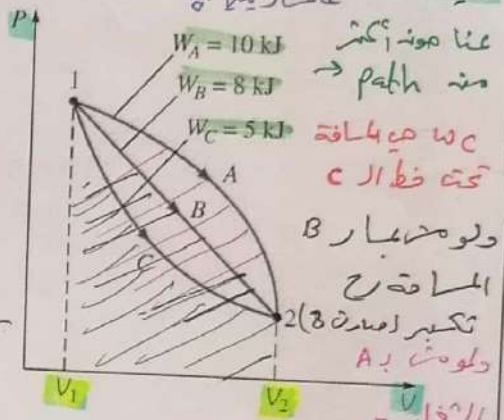


The area under the process curve on a *P-V* diagram represents the boundary work.

$$\text{Area} = A = \int_1^2 dA = \int_1^2 P\,dV$$



The boundary work done during a process depends on the path followed as well as the end states.



The net work done during a cycle is the difference between the work done by the system and the work done on the system.

Polytropic, Isothermal, and Isobaric processes

Polytropic process: C, n (polytropic exponent) constants

$$P = CV^{-n}$$

$$W_b = \int_1^2 P\,dV = \int_1^2 CV^{-n}\,dV = C\frac{V_2^{-n+1} - V_1^{-n+1}}{-n+1} = \frac{P_2V_2 - P_1V_1}{1-n}$$

Polytropic and for ideal gas

$$W_b = \frac{mR(T_2 - T_1)}{1-n}$$

When $n = 1$ (isothermal process)

$$W_b = \int_1^2 P\,dV = \int_1^2 CV^{-1}\,dV = RV\ln\left(\frac{V_2}{V_1}\right)$$

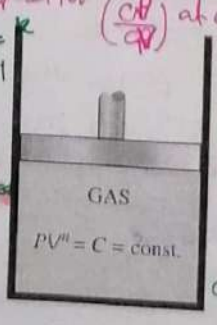
Constant pressure process

$$W_b = \int_1^2 P\,dV = P_0\int_1^2 dV = P_0(V_2 - V_1)$$

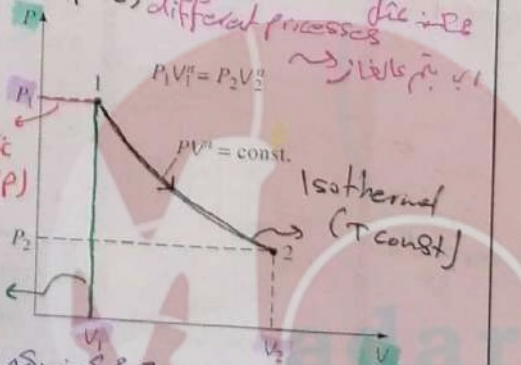
Q: What is the boundary work for a constant-volume process? equal zero

$$W_b = 0$$

because $W_b = \int P\Delta V$



Schematic and *P-V* diagram for a polytropic process.



الممسوحة ضوئيا بـ CamScanner

ENERGY BALANCE FOR CLOSED SYSTEMS

$$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic, potential, etc., energies}} \quad \text{(kJ)}$$

Energy balance for any system undergoing any process

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} \quad \text{(kW)}$$

Energy balance in the rate form

The total quantities are related to the quantities per unit time is:

$$Q = \dot{Q}\Delta t, \quad W = \dot{W}\Delta t, \quad \text{and} \quad \Delta E = (dE/dt)\Delta t \quad \text{(kJ)}$$

$$e_{in} - e_{out} = \Delta e_{system} \quad \text{(kJ/kg)}$$

Energy balance per unit mass basis

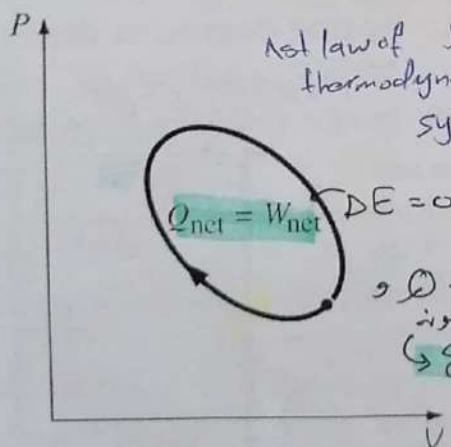
$$W_{net,out} = Q_{net,in} \quad \text{or} \quad \dot{W}_{net,out} = \dot{Q}_{net,in}$$

Energy balance for a cycle

$$Q_{net,in} - W_{net,out} = \Delta E_{system} \quad \text{or} \quad Q - W = \Delta E$$

$$Q = Q_{net,in} = Q_{in} - Q_{out}$$
$$W = W_{net,out} = W_{out} - W_{in}$$

Energy balance when sign convention is used (i.e., heat input and work output are positive; heat output and work input are negative).



For a cycle $\Delta E = 0$, thus $Q = W$.

General	$Q - W = \Delta E$
Stationary systems	$Q - W = \Delta U$
Per unit mass	$q - w = \Delta e$
Differential form	$\delta q - \delta w = de$

Various forms of the first-law relation for closed systems when sign convention is used.

The first law cannot be proven mathematically, but no process in nature is known to have violated the first law, and this should be taken as sufficient proof.

CamScanner الممسوحة ضوئيا بـ

Energy balance for a constant-pressure expansion or compression process

General analysis for a closed system undergoing a quasi-equilibrium constant-pressure process. *Q* is *to* the system and *W* is *from* the system.

$$E_{in} - E_{out} = \Delta E_{system}$$

Net energy transfer by heat, work, and mass = Change in internal, kinetic, potential, etc., energies

$$Q - W = \Delta U + \Delta KE^{0} + \Delta PE^{0}$$

$$Q - W_{other} - W_b = U_2 - U_1$$

$$Q - W_{other} - P_0(V_2 - V_1) = U_2 - U_1$$

$$Q - W_{other} = (U_2 + P_2V_2) - (U_1 + P_1V_1)$$

$H = U + PV$ ← H = U+PV ال by definition

$$Q - W_{other} = H_2 - H_1$$

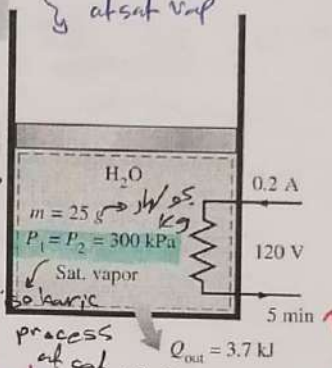
For a constant-pressure expansion or compression process:

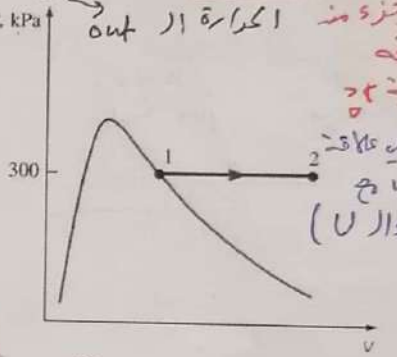
$$\Delta U + W_b = \Delta H$$

An example of constant-pressure process

$$W_{e,in} - Q_{out} - W_b = \Delta U$$

$$W_{e,in} - Q_{out} = \Delta H = m(h_2 - h_1)$$

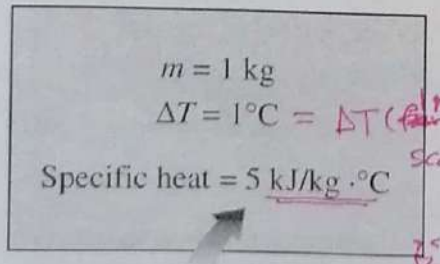




SPECIFIC HEATS

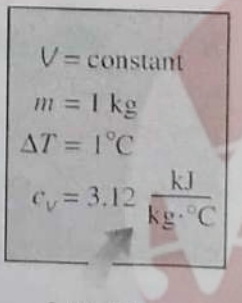
Specific heat at constant volume, c_v: The energy required to raise the temperature of the unit mass of a substance by one degree as the volume is maintained constant.

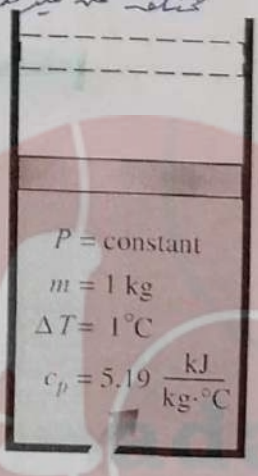
Specific heat at constant pressure, c_p: The energy required to raise the temperature of the unit mass of a substance by one degree as the pressure is maintained constant.



Specific heat is the energy required to raise the temperature of a unit mass of a substance by one degree in a specified way.

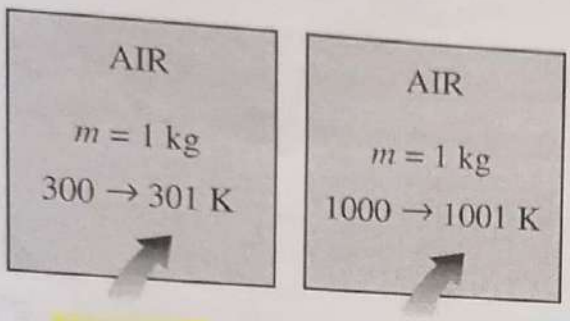
Constant-volume and constant-pressure specific heats c_v and c_p (values are for helium gas).





CamScanner الممسوحة ضوئيا بـ

- The equations in the figure are valid for *any* substance undergoing *any* process.
- c_v and c_p are properties.
- c_v is related to the changes in *internal energy* and c_p to the changes in *enthalpy*.
- A common unit for specific heats is kJ/kg · °C or kJ/kg · K. ***Are these units identical?***



0.718 kJ 0.855 kJ

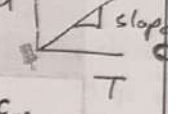
The specific heat of a substance changes with temperature.

Q: True or False:
c_p is always greater than c_v

$\Delta U = \int c_v dT$

$c_v = \left(\frac{\partial u}{\partial T}\right)_v$ = the change in internal energy with temperature at constant volume

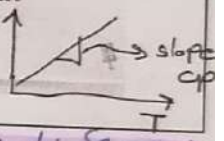
معدل تغير الـ internal energy بالنسبة لدرجة الحرارة عند حجم ثابت



Formal definitions of c_v and c_p.

$c_p = \left(\frac{\partial h}{\partial T}\right)_p$ = the change in enthalpy with temperature at constant pressure

معدل تغير الـ enthalpy مع درجة الحرارة عند ضغط ثابت



$c_p > c_v$ always

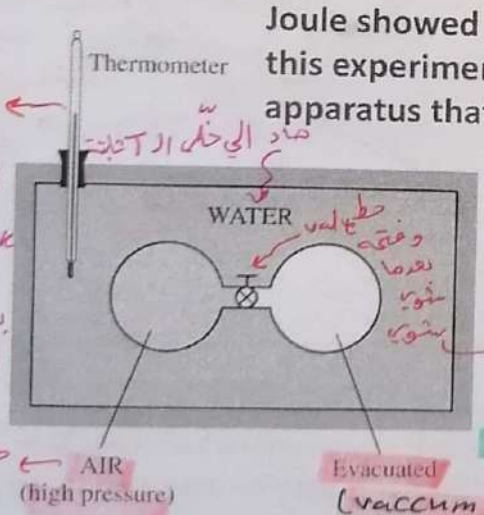
$R = c_p - c_v$ (only on ideal gas) because $h = u + pv$ so $h > u$

$\frac{dh}{dT} > \frac{du}{dT} \rightarrow c_p > c_v$

In real gas it differ ; * In liq & solid $c_p = c_v = c$ (because they are incompressible)

INTERNAL ENERGY, ENTHALPY, and SPECIFIC HEATS OF IDEAL GASES

Joule showed using this experimental apparatus that $u = u(T)$



$$\left.\begin{aligned} h &= u + Pv \\ Pv &= RT \end{aligned}\right\} \quad h = u + RT$$

$u = u(T)$ $h = h(T)$ تبين ان الـ Internal E & enth تعتمد على الحرارة

also c_v & c_p depend on Temp (not depend on P)

$du = c_v(T)\,dT$ $dh = c_p(T)\,dT$

$\Delta u = u_2 - u_1 = \int_1^2 c_v(T)\,dT$ change in Internal E

$\Delta h = h_2 - h_1 = \int_1^2 c_p(T)\,dT$ change in enth

$\Delta H = \int_{T_1}^{T_2} c_p dT = \int_{T_1}^{T_2} (a + bT + cT^2 + dT^3)\,dT$

$\Delta H = \left(a\,dT + bT\,dT + cT^2\,dT\right)\Big]_{T_1}^{T_2}$

$\Delta H = aT + b\frac{T^2}{2} + c\frac{T^3}{3}\Big]_{T_1}^{T_2}$

$c_v(T)$ $c_p(T)$

Δu & ΔH هو طول بحيث ان c_v دالة c_p تقدر تطلع من التكامل

ما تغيرت بالـ T ما تغير الـ U (Internal E) ما تغير

$u = u(T)$
$h = h(T)$
$c_v = c_v(T)$
$c_p = c_p(T)$

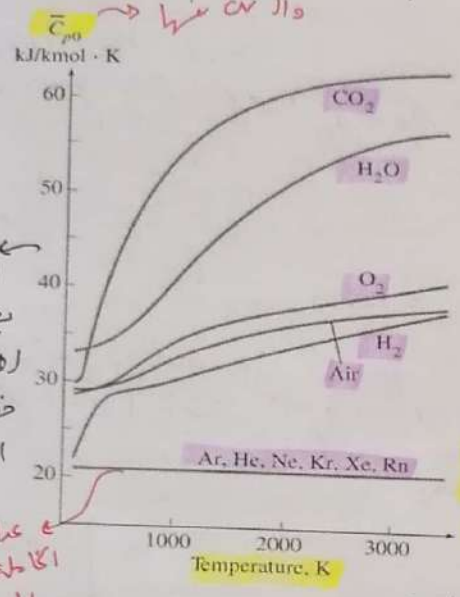
For ideal gases, u, h, c_v, and c_p vary with temperature only.

Internal energy and enthalpy change of an ideal gas because they are fun on T

c_p جامدة دائما بتكون أصغر من c_v بمقدار ثابت

الممسوحة ضوئيا بـ CamScanner

- At low pressures, all real gases approach ideal-gas behavior, and therefore their specific heats depend on temperature only.
- The specific heats of real gases at low pressures are called *ideal-gas specific heats*, or *zero-pressure specific heats*, and are often denoted c_{p0} and c_{v0}.



Ideal-gas constant-pressure specific heats for some gases (see Table A–2c for c_p equations).

- u and h data for a number of gases have been tabulated.
- These tables are obtained by choosing an arbitrary reference point and performing the integrations by treating state 1 as the reference state.

AIR

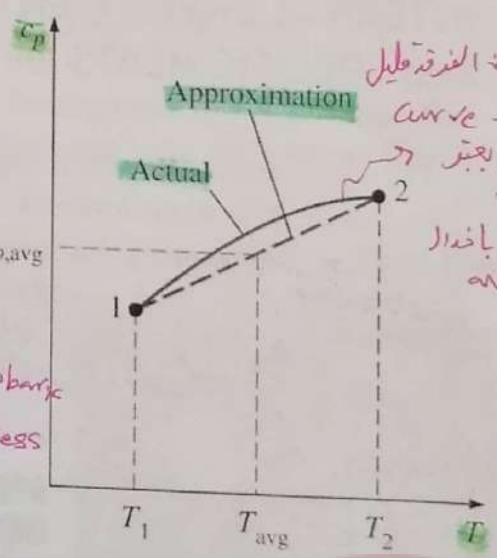
T, K	u, kJ/kg	h, kJ/kg
0	0	0
.	.	.
.	.	.
300	214.07	300.19
310	221.25	310.24
.	.	.
.	.	.

In the preparation of ideal-gas tables, 0 K is chosen as the reference temperature.

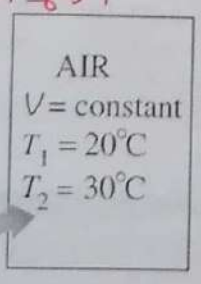
Internal energy and enthalpy change when specific heat is taken constant at an average value:

$$\Delta u = u_2 - u_1 = c_{v,\text{avg}}(T_2 - T_1) \quad \text{(kJ/kg)}$$

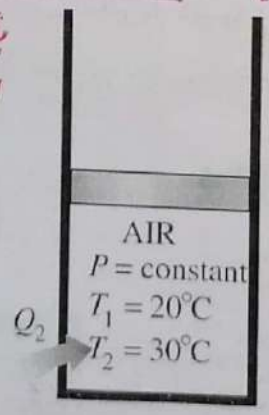
$$\Delta h = h_2 - h_1 = c_{p,\text{avg}}(T_2 - T_1)$$



For small temperature intervals, the specific heats may be assumed to vary linearly with temperature.



$\Delta u = c_v \Delta T = 7.18$ kJ/kg



$\Delta u = c_v \Delta T = 7.18$ kJ/kg

The relation $\Delta u = c_v \Delta T$ is valid for any kind of process, constant-volume or not.

CamScanner الممسوحة ضوئيا بـ

Three ways of calculating Δu and Δh

1. By using the tabulated u and h data. This is the easiest and ***most accurate*** way when tables are readily available.
2. By using the c_v or c_p relations (Table A-2c) as a function of temperature and performing the integrations. This is very inconvenient for hand calculations but quite desirable for computerized calculations. The results obtained are ***very accurate.***
3. By using average specific heats. This is very simple and certainly very convenient when property tables are not available. The results obtained are ***reasonably accurate*** if the temperature interval is not very large.

$$\Delta u = u_2 - u_1 \text{ (table)}$$

$$\Delta u = \int_1^2 c_v(T)\, dT$$

$$\Delta u \cong c_{v,\text{avg}}\, \Delta T$$

Three ways of calculating Δu.

13

Specific Heat Relations of Ideal Gases

$$h = u + RT \quad (R = \text{const})$$

$$dh = du + R\,dT$$

$dh = c_p dT$ and $du = c_v dT$

The relationship between c_p, c_v and R

$$c_p = c_v + R \qquad (\text{kJ/kg} \cdot \text{K})$$

On a molar basis

$$\bar{c}_p = \bar{c}_v + R_u \qquad (\text{kJ/kmol} \cdot \text{K})$$

Specific heat ratio:

$$k = \frac{c_p}{c_v}$$

AIR at 300 K

$$\left.\begin{aligned} c_v &= 0.718 \text{ kJ/kg} \cdot \text{K} \\ R &= 0.287 \text{ kJ/kg} \cdot \text{K} \end{aligned}\right\} c_p = 1.005 \text{ kJ/kg} \cdot \text{K}$$

or

$$\left.\begin{aligned} \bar{c}_v &= 20.80 \text{ kJ/kmol} \cdot \text{K} \\ R_u &= 8.314 \text{ kJ/kmol} \cdot \text{K} \end{aligned}\right\} \bar{c}_p = 29.114 \text{ kJ/kmol} \cdot \text{K}$$

The c_p of an ideal gas can be determined from a knowledge of c_v and R.

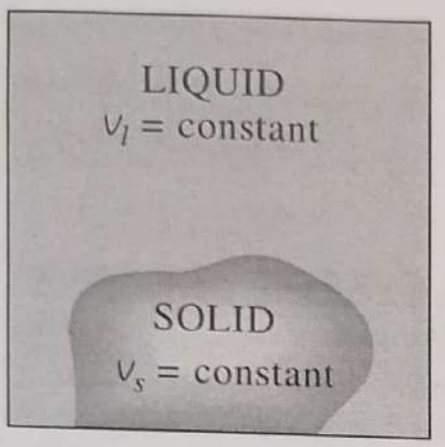
- The specific ratio varies with temperature, but this variation is very mild.
- For monatomic gases (helium, argon, etc.), its value is essentially constant at 1.667.
- Many diatomic gases, including air, have a specific heat ratio of about 1.4 at room temperature.

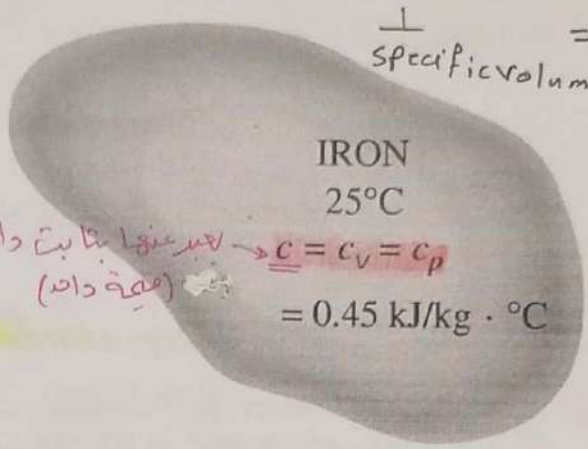
CamScanner الممسوحة ضوئيا بـ

INTERNAL ENERGY, ENTHALPY, and SPECIFIC HEATS OF SOLIDS AND LIQUIDS

Incompressible substance: A substance whose specific volume (or density) is constant. **Solids and liquids** are incompressible substances.

density = $\frac{1}{\text{specific volume}}$





يعبر عنها بثابت واحد (حجمة واحد)

The specific volumes of incompressible substances remain constant during a process.

The c_v and c_p values of incompressible substances are identical and are denoted by c. 15

Internal Energy Changes

$$du = c_v\,dT = c(T)\,dT$$

إذا لاحظنا في فرق بال C هو ال c_{avg} بناخد temp

$$\Delta u = u_2 - u_1 = \int_1^2 c(T)\,dT \qquad \text{(kJ/kg)}$$

واذا ما في بتكون ثابتة

$$\Delta u \cong c_{avg}(T_2 - T_1) \qquad \text{(kJ/kg)}$$

إما بتكون Const أو c_{avg}

Enthalpy Changes

$$h = u + Pv \quad \text{(for all substances)}$$

$$dh = du + v\,dP + P\,dv = du + v\,dP$$

$$\Delta h = \Delta u + v\,\Delta P \cong c_{avg}\,\Delta T + v\,\Delta P \qquad \text{(kJ/kg)}$$

(for liq & solid) no change in v

$h = u + Pv$

$dh = du + d(Pv)$

$= (v\,dP + P\,dv)$

For *solids*, the term $v\,\Delta P$ is insignificant and thus $\Delta h = \Delta u \cong c_{avg}\Delta T$. For *liquids*, two special cases are commonly encountered:

1. *Constant-pressure processes*, as in heaters ($\Delta P = 0$): $\Delta h = \Delta u \cong c_{avg}\Delta T$
2. *Constant-temperature processes*, as in pumps ($\Delta T = 0$): $\Delta h = v\,\Delta P$

$$h_{@P,T} \cong h_{f@T} + v_{f@T}(P - P_{sat@T})$$

The enthalpy of a compressed liquid

A more accurate relation than $h_{@P,T} \cong h_{f@T}$ (compressed ← saturated)

Qadar ask & believe & recieve

الممسوحة ضوئيا بـ CamScanner

EXAMPLE 4–1 Boundary Work for a Constant-Volume Process

A rigid tank contains air at 500 kPa and 150°C. As a result of heat transfer to the surroundings, the temperature and pressure inside the tank drop to 65°C and 400 kPa, respectively. Determine the boundary work done during this process.

SOLUTION Air in a rigid tank is cooled, and both the pressure and temperature drop. The boundary work done is to be determined.

Analysis A sketch of the system and the *P-V* diagram of the process are shown in Fig. 4–6. The boundary work can be determined from Eq. 4–2 to be

$$W_b = \int_1^2 P\,dV = 0$$

Discussion This is expected since a rigid tank has a constant volume and $dV = 0$ in this equation. Therefore, there is no boundary work done during this process. That is, the boundary work done during a constant-volume process is always zero. This is also evident from the *P-V* diagram of the process (the area under the process curve is zero).

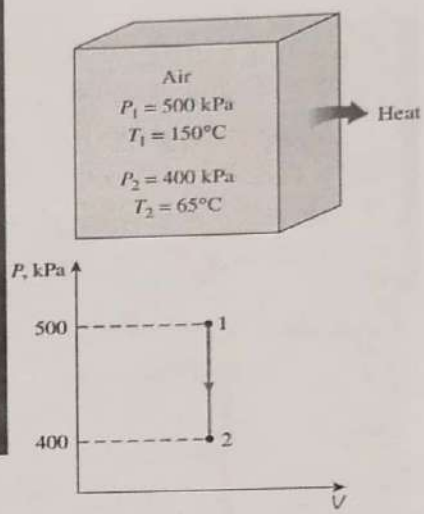


FIGURE 4–6
Schematic and *P-V* diagram for Example 4–1.

EXAMPLE 4–3 Isothermal Compression of an Ideal Gas

A piston–cylinder device initially contains 0.4 m^3 of air at 100 kPa and 80°C. The air is now compressed to 0.1 m^3 in such a way that the temperature inside the cylinder remains constant. Determine the work done during this process.

SOLUTION Air in a piston–cylinder device is compressed isothermally. The boundary work done is to be determined.

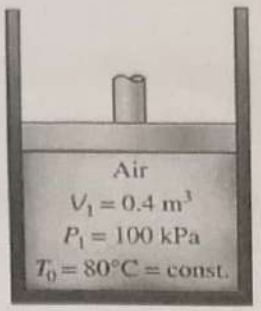
Analysis A sketch of the system and the *P-V* diagram of the process are shown in Fig. 4–8.

Assumptions 1 The compression process is quasi-equilibrium. 2 At specified conditions, air can be considered to be an ideal gas since it is at a high temperature and low pressure relative to its critical-point values.

Analysis For an ideal gas at constant temperature T_0,

$$PV = mRT_0 = C \quad \text{or} \quad P = \frac{C}{V}$$

CamScanner الممسوحة ضوئيا بـ



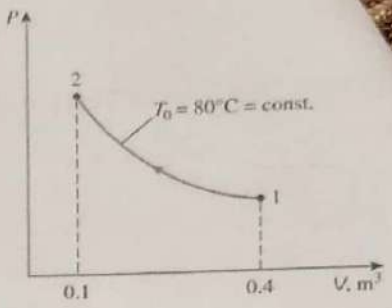


FIGURE 4–8
Schematic and *P-V* diagram for Example 4–3.

where C is a constant. Substituting this into Eq. 4–2, we have

$$W_b = \int_1^2 P\,dV = \int_1^2 \frac{C}{V}\,dV = C\int_1^2 \frac{dV}{V} = C \ln \frac{V_2}{V_1} = P_1V_1 \ln \frac{V_2}{V_1} \qquad (4\text{–}7)$$

In Eq. 4–7, P_1V_1 can be replaced by P_2V_2 or mRT_0. Also, V_2/V_1 can be replaced by P_1/P_2 for this case since $P_1V_1 = P_2V_2$.

Substituting the numerical values into Eq. 4–7 yields

$$W_b = (100\ \text{kPa})(0.4\ \text{m}^3)\left(\ln \frac{0.1}{0.4}\right)\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right)$$

$$= -55.5\ \text{kJ}$$

Discussion The negative sign indicates that this work is done on the system (a work input), which is always the case for compression processes.

EXAMPLE 4–5 Electric Heating of a Gas at Constant Pressure

A piston–cylinder device contains 25 g of saturated water vapor that is maintained at a constant pressure of 300 kPa. A resistance heater within the cylinder is turned on and passes a current of 0.2 A for 5 min from a 120-V source. At the same time, a heat loss of 3.7 kJ occurs. (*a*) Show that for a closed system the boundary work W_b and the change in internal energy ΔU in the first-law relation can be combined into one term, ΔH, for a constant-pressure process. (*b*) Determine the final temperature of the steam.

SOLUTION Saturated water vapor in a piston–cylinder device expands at constant pressure as a result of heating. It is to be shown that $\Delta U + W_b = \Delta H$, and the final temperature is to be determined.

Assumptions 1 The tank is stationary and thus the kinetic and potential energy changes are zero, $\Delta KE = \Delta PE = 0$. Therefore, $\Delta E = \Delta U$ and internal energy is the only form of energy of the system that may change during this process. 2 Electrical wires constitute a very small part of the system, and thus the energy change of the wires can be neglected.

Analysis We take the contents of the cylinder, including the resistance wires, as the *system* (Fig. 4–13). This is a *closed system* since no mass crosses the system boundary during the process. We observe that a piston–cylinder device typically involves a moving boundary and thus boundary work W_b. The pressure remains constant during the process and thus $P_2 = P_1$. Also, heat is lost from the system and electrical work W_e is done on the system.

CamScanner الممسوحة ضوئيا بـ

(*a*) This part of the solution involves a general analysis for a closed system undergoing a quasi-equilibrium constant-pressure process, and thus we consider a general closed system. We take the direction of heat transfer Q to be to the system and the work W to be done by the system. We also express the work as the sum of boundary and other forms of work (such as electrical and shaft). Then, the energy balance can be expressed as

$$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic, potential, etc., energies}}$$

$$Q - W = \Delta U + \Delta KE^{\nearrow 0} + \Delta PE^{\nearrow 0}$$

$$Q - W_{other} - W_b = U_2 - U_1$$

For a constant-pressure process, the boundary work is given as $W_b = P_0(V_2 - V_1)$. Substituting this into the preceding relation gives

$$Q - W_{other} - P_0(V_2 - V_1) = U_2 - U_1$$

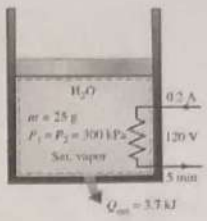
However,

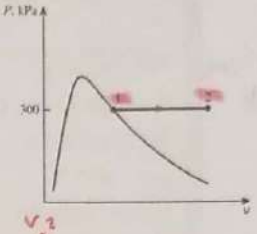
$$P_0 = P_2 = P_1 \rightarrow Q - W_{other} = (U_2 + P_2V_2) - (U_1 + P_1V_1)$$

Also $H = U + PV$, and thus

$$Q - W_{other} = H_2 - H_1 \quad \text{(kJ)} \qquad \textbf{(4–18)}$$

which is the desired relation (Fig. 4–14). This equation is very convenient to use in the analysis of closed systems undergoing a ***constant-pressure quasi-equilibrium process*** since the boundary work is automatically taken care of by the enthalpy terms, and one no longer needs to determine it separately.





$\rightarrow w_b = \int_{v_1}^{v_2} P\,dv = P(v_2 - v_1)$ ln Isobaric

$\rightarrow w_b = \int_{v_1}^{v_2} P\,dv$ (Isothermal)

ln Isothermal Ideal gas law

$PV = mRT \rightarrow$ const $= C$ ($PV = C$)

So $P_1V_1 = P_2V_2 \Rightarrow \frac{V_2}{V_1} = \frac{P_1}{P_2}$

$\rightarrow w_b = \int_{v_1}^{v_2} P\,dv = \int_{v_1}^{v_2} \frac{C}{V}\,dv$

$w_b = C\int \frac{dv}{v}$

$\therefore w_b = P_1V_1 \ln\frac{V_2}{V_1} = P_2V_2 \ln\frac{V_2}{V_1}$

$= \ln\frac{P_1}{P_2}$

(*b*) The only other form of work in this case is the electrical work, which can be determined from

$$W_e = VI\Delta t = (120\text{ V})(0.2\text{ A})(300\text{ s})\left(\frac{1\text{ kJ/s}}{1000\text{ VA}}\right) = 7.2\text{ kJ}$$

State 1: $\left.\begin{matrix} P_1 = 300\text{ kPa} \\ \text{sat. vapor} \end{matrix}\right\} h_1 = h_{g\,@\,300\text{ kPa}} = 2724.9\text{ kJ/kg}$ (Table A–5)

The enthalpy at the final state can be determined directly from Eq. 4–18 by expressing heat transfer from the system and work done on the system as negative quantities (since their directions are opposite to the assumed directions). Alternately, we can use the general energy balance relation with the simplification that the boundary work is considered automatically by replacing ΔU by ΔH for a constant-pressure expansion or compression process:

$$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic, potential, etc., energies}}$$

$$W_{e,in} - Q_{out} - W_b = \Delta U$$

$$W_{e,in} - Q_{out} = \Delta H = m(h_2 - h_1) \quad \text{(since } P = \text{constant)}$$

$$7.2\text{ kJ} - 3.7\text{ kJ} = (0.025\text{ kg})(h_2 - 2724.9)\text{ kJ/kg}$$

$$h_2 = 2864.9\text{ kJ/kg}$$

Now the final state is completely specified since we know both the pressure and the enthalpy. The temperature at this state is

State 2: $\left.\begin{matrix} P_2 = 300\text{ kPa} \\ h_2 = 2864.9\text{ kJ/kg} \end{matrix}\right\} T_2 = 200°\text{C}$ (Table A–6)

Therefore, the steam will be at 200°C at the end of this process.

CamScanner الممسوحة ضوئيا بـ

EXAMPLE 4–7 Evaluation of the Δu of an Ideal Gas

Air at 300 K and 200 kPa is heated at constant pressure (isobaric) to 600 K. Determine the change in internal energy of air per unit mass, using (*a*) data from the air table (Table A–17), (*b*) the functional form of the specific heat (Table A–2*c*), and (*c*) the average specific heat value (Table A–2*b*).

SOLUTION The internal energy change of air is to be determined in three different ways.

Assumptions At specified conditions, air can be considered to be an ideal gas since it is at a high temperature and low pressure relative to its critical-point values.

Analysis The internal energy change Δu of ideal gases depends on the initial and final temperatures only, and not on the type of process. Thus, the following solution is valid for any kind of process.

(*a*) One way of determining the change in internal energy of air is to read the u values at T_1 and T_2 from Table A–17 and take the difference:

$$u_1 = u_{@\,300\,K} = 214.07 \text{ kJ/kg}$$

$$u_2 = u_{@\,600\,K} = 434.78 \text{ kJ/kg}$$

Thus,

$$\Delta u = u_2 - u_1 = (434.78 - 214.07) \text{ kJ/kg} = 220.71 \text{ kJ/kg}$$

(*b*) The $\bar{c}_p(T)$ of air is given in Table A–2*c* in the form of a third-degree polynomial expressed as

$$\bar{c}_p(T) = a + bT + cT^2 + dT^3$$

where $a = 28.11$, $b = 0.1967 \times 10^{-2}$, $c = 0.4802 \times 10^{-5}$, and $d = -1.966 \times 10^{-9}$. From Eq. 4–30,

$$\bar{c}_v(T) = \bar{c}_p - R_u = (a - R_u) + bT + cT^2 + dT^3$$

From Eq. 4–25,

$$\Delta \bar{u} = \int_1^2 \bar{c}_v(T)\, dT = \int_{T_1}^{T_2} [(a - R_u) + bT + cT^2 + dT^3]\, dT$$

Performing the integration and substituting the values, we obtain

$$\Delta \bar{u} = 6447 \text{ kJ/kmol}$$

The change in the internal energy on a unit-mass basis is determined by dividing this value by the molar mass of air (Table A–1):

$$\Delta u = \frac{\Delta \bar{u}}{M} = \frac{6447 \text{ kJ/kmol}}{28.97 \text{ kg/kmol}} = 222.5 \text{ kJ/kg}$$

which differs from the tabulated value by 0.8 percent.

(*c*) The average value of the constant-volume specific heat $c_{v,\text{avg}}$ is determined from Table A–2*b* at the average temperature of $(T_1 + T_2)/2 = 450$ K to be

$$c_{v,\text{avg}} = c_{v\,@\,450\,K} = 0.733 \text{ kJ/kg·K}$$

Thus,

$$\Delta u = c_{v,\text{avg}}(T_2 - T_1) = (0.733 \text{ kJ/kg·K})[(600 - 300)\text{K}] = 220 \text{ kJ/kg}$$

EXAMPLE 4–11 **Enthalpy of Compressed Liquid**

Determine the enthalpy of liquid water at 100°C and 15 MPa (*a*) by using compressed liquid tables, (*b*) by approximating it as a saturated liquid, and (*c*) by using the correction given by Eq. 4–38.

SOLUTION The enthalpy of liquid water is to be determined exactly and approximately.

Analysis At 100°C, the saturation pressure of water is 101.42 kPa, and since $P > P_{sat}$, the water exists as a compressed liquid at the specified state.

(*a*) From compressed liquid tables, we read

$$\left.\begin{matrix} P = 15\ \text{MPa} \\ T = 100°\text{C} \end{matrix}\right\} \quad h = 430.39\ \text{kJ/kg} \qquad \text{(Table A–7)}$$

This is the exact value.

(*b*) Approximating the compressed liquid as a saturated liquid at 100°C, as is commonly done, we obtain

$$h \cong h_{f\,@\,100°\text{C}} = 419.17\ \text{kJ/kg}$$

This value is in error by about 2.6 percent.

(*c*) From Eq. 4–38,

$$h_{@P,T} \cong h_{f\,@\,T} + v_{f\,@\,T}(P - P_{sat\,@\,T})$$

$$= (419.17\ \text{kJ/kg}) + (0.001\ \text{m}^3/\text{kg})[(15{,}000 - 101.42)\ \text{kPa}]\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right)$$

$$= 434.07\ \text{kJ/kg}$$

Discussion Note that the correction term reduced the error from 2.6 to about 1 percent in this case. However, this improvement in accuracy is often not worth the extra effort involved.

CamScanner الممسوحة ضوئيا بـ



Chapter 5

MASS AND ENERGY ANALYSIS OF OPEN SYSTEMS (Control Volumes)

Thermodynamics: An Engineering Approach
Yunus A. Cengel, Michael A. Boles, Mehmet Kanoglu
McGraw-Hill

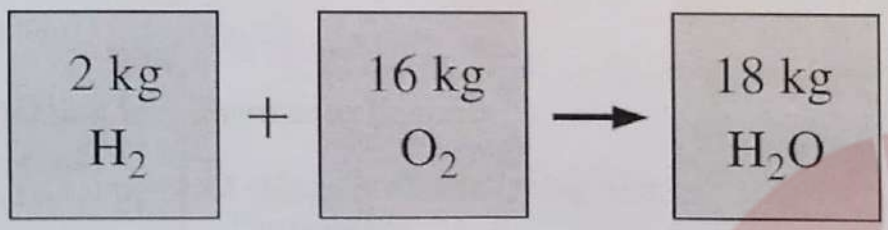
Dr. Ahmad M. AbuYaghi
October 2023

CONSERVATION OF MASS

Conservation of mass: Mass, like energy, is a conserved property, and it cannot be created or destroyed during a process.

Closed systems: The mass of the system remain constant during a process.

Control volumes: Mass can cross the boundaries, and so we must keep track of the amount of mass entering and leaving the control volume.



Mass is conserved even during chemical reactions.

Mass m and energy E can be converted to each other according to

$$E = mc^2$$

where c is the speed of light in a vacuum, which is $c = 2.9979 \times 10^8$ m/s.

The mass change due to energy change is absolutely negligible.

CamScanner الممسوحة ضوئيا بـ

Mass and Volume Flow Rates

$$\delta \dot{m} = \rho V_n \, dA_c$$

$$\dot{m} = \int_{A_c} \delta \dot{m} = \int_{A_c} \rho V_n \, dA_c$$

$$\dot{m} = \rho V_{\text{avg}} A_c \qquad (\text{kg/s})$$

$$V_{\text{avg}} = \frac{1}{A_c} \int_{A_c} V_n \, dA_c$$

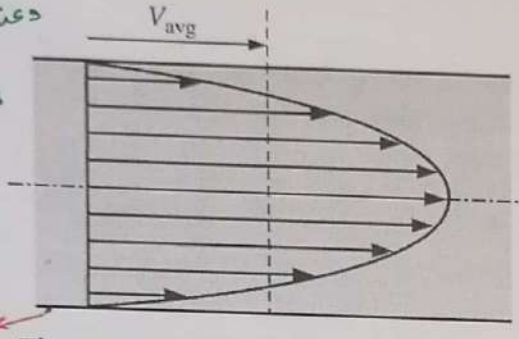
Definition of average velocity

Volume flow rate

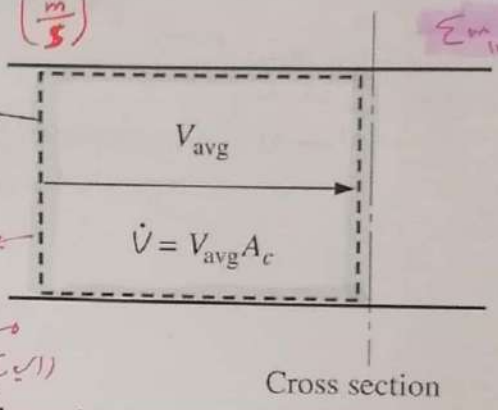
$$\dot{V} = \int_{A_c} V_n \, dA_c = V_{\text{avg}} A_c = VA_c \qquad (\text{m}^3/\text{s})$$

$$\dot{m} = \rho \dot{V} = \frac{\dot{V}}{v}$$

Mass flow rate



The average velocity V_{avg} is defined as the average speed through a cross section.



The volume flow rate is the volume of fluid flowing through a cross section per unit time.

Conservation of Mass Principle

The conservation of mass principle for a control volume: **The net mass transfer to or from a control volume during a time interval Δt is equal to the net change (increase or decrease) in the total mass within the control volume during Δt.**

$$\begin{pmatrix}\text{Total mass entering}\\ \text{the CV during } \Delta t\end{pmatrix} - \begin{pmatrix}\text{Total mass leaving}\\ \text{the CV during } \Delta t\end{pmatrix} = \begin{pmatrix}\text{Net change in mass}\\ \text{within the CV during } \Delta t\end{pmatrix}$$

$$m_{\text{in}} - m_{\text{out}} = \Delta m_{\text{CV}} \qquad (\text{kg})$$

$$\dot{m}_{\text{in}} - \dot{m}_{\text{out}} = dm_{\text{CV}}/dt \qquad (\text{kg/s})$$

General conservation of mass

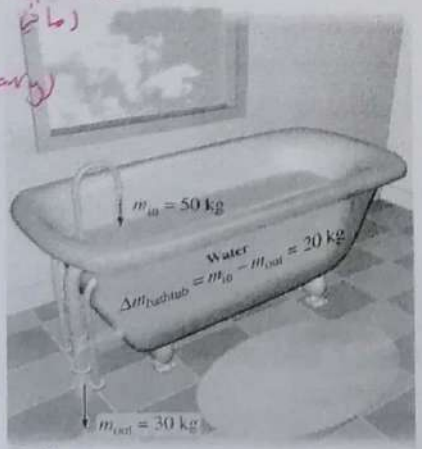
$$\frac{d}{dt}\int_{\text{CV}} \rho \, dV + \int_{\text{CS}} \rho(\vec{V} \cdot \vec{n}) \, dA = 0$$

General conservation of mass in rate form

$$\frac{d}{dt}\int_{\text{CV}} \rho \, dV = \sum_{\text{in}} \dot{m} - \sum_{\text{out}} \dot{m}$$

or

$$\frac{dm_{\text{CV}}}{dt} = \sum_{\text{in}} \dot{m} - \sum_{\text{out}} \dot{m}$$

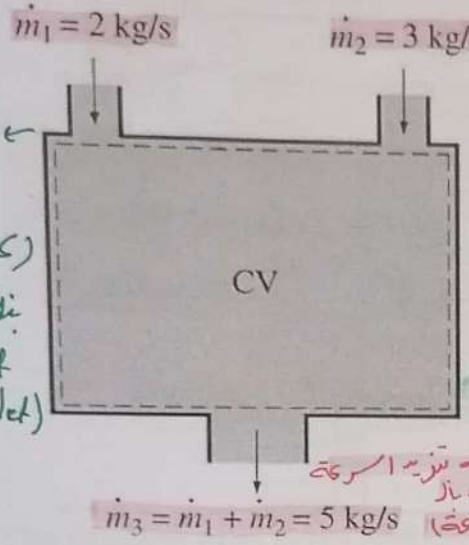


Conservation of mass principle for an ordinary bathtub.

Mass Balance for Steady-Flow Processes

During a steady-flow process, the total amount of mass contained within a control volume does not change with time (m_{CV} = constant).

Then the conservation of mass principle requires that the total amount of mass entering a control volume equal the total amount of mass leaving it.



Conservation of mass principle for a two-inlet–one-outlet steady-flow system.

For steady-flow processes, we are interested in the amount of mass flowing per unit time, that is, *the mass flow rate.*

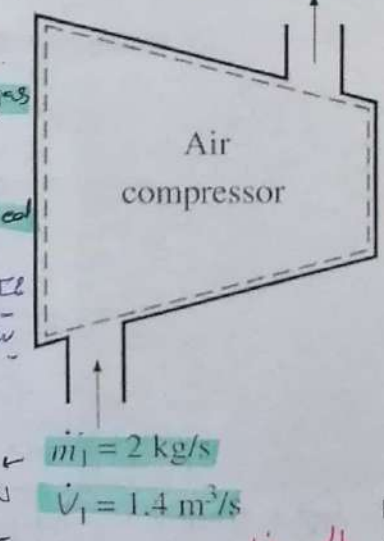
$$\sum_{in} \dot{m} = \sum_{out} \dot{m} \quad (kg/s)$$ Multiple inlets and exits

$$\dot{m}_1 = \dot{m}_2 \rightarrow \rho_1 V_1 A_1 = \rho_2 V_2 A_2$$ Single stream

Many engineering devices such as nozzles, diffusers, turbines, compressors, and pumps involve a single stream (only one inlet and one outlet).

Special Case: Incompressible Flow

The conservation of mass relations can be simplified even further when the fluid is incompressible, which is usually the case for liquids.



$$\sum_{in} \dot{V} = \sum_{out} \dot{V} \quad (m^3/s)$$ Steady, incompressible

$$\dot{V}_1 = \dot{V}_2 \rightarrow V_1 A_1 = V_2 A_2$$ Steady, incompressible flow (single stream)

- **There is no such thing as a "conservation of volume" principle.**
- **However, for steady flow of liquids, the volume flow rates, as well as the mass flow rates, remain constant since liquids are essentially incompressible substances.**

During a steady-flow process, volume flow rates are not necessarily conserved although mass flow rates are.

CamScanner الممسوحة ضوئيا بـ

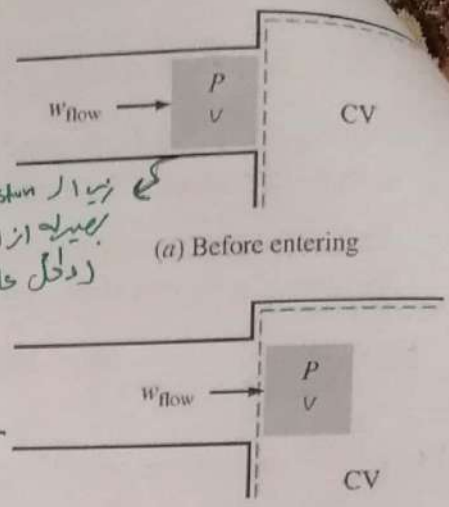
FLOW WORK AND THE ENERGY OF A FLOWING FLUID

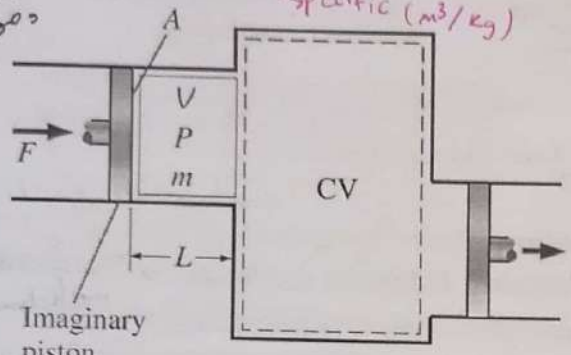
Flow work, or flow energy: The work (or energy) required to push the mass into or out of the control volume. This work is necessary for maintaining a continuous flow through a control volume.

$$F = PA$$

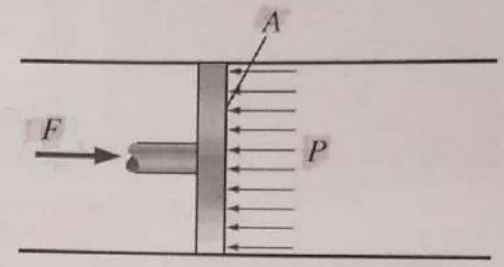
$$W_{flow} = FL = PAL = PV \quad \text{(kJ)}$$

$$w_{flow} = Pv \quad \text{(kJ/kg)}$$





Schematic for flow work.



In the absence of acceleration, the force applied on a fluid by a piston is equal to the force applied on the piston by the fluid.

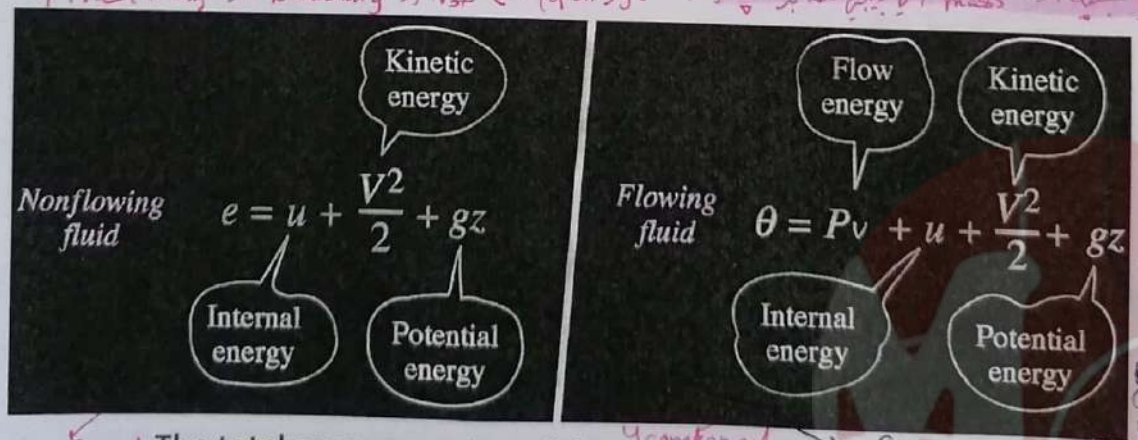
Total Energy of a Flowing Fluid

$$e = u + \text{ke} + \text{pe} = u + \frac{V^2}{2} + gz \quad \text{(kJ/kg)}$$

$$\theta = Pv + e = Pv + (u + \text{ke} + \text{pe}) \qquad h = u + Pv$$

$$\theta = h + \text{ke} + \text{pe} = h + \frac{V^2}{2} + gz \quad \text{(kJ/kg)}$$

The flow energy is automatically taken care of by enthalpy. In fact, this is the main reason for defining the property enthalpy.

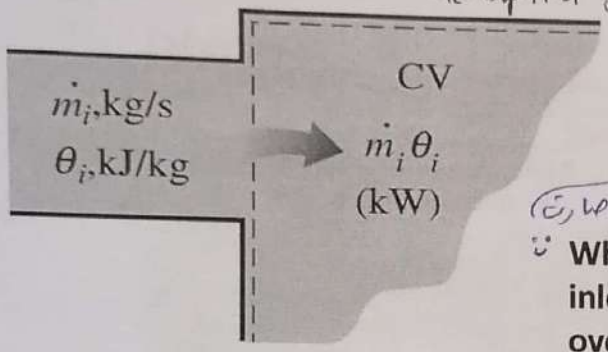


The total energy consists of three parts for a nonflowing fluid and four parts for a flowing fluid.

Energy Transport by Mass

Amount of energy transport: $E_{\text{mass}} = m\theta = m\left(h + \frac{V^2}{2} + gz\right)$ (kJ)

Rate of energy transport: $\dot{E}_{\text{mass}} = \dot{m}\theta = \dot{m}\left(h + \frac{V^2}{2} + gz\right)$ (kW)



When the kinetic and potential energies of a fluid stream are negligible

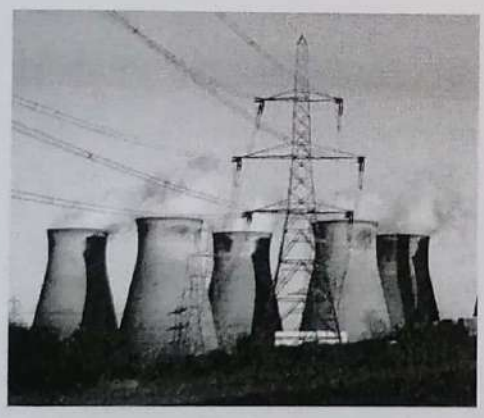
$$E_{\text{mass}} = mh \qquad \dot{E}_{\text{mass}} = \dot{m}h$$

When the properties of the mass at each inlet or exit change with time as well as over the cross section

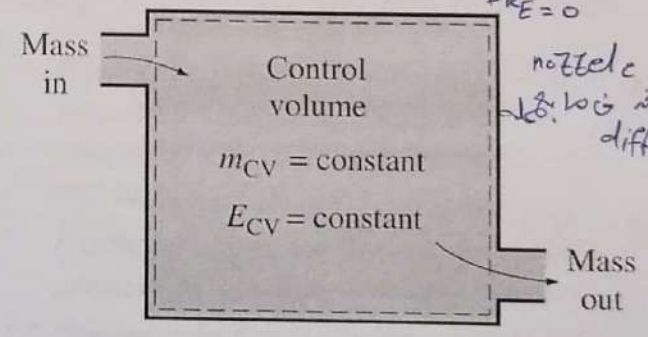
$$E_{\text{in,mass}} = \int_{m_i} \theta_i\, \delta m_i = \int_{m_i} \left(h_i + \frac{V_i^2}{2} + gz_i\right) \delta m_i$$

The product $\dot{m}_i\theta_i$ is the energy transported into control volume by mass per unit time.

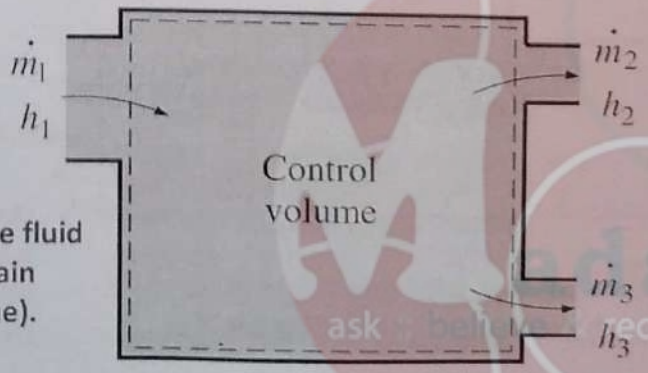
ENERGY ANALYSIS OF STEADY-FLOW SYSTEMS



Many engineering systems such as power plants operate under steady conditions.



Under steady-flow conditions, the mass and energy contents of a control volume remain constant.



Under steady-flow conditions, the fluid properties at an inlet or exit remain constant (do not change with time).

CamScanner الممسوحة ضوئيا بـ

Introduction and Basic Concepts

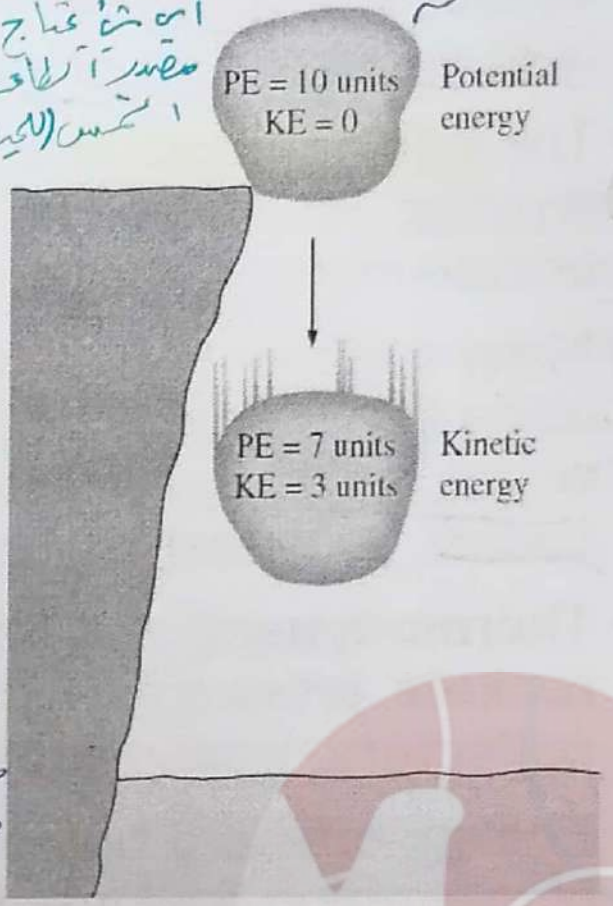
- One of the most fundamental laws of nature is the conservation of energy principle. It simply states that during an interaction, energy can change from one form to another, but the **total amount of energy** remains constant. That is, energy cannot be created or destroyed.
- A rock falling off a cliff, for example, picks up speed as a result of its potential energy being converted to kinetic energy.
- A person who has a greater energy input (food) than energy output (exercise) will gain weight (store energy in the form of fat), and a person who has a smaller energy input than output will lose weight.
- The change in the energy content of a body or any other system is equal to the difference between the energy input and the energy output, and the energy balance is expressed as:

$$E_{in} - E_{out} = \Delta E.$$

CamScanner الممسوحة ضوئيا بـ

THERMODYNAMICS AND ENERGY-1

- **Thermodynamics**: The science of *energy*.
- **Energy**: The ability to cause changes.
- The name *thermodynamics* stems from the Greek words *therme* (heat) and *dynamis* (power).
- **Conservation of energy principle**: During an interaction, *energy can change from one form to another*, but the total amount of energy remains constant.
- Energy cannot be created or destroyed.
- **The first law of thermodynamics**: An expression of the conservation of energy principle.
- The first law asserts that *energy* is a thermodynamic property.



Energy cannot be created or destroyed; it can only change forms (the first law).

CamScanner الممسوحة ضوئيا بـ

THERMODYNAMICS AND ENERGY-2

- **The second law of thermodynamics**: It asserts that energy has *quality* as well as *quantity*, and actual processes occur in the direction of decreasing quality of energy.



Heat flows in the direction of decreasing temperature.

Types of Thermodynamic Studies:

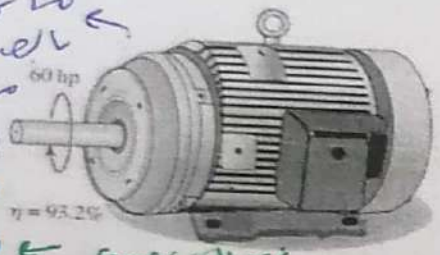
- **Classical thermodynamics**: A macroscopic approach to the study of thermodynamics that does not require a knowledge of the behavior of individual particles.
  - It provides a direct and easy way to the solution of engineering problems (used in this course).
- **Statistical thermodynamics**: A microscopic approach, based on the average behavior of large groups of individual particles (molecules).

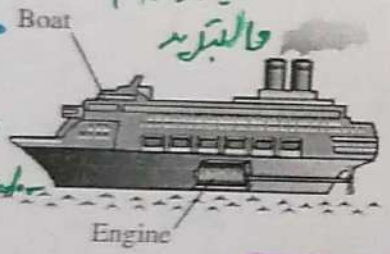
Applications of Thermodynamics

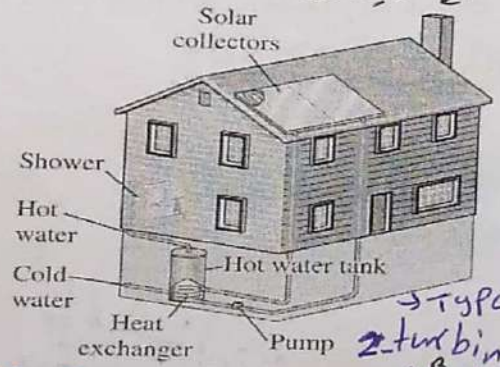
- **Thermodynamics** is encountered in many engineering systems and other aspects of life.
- The **heart** is constantly pumping blood to all parts of the human body, various energy conversions occur in trillions of body cells, and the body heat generated is constantly rejected to the environment.
- The **human comfort** is closely tied to the rate of this metabolic heat rejection (controlling heat transfer rate by adjusting clothing to environmental conditions).
- Many ordinary **household appliances** are designed, in whole or in part, by using the principles of **thermodynamics.** Some examples include electric or gas range, heating and air-conditioning systems, refrigerator, pressure cooker, water heater, computer, etc.
- **Thermodynamics** is basic in design and analysis of **automotive engines, rockets, jet engines, power plants, electrochemical cells, solar collectors, transportation vehicles from ordinary cars to airplanes.**
- **Energy-efficient home** that you may be living in is designed on the basis of minimizing heat loss in winter and heat gain in summer.
- Size, location, and power input of the **fan of your computer** is also selected after an analysis that involves **th**

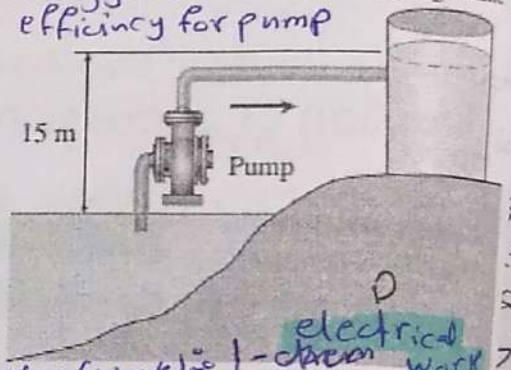
CamScanner الممسوحة ضوئيا بـ

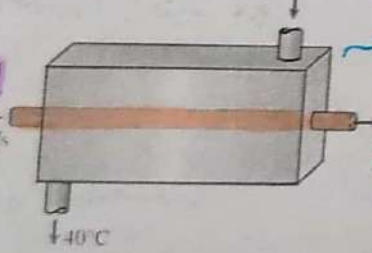
Applications of Thermodynamics



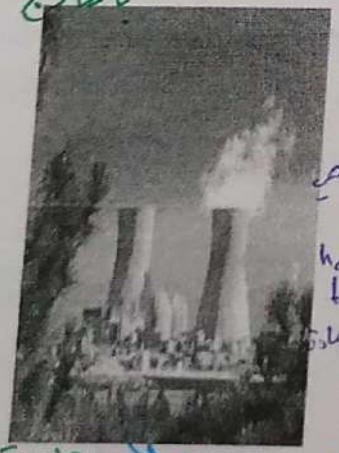


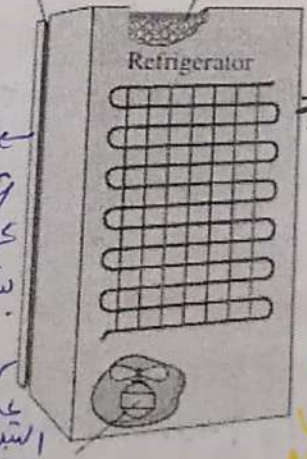


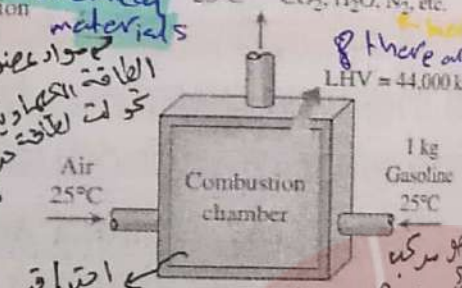


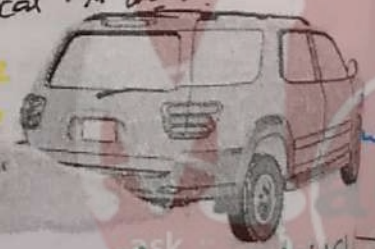












IMPORTANCE OF DIMENSIONS AND UNITS

Two types of units :-

- Any physical quantity can be characterized by **dimensions**.
- The magnitudes assigned to the dimensions are called **units**.
- Some basic dimensions such as **mass *m*, length *L*, time *t*, and temperature *T*** are selected as **primary** or **fundamental dimensions**.
- Others such as **velocity *V*, energy *E*, and volume *V*** are expressed in terms of the primary dimensions and are called **secondary dimensions**, or **derived dimensions**.

primary أي وحدة مشتقة من الـ

TABLE 1–1

The seven fundamental (or primary) dimensions and their units in SI

Dimension	Unit
Length	meter (m)
Mass	kilogram (kg)
Time	second (s)
Temperature	kelvin (K)
Electric current	ampere (A)
Amount of light	candela (cd)
Amount of matter	mole (mol)

(kg · m · s)

TABLE 1–2

Standard prefixes in SI units

Multiple	Prefix
10^{12}	tera, T
10^{9}	giga, G
10^{6}	mega, M
10^{3}	kilo, k
10^{2}	hecto, h
10^{1}	deka, da
10^{-1}	deci, d
10^{-2}	centi, c
10^{-3}	milli, m
10^{-6}	micro, μ
10^{-9}	nano, n
10^{-12}	pico, p

ask : believe & recieve
CamScanner الممسوحة ضوئيا بـ

12/10/2023

SYSTEMS AND CONTROL VOLUMES

- **System**: A quantity of matter or a region in space chosen for study.
- **Surroundings**: The mass or region outside the system.
- **Boundary (Control Surface)**: The real or imaginary surface that separates the system from its surroundings.
- The boundary of a system can be *fixed* or *movable*.
- Systems may be considered to be *closed* or *open*.

Types of Systems

I) Closed (Control mass).

II) Open (Control volume).

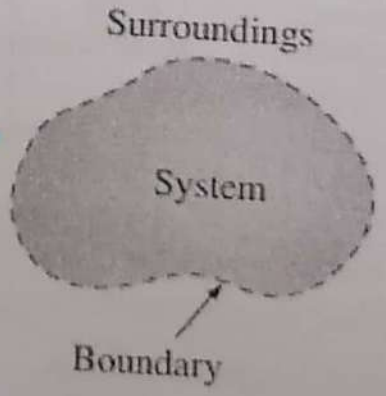


FIGURE 1–18
System, surroundings, and boundary.

Madar
ask & believe & recieve
الممسوحة ضوئيا بـ CamScanner

* Closed Systems (Control Mass) *

* اذا ثبتت ال mass بغض النظر volume والعكس ع

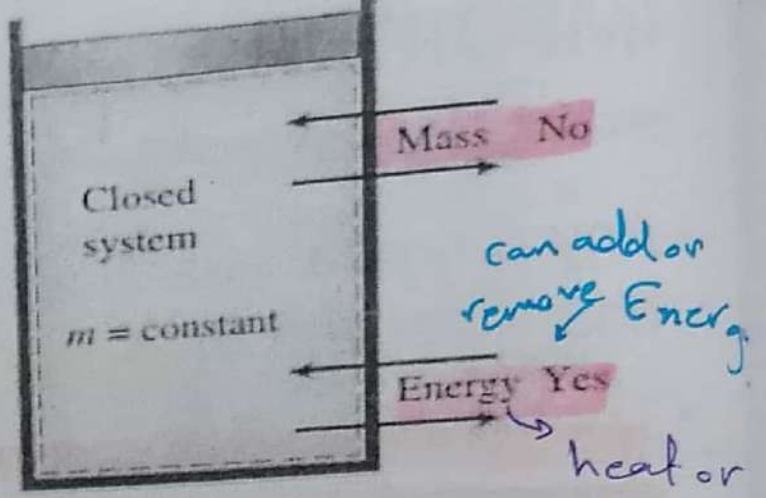


FIGURE 1–19
Mass cannot cross the boundaries of a closed system, but energy can.

- Energy, not Mass, crosses Closed System boundaries.

- **Example Applications:**

1) Piston-cylinder devices.
2) Batch reactor tank.
3) Refrigerator.
4) Air conditioner.
5) Small electric heater.

اذا قللت حرارة أو قللت ضغط بترتفع piston بتحرك

ماسه ← عجلة القاز ثابتة

ع الغاز ثابتة

(كمية الحارة فيه flow ثابتة)

If we do mixing we add ing work

← تخانه الكهرباء العاديه ع

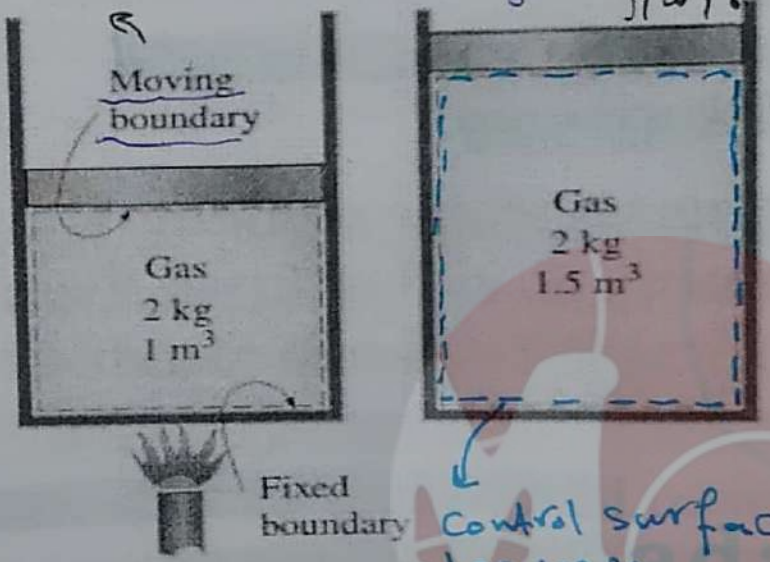


FIGURE 1–20
A closed system with a moving boundary.

fixed sys

لا طاقة ال sys بالمار ع ثابتة HEat ك عجلة بضغط وبنوع

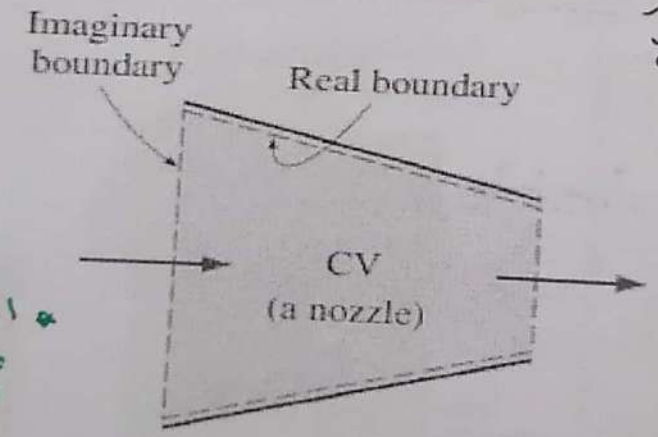
Control surfaces ممكن ع عند ال

CamScanner الممسوحة ضوئيا بـ

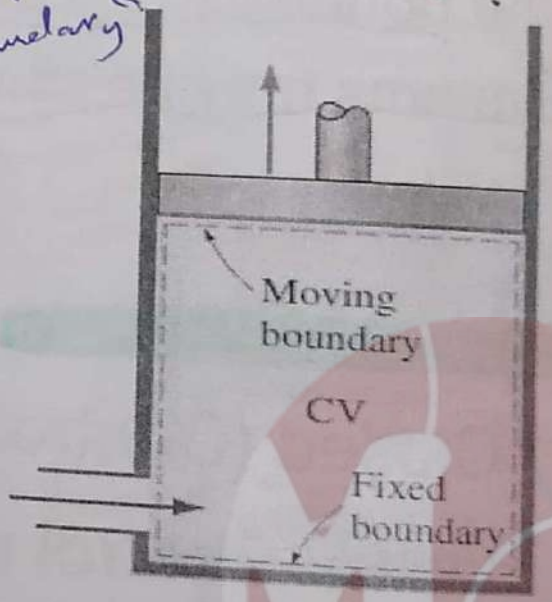
*Open Systems (Control Volume)

- Both Mass and Energy Cross Open System (Control Volume) Boundaries.
- Control surface: The boundaries of a control volume. It can be *real or imaginary.*
- **Example applications:**

1) Fluid flow in pipes, water pumps, air compressors, heat exchangers, etc.
2) Continuous-flow chemical reactors.
3) Automobile motor engines.
4) Power plant turbine systems.



(a) A control volume (CV) with real and imaginary boundaries



(b) A control volume (CV) with fixed and moving boundaries as well as real and imaginary boundaries

CamScanner الممسوحة ضوئيا بـ

PROPERTIES OF A SYSTEM

- **Property**: Any characteristic of a system.
- Some familiar properties are pressure P, temperature T, volume V, and mass m.
- Properties are considered to be either *intensive* or *extensive*.

❑ **Intensive properties**: Those that are *independent of the mass* of a system, such as temperature, pressure, and density.

❑ **Extensive properties**: Those whose values *depend on the size* (or extent) of the system.

- **Specific properties**: Extensive properties *per unit mass.*

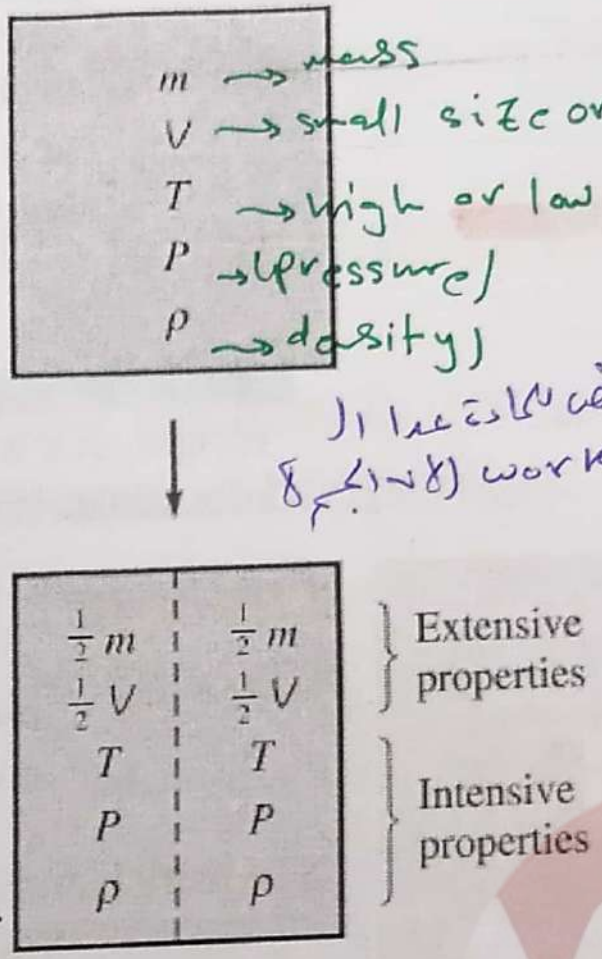


FIGURE 1–23
Criterion to differentiate intensive and extensive properties.

CamScanner الممسوحة ضوئيا بـ

properties *per unit mass.*

13

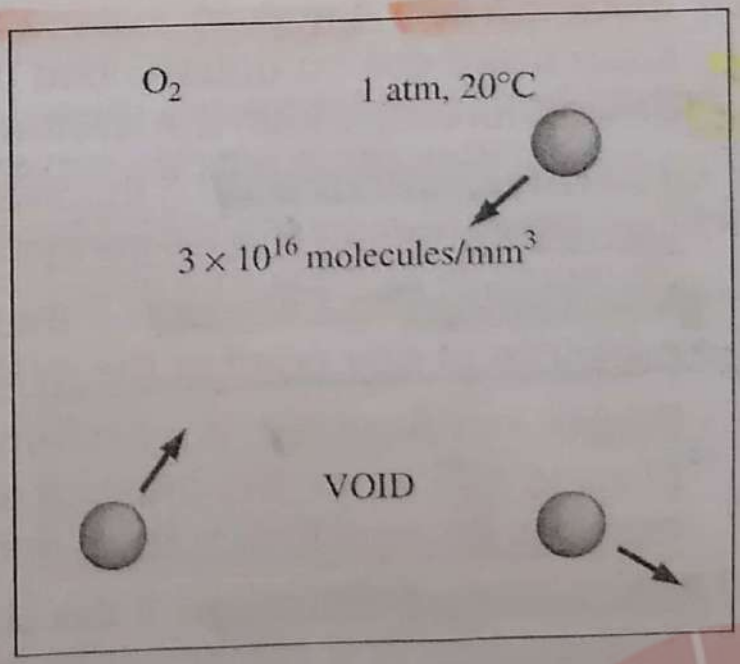
* الفرق بين Intensive properties و Extensive properties

Continuum

* المادة تتكون من molecules متفرقة (في الغازات) لكنه احنا بنتعاملها بنعتبره Continuous

* عشان اقدر احسب الـ specific volume (م³/kg)

- Matter is made up of atoms that are widely spaced in the gas phase. Yet it is very convenient to disregard the atomic nature of a substance and view it as a *continuous, homogeneous matter* with no holes, that is, a ***continuum***.
- The continuum idealization allows us to treat properties as point functions and to assume the properties vary continually in space with no jump discontinuities.
- This idealization is valid as long as the size of the system we deal with is large relative to the space between the molecules.
- This is the case in practically all problems.
- In this text we will limit our consideration to substances that can be modeled as a ***continuum.***



Despite the large gaps between molecules, a substance can be treated as a *continuum* because of the very large number of molecules even in an extremely small volume.

14

Nadar ask & believe & recieve
الممسوحة ضوئيا بـ CamScanner

DENSITY AND SPECIFIC GRAVITY

Density

$$\rho = \frac{m}{V} \qquad (\text{kg/m}^3)$$

Specific volume

$$v = \frac{V}{m} = \frac{1}{\rho}$$

$V = 12\ \text{m}^3$
$m = 3\ \text{kg}$

$\rho = 0.25\ \text{kg/m}^3$

$v = \frac{1}{\rho} = 4\ \text{m}^3/\text{kg}$

Specific gravity: The ratio of the density of a substance to the density of some standard substance at a specified temperature (usually water at 4°C).

$$\text{SG} = \frac{\rho}{\rho_{H_2O}}$$

It is a ratio between ρ of any substance with ρ of water (dimentionless)

Specific weight: The weight of a unit volume of a substance.

$$\gamma_s = \rho g \qquad (\text{N/m}^3)$$

weight = mass * acc of gravity
$w = m * g$

→ Density is mass per unit volume;
→ specific volume is volume per unit mass.

TABLE 1–3

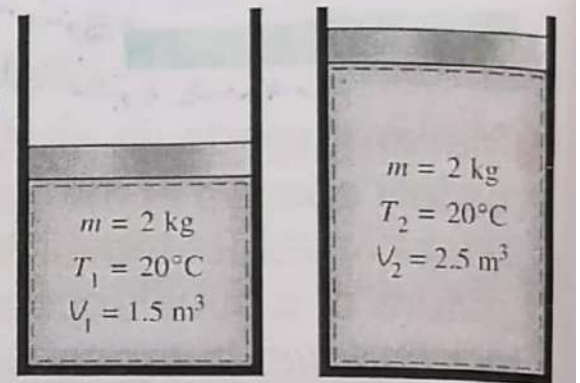
Specific gravities of some substances at 0°C

Substance	SG
Water	1.0
Blood	1.05
Seawater	1.025
Gasoline	0.7
Ethyl alcohol	0.79
Mercury	13.6
Wood	0.3–0.9
Gold	19.2
Bones	1.7–2.0
Ice	0.92
Air (at 1 atm)	0.0013

CamScanner الممسوحة ضوئيا بـ

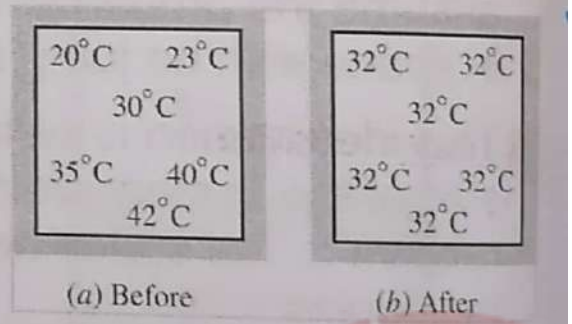
STATE AND EQUILIBRIUM

- Thermodynamics deals with ***equilibrium* states.**
- **Equilibrium:** A state of balance. In an equilibrium state there are no unbalanced potentials (or driving forces) within the system.
- **Thermal equilibrium:** If the temperature is the same throughout the entire system.
- **Mechanical equilibrium:** If there is no change in pressure at any point of the system with time.
- **Phase equilibrium:** If a system involves two phases and when the mass of each phase reaches an equilibrium level and stays there.
- **Chemical equilibrium:** If the chemical composition of a system does not change with time, that is, no chemical reactions occur.



(a) State 1 (b) State 2

A system at two different states



(a) Before (b) After

A closed system reaching thermal equilibrium.

❑ A system is said to be "in **thermodynamic equilibrium**" if it maintains:

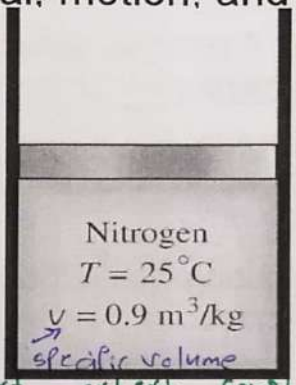
(1) thermal (uniform temp.), (2) mechanical (uniform pressure), (3) phase (mass of two phases, e.g., ice and liquid water, in equilibrium), and (4) chemical equilibrium (uniform composition).

الممسوحة ضوئيا بـ CamScanner

The State Postulate

- The state of a system is described by its properties.
- But, by experience not all properties must be known before the state is specified.
- The number of properties required to fix the state of a system is given by the **state postulate**:
  - *The state of a simple compressible system is completely specified by two independent, intensive properties.*
- **Simple compressible system:** If a system involves no electrical, magnetic, gravitational, motion, and surface tension effects.

The state of nitrogen is fixed by two independent, intensive properties.



equation of state

ideal gas law: $PV = nRT$

$PV_m = RT$, $[v_m] = m^3/kmol$, $[v] = m^3/kg = \frac{V}{mass}$

PROCESSES AND CYCLES-1

Process: Any change that a system undergoes from one equilibrium state to another.

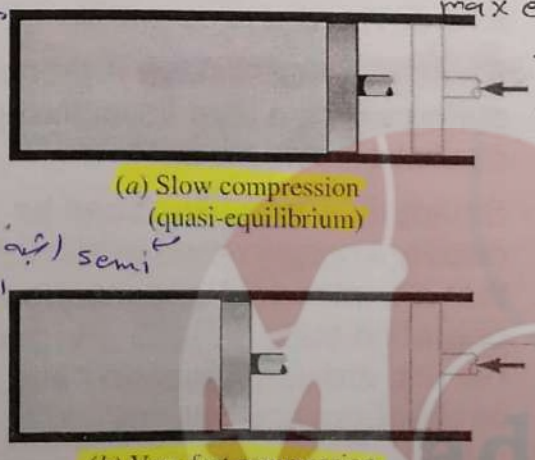
Path: The series of states through which a system passes during a process.

To describe a process completely, one should specify **the initial and final states**, as well as **the path** it follows, and the interactions with the surroundings.

Quasi-equilibrium process: When a process proceeds in such a manner that the system remains **infinitesimally close to an equilibrium** state at all times.

Characteristics:

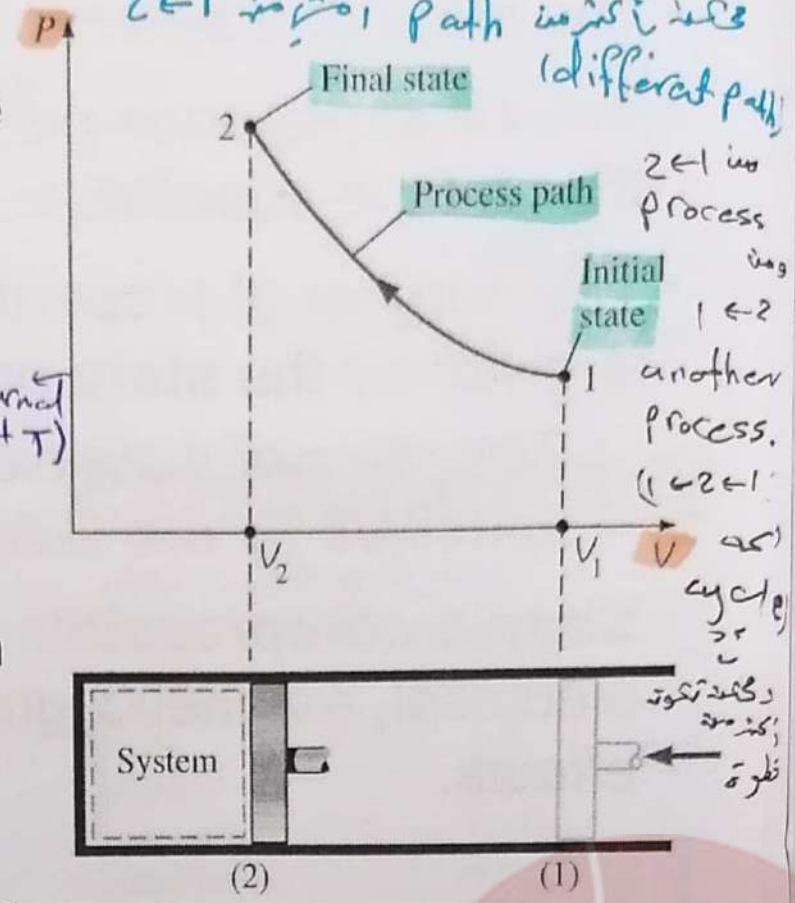
1) During a quasi-equilibrium (slow) process, the system remains practically at equilibrium at all times.
2) They are Easier to analyze (equations of state can apply).
3) Work-producing devices deliver the most work.
4) Work-consuming devices consume the least amount of work.



CamScanner الممسوحة ضوئيا بـ

PROCESSES AND CYCLES-2

- Process diagrams plotted by employing thermodynamic properties as coordinates are very useful in visualizing the processes.
- Some common properties that are used as coordinates are temperature T, pressure P, and volume V (or specific volume v).
- The prefix ***iso***- is often used to designate a process for which a particular property remains constant.
- **Isothermal process**: A process during which the temperature T remains constant.
- **Isobaric process**: A process during which the pressure P remains constant.
- **Isochoric (or isometric) process**: A process during which the specific volume v remains constant.
- **Cycle**: A process during which the initial and final states are identical.



The *P-V* diagram of a compression process.

The Steady-Flow Process

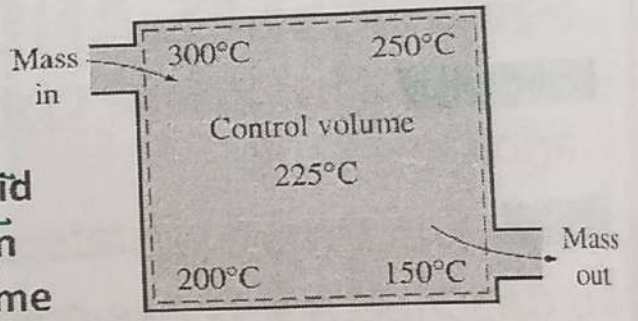
change with space → uniform

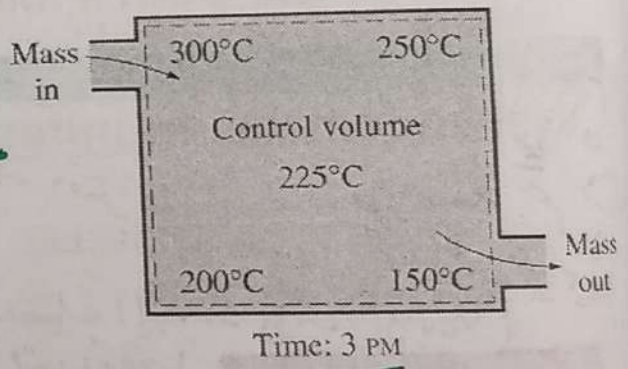
- The term *steady* implies *no change with time*. The opposite of steady is *unsteady*, or *transient*.
- A large number of engineering devices operate for long periods of time under the same conditions, and they are classified as *steady-flow devices*.
- **Steady-flow process**: A process during which a fluid flows through a control volume steadily.
- Steady-flow conditions can be closely approximated by devices that are intended for continuous operation such as turbines, pumps, boilers, condensers, and heat exchangers or power plants or refrigeration systems.

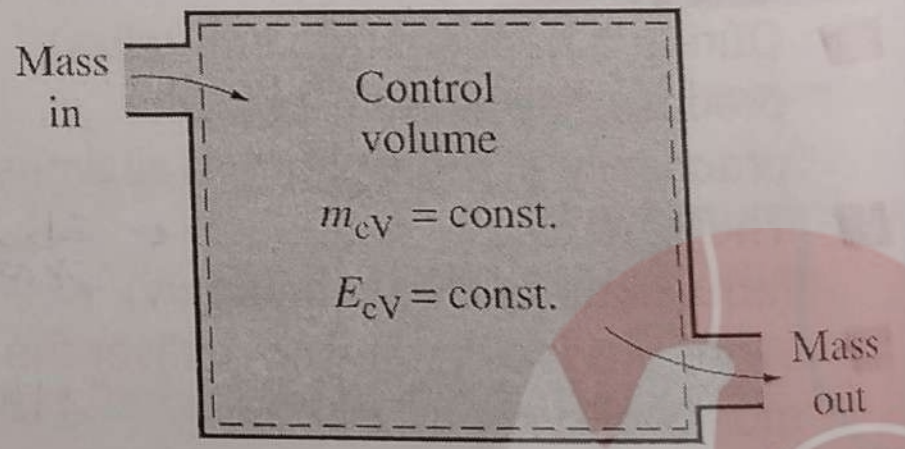
معظم اة اجهزة والمصانع تشتغل Steady state عند

During a steady-flow process, fluid properties within the control volume may change with position but not with time.

ما تتغير مع الزمن







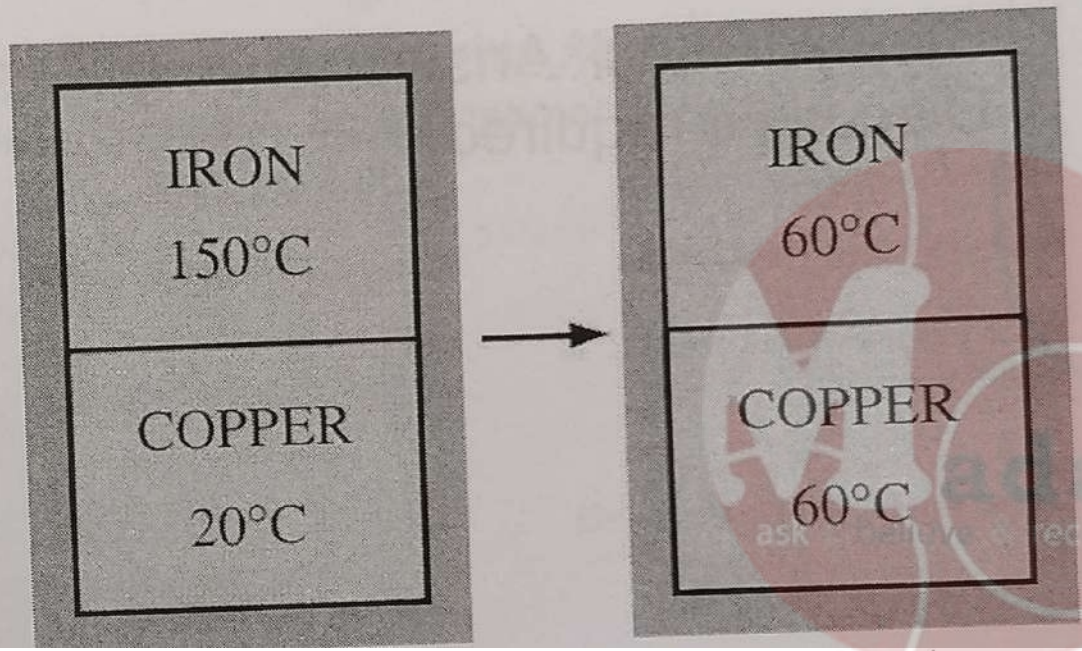
Under steady-flow conditions, the mass and energy contents of a control volume remain constant.

الممسوحة ضوئيا بـ CamScanner

TEMPERATURE AND THE ZEROTH LAW OF THERMODYNAMICS

thermal equilibrium نفس قانون ال

- **The zeroth law of thermodynamics**: If two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other.
- By replacing the third body with a thermometer, the zeroth law can be restated as *two bodies are in thermal equilibrium if both have the same temperature reading even if they are not in contact.*



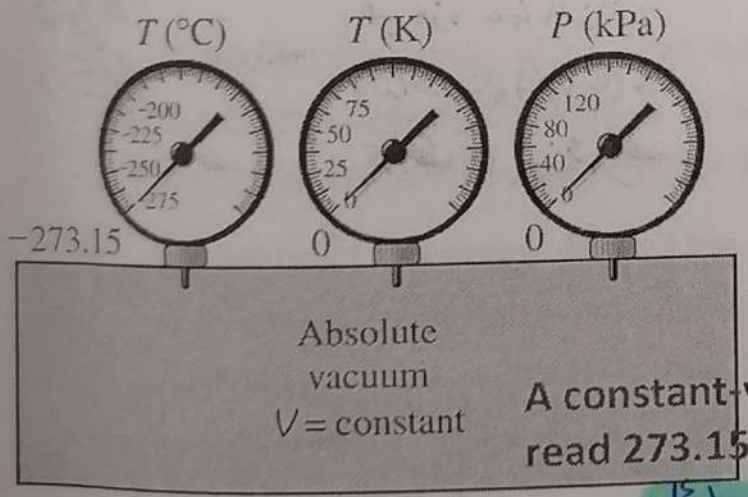
Two bodies reaching thermal equilibrium after being brought into contact in an isolated enclosure.

الممسوحة ضوئيا بـ CamScanner

absolute temp scale ليس relative temp scale لانه

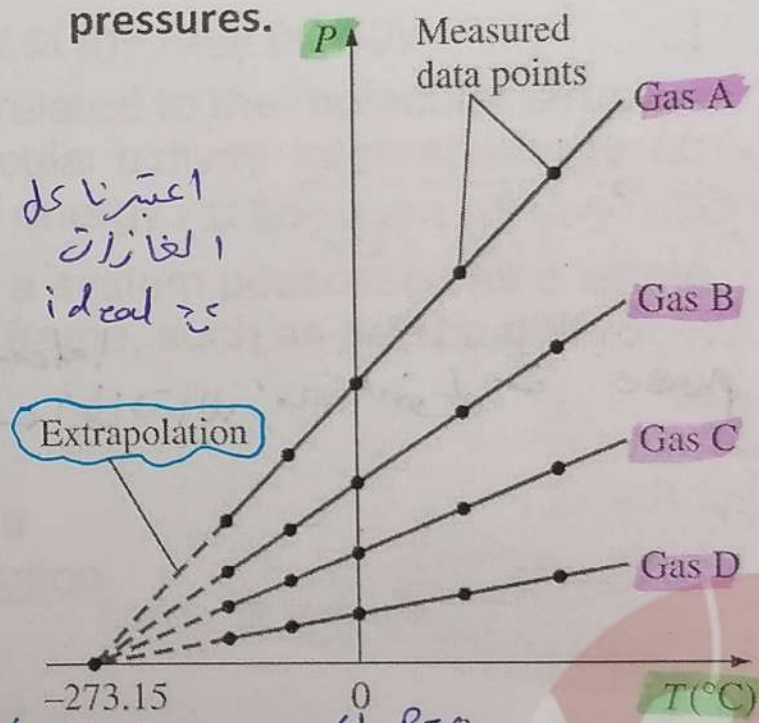
Temperature Scales

- All temperature scales are based on some easily reproducible states such as the freezing and boiling points of water: the *ice point* and the *steam point.*
- **Thermodynamic temperature scale**: A temperature scale that is independent of the properties of any substance.
- **Kelvin scale** (SI) يعتمد على
- A temperature scale nearly identical to the Kelvin scale is the **ideal-gas temperature scale**. The temperatures on this scale are measured using a constant-volume gas thermometer.



A constant-volume gas thermometer would read 273.15°C at absolute zero pressure.

P versus T plots of the experimental data obtained from a constant-volume gas thermometer using four different gases at different (but low) pressures.



CamScanner الممسوحة ضوئيا بـ

Forms of Energy

- Energy can exist in numerous forms such as thermal, mechanical, kinetic, potential, electric, magnetic, chemical, and nuclear, and their sum constitutes the total energy, E of a system.
- Thermodynamics deals with the *change* of the total energy.
- **Microscopic forms of energy**: Those related to the molecular structure of a system and the degree of the molecular activity. Internal energy, U: The sum of all the microscopic forms of energy.
- **Macroscopic forms of energy**: Those a system possesses as a whole with respect to some outside reference frame, such as *kinetic and potential energies*.

- **Kinetic energy, KE**: The energy that a system possesses as a result of its motion relative to some reference frame.
- **Potential energy, PE**: The energy that a system possesses as a result of its elevation in a gravitational field.

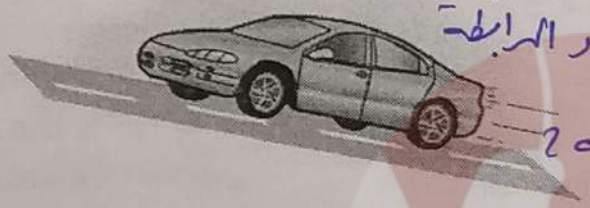


FIGURE 2–4
The macroscopic energy of an object changes with velocity and elevation.

CamScanner الممسوحة ضوئيا بـ

Energy ... numerous forms:

- Thermal
- Mechanical
- Kinetic
- Potential
- Electric
- Magnetic
- Chemical
- Nuclear

Their sum constitutes the total energy, E of a system

The total energy of a system on a unit mass:

$$e = \frac{E}{m} \quad (kJ/kg)$$

Those related to the molecular structure of a system and the degree of the molecular activity.

Internal energy, U

The sum of all the microscopic forms of energy.

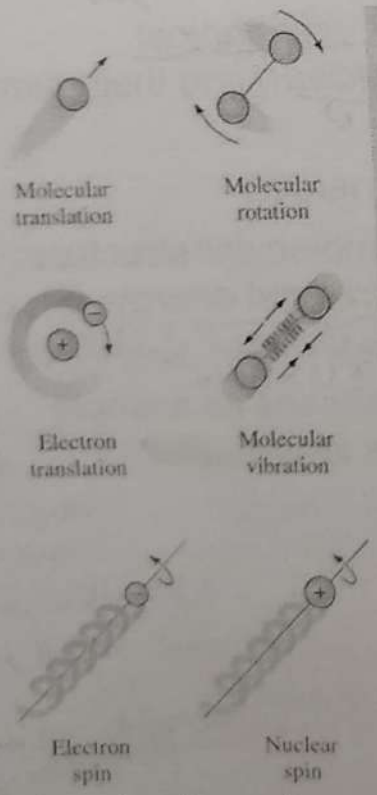
Kinetic energy, KE

The energy that a system possesses as a result of its motion relative to some reference frame.

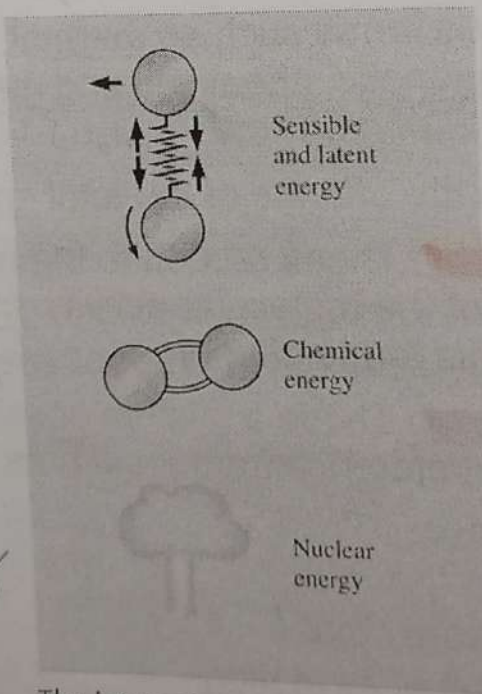
Potential energy, PE

The energy that a system possesses as a result of its elevation in a gravitational field.

Some Physical Insight to Internal Energy



The various forms of microscopic energies that make up ***sensible*** **energy.**



The internal energy of a system is the sum of all forms of the ***microscopic energies***.

Sensible energy: The portion of the internal energy of a system associated with the kinetic energies of the molecules.

Latent energy: The internal energy associated with the phase of a system.

Chemical energy: The internal energy associated with the atomi bonds in a molecule.

Nuclear energy: The tremendous amount of energy associated wit the strong bonds within the nucleus of the atom itself.

Thermal = Sensible + Latent

Internal = Sensible + Latent + Chemical + Nuclear

الممسوحة ضوئيا بـ CamScanner

Energy of A System

* heat & work not properties for the sys (ظواهر process أثناء)

*KE, PE & IE → are properties for the sys

1) The **total energy of a system**, can be *contained* or ***stored*** in a system, and thus can be viewed as the ***static* forms of energy**. like PE, KE, IE

2) The forms of energy ***not stored*** in a system can be viewed as the ***dynamic* forms of energy** or as ***energy interactions***. like heat & work

- ❑ The dynamic forms of energy are recognized at the system boundary as they cross it, and they represent the *energy gained or lost by a system during a process.* (عند عبورها للـ boundary)
- ❑ The only two forms of energy interactions associated with a **closed system** are **heat transfer** and **work**.

3) The difference between **heat transfer** and **work:**

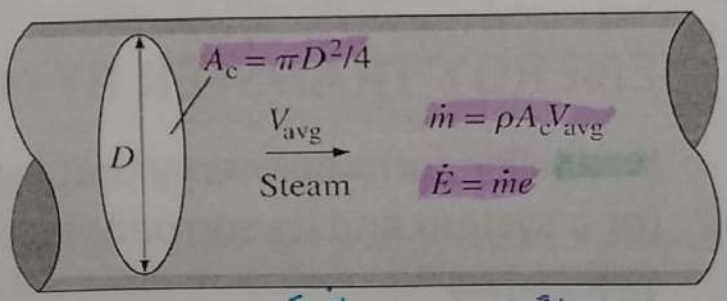
An energy interaction is heat transfer if its driving force is a temperature difference. Otherwise, it is work.

-: work أمثلة

1- piston rising (piston حركة)
2- rotation like mixers
3- wire passes through current

Energy of A System

(not energy balance)



Capital letter : tot energy
small : per unit mass

$$KE = m\frac{V^2}{2} \quad (kJ)$$ **Kinetic energy**

$$ke = \frac{V^2}{2} \quad (kJ/kg)$$ **Kinetic energy per unit mass**

$$PE = mgz \quad (kJ)$$ **Potential energy**

$$pe = gz \quad (kJ/kg)$$ **Potential energy per unit mass**

$$E = U + KE + PE = U + m\frac{V^2}{2} + mgz \quad (kJ)$$ **Total energy of a system**

Mass flow rate ← energy flow rate

$$\dot{m} = \rho\dot{V} = \rho A_c V_{avg} \quad (kg/s)$$

volume flow rate

Energy flow rate

$$\dot{E} = \dot{m}e \quad (kJ/s \text{ or } kW)$$

cross sectional area * velocity

$A_c = \pi D^2$

$V_{avg} = \frac{}{4}$

الممسوحة ضوئيا بـ CamScanner

Energy of A System

(not energy balance)

Capital letter : tot energy
small " : per unit mass

$$KE = m\frac{V^2}{2} \quad (kJ)$$ Kinetic energy

$$ke = \frac{V^2}{2} \quad (kJ/kg)$$ Kinetic energy per unit mass

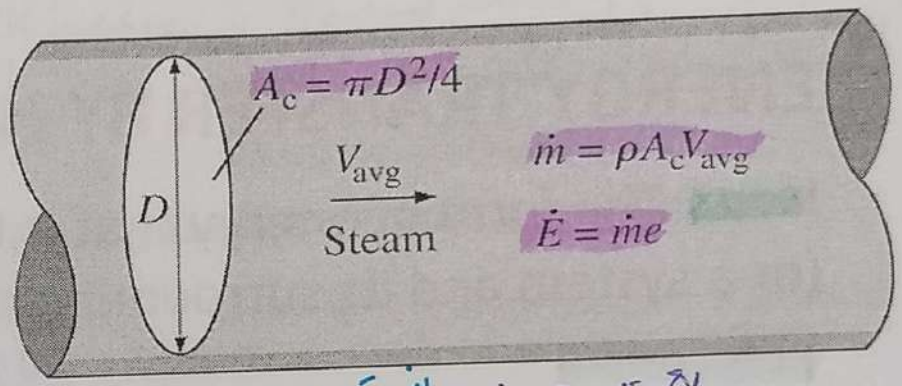
$$PE = mgz \quad (kJ)$$ Potential energy

$$pe = gz \quad (kJ/kg)$$ Potential energy per unit mass

$$E = U + KE + PE = U + m\frac{V^2}{2} + mgz \quad (kJ)$$ Total energy of a system

$$e = u + ke + pe = u + \frac{V^2}{2} + gz \quad (kJ/kg)$$ Energy of a system per unit mass

$$e = \frac{E}{m} \quad (kJ/kg)$$ Total energy per unit mass



Mass flow rate

$$\dot{m} = \rho\dot{V} = \rho A_c V_{avg} \quad (kg/s)$$

Energy flow rate

$$\dot{E} = \dot{m}e \quad (kJ/s \text{ or } kW)$$

ask & believe & recieve
6

الممسوحة ضوئيا بـ CamScanner

$$e = \frac{E}{m} \qquad (\text{kJ/kg})$$

Mechanical Energy

- **Mechanical energy:** The form of energy ***that can be converted to mechanical work completely*** and directly by an ideal mechanical device such as an ideal turbine.
- **Kinetic and potential energies:** The **familiar forms** of mechanical energy.

Mechanical energy of a flowing fluid per unit mass

$$e_{\text{mech}} = \frac{P}{\rho} + \frac{V^2}{2} + gz$$

Rate of mechanical energy of a flowing fluid

$$\dot{E}_{\text{mech}} = \dot{m} e_{\text{mech}} = \dot{m}\left(\frac{P}{\rho} + \frac{V^2}{2} + gz\right)$$

Mechanical energy change of a fluid during incompressible flow per unit mass

$$\Delta e_{\text{mech}} = \frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \qquad (\text{kJ/kg})$$

= rate of change

Rate of mechanical energy change of a fluid during incompressible flow

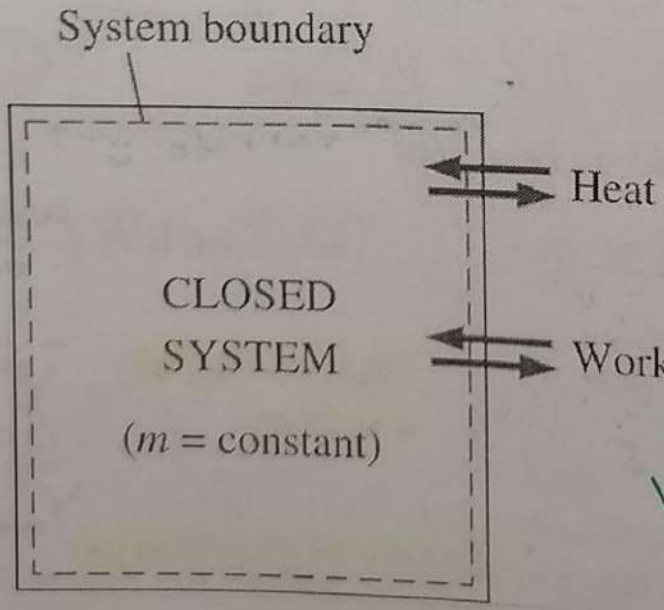
$$\Delta \dot{E}_{\text{mech}} = \dot{m} \Delta e_{\text{mech}} = \dot{m}\left(\frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right) \qquad (\text{kW})$$

(small P بس) ≠ مش property of pressure

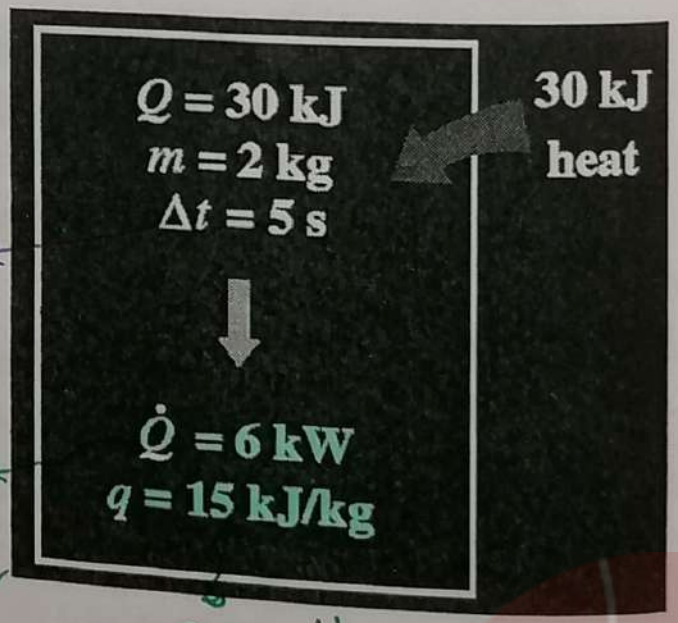
ask & learn & recieve
CamScanner الممسوحة ضوئيا بـ

ENERGY TRANSFER BY HEAT

Heat: The form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a *temperature difference.*



Energy can cross the boundaries of a closed system in the form of **heat** and **work.**



Heat transfer is expressed both:

- As time rate (kJ/s or KW), and
- As specific heat transfer, kJ/kg of system mass

heat & work can be express in two ways

ENERGY TRANSFER BY HEAT

$$q = \frac{Q}{m} \quad (\text{kJ/kg})$$

Heat transfer per unit mass

$$Q = \dot{Q}\,\Delta t \quad (\text{kJ})$$

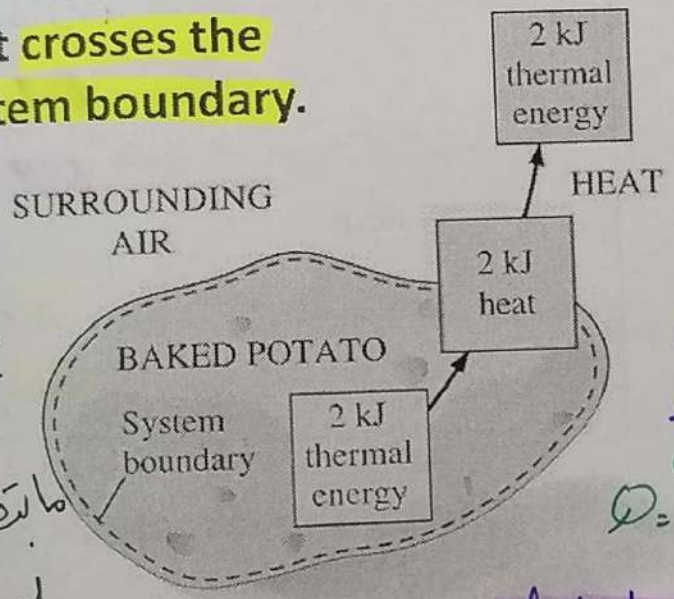
Amount of heat transfer when heat transfer rate is constant

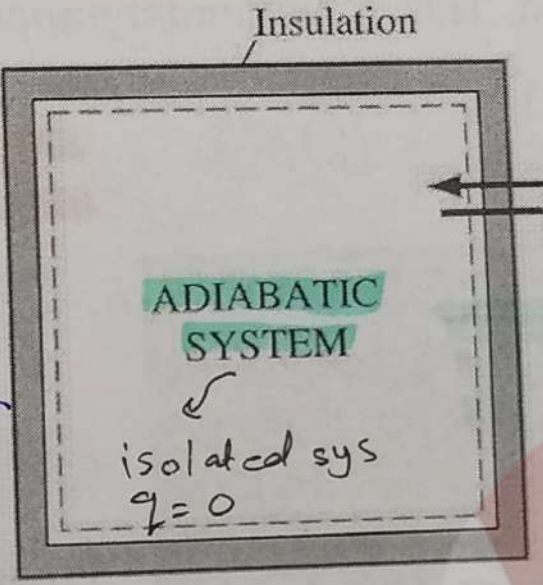
rate of heat transfer or specific heat

$$Q = \int_{t_1}^{t_2} \dot{Q}\,dt \quad (\text{kJ})$$

Amount of heat transfer when heat transfer rate changes with time

Energy is recognized as heat transfer only as it crosses the system boundary.





During an adiabatic process, a system exchanges no heat with its surroundings.

adiabatic = isentropic

CamScanner الممسوحة ضوئيا بـ

Kinetic & thermal energy مرتبطة
اذا كانت الحرارة قليلة في تفاعل

Historical Background on Heat

طاقة حركية
- **Kinetic theory**: Treats molecules as tiny balls that are in motion and thus possess kinetic energy.
- **Heat**: The energy associated with the random motion of atoms and molecules.

molecule

كيف تنتقل الحرارة من ال sys لل surrounding والعكس!

Heat transfer mechanisms:

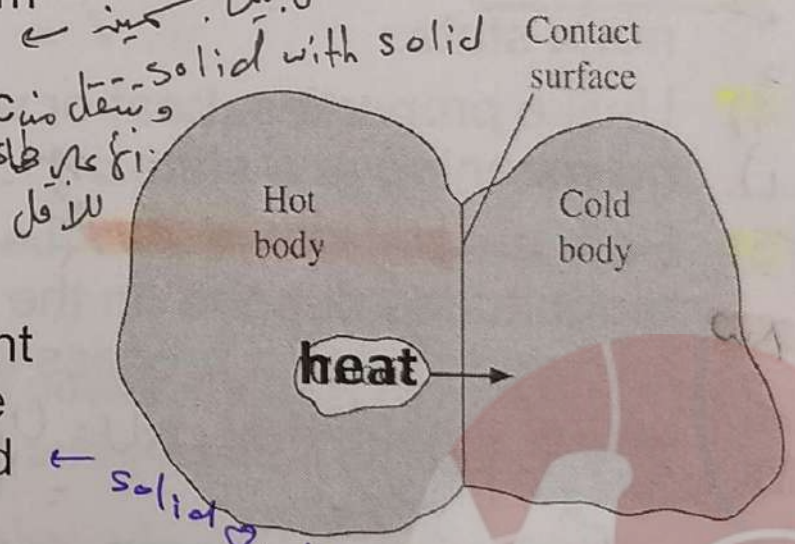
by 3 mechanisms :-

1. **Conduction**: The transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interaction between particles.
2. **Convection**: The transfer of energy between a solid surface and the adjacent fluid that is in motion, and it involves the combined effects of conduction and fluid motion.
3. **Radiation**: The transfer of energy due to the emission of electromagnetic waves (or photons). at high tem

انتقال بين جسمين ← solid with solid وتنتقل من الأعلى طاقة للأقل

الحمل الحرارة

فوتونات واشعاعات



← solid & liq phase

(واحد يكون بارد وواحد يكون ساخن) السطح ساخن ونبرد عليه بفلويد أو الفلويد ساخن بخلي السطح يبرد

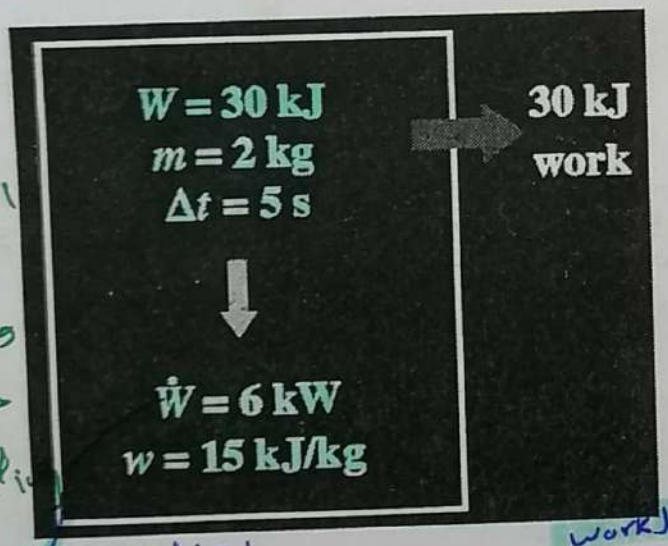
CamScanner الممسوحة ضوئيا بـ

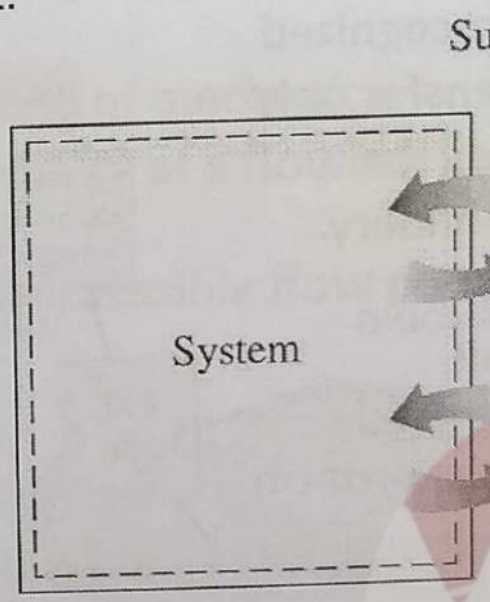
ENERGY TRANSFER BY WORK

- **Work:** The energy transfer associated with a force acting through a distance.
- **A rising piston, a rotating shaft, and an electric wire crossing the system boundaries** are all associated with work interactions
- **Formal sign convention**: *Heat transfer to a system and work done by a system are positive; heat transfer from a system and work done on a system are negative.*
- **Alternative to sign convention** is to use the subscripts ***in*** and ***out*** to indicate direction. This is the primary approach in this text.

$$w = \frac{W}{m} \qquad (\text{kJ/kg})$$

Work done per unit mass

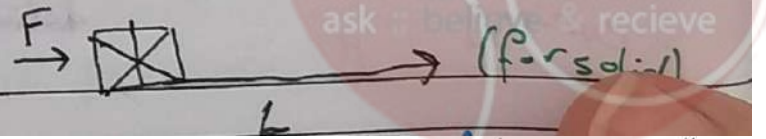




Power is the work done per unit time (kW)

$$\dot{W} = \frac{\delta W}{\delta t}$$

Specifying the directions of heat and work.



CamScanner الممسوحة ضوئيا بـ

heat and work.

rate of work transfer = power

$dW = F\,dL$ (function) — أول تعريف للـ work

$W = \int F\,dL$ (for solid)

Heat and Work مقارنة بينهم

1) Both are recognized at the boundaries of a system as they cross the boundaries. That is, both heat and work are *boundary* phenomena.

2) Systems possess energy, but **not** heat or work.

3) Both are associated with a *process*, not a state.

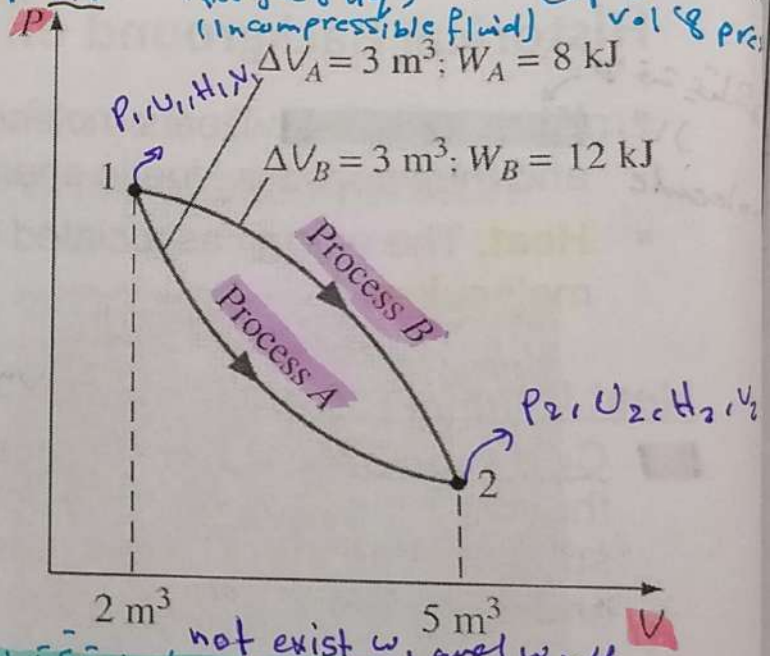
4) Unlike properties, heat or work has no meaning at a state.

5) Both are *path functions* (i.e., their magnitudes depend on the path followed during a process as well as the end states).

$dW = P(A\,dL)$

$W = \int P\,dV$ (for gas & liq) (incompressible fluid)

for gas we express it with vol & pressure



Properties are point functions; but heat and work are path functions (their magnitudes depend on the path followed).

not exist w_1 and w_2 — الـ work مش بالحالة دي

curve يتكون w_{12}

$\Delta U = U_2 - U_1 = \int_{P_1}^{P_2} dP$

$w_1 \& w_2$ $q_1 \& q_2$ ✗

$$\int_1^2 dV = V_2 - V_1 = \Delta V$$ تفاضل كامل

$$\int_1^2 \delta W = W_{12} \quad (not\ \Delta W)$$ inexact يعني تفاضل غير تامة

Properties are point functions; they have exact differentials (d)

Path functions have inexact differentials (δ)

Qadar recieve
الممسوحة ضوئيا بـ CamScanner

Forms of Work

❑ **Various forms of work are expressed as follows:**

› ***Electrical work:***
$$W_e = VI\Delta t \quad \text{(kJ)}$$

› ***Boundary work:*** or (flow work)
$$W_b = \int_1^2 P dV$$

› ***Gravitational work*** **(= ΔPE):**
$$W_g = mg(z_2 - z_1)$$

› ***Acceleration work*** **(= ΔKE):**
$$W_a = \frac{1}{2} m(\vec{V}_2^2 - \vec{V}_1^2)$$

› ***Shaft (stirring) work:***
$$W_{sh} = 2\pi n \tau$$

› ***Spring work:***
$$W_{spring} = \frac{1}{2} k(x_2^2 - x_1^2)$$

CamScanner الممسوحة ضوئيا بـ

قانون أوم: التيار يتناسب طردياً مع فرق الجهد أي يعني ← طاقة كهربائية

$V = IR$ ∴

Electrical Work

Electrical work — كمية الكهرباء

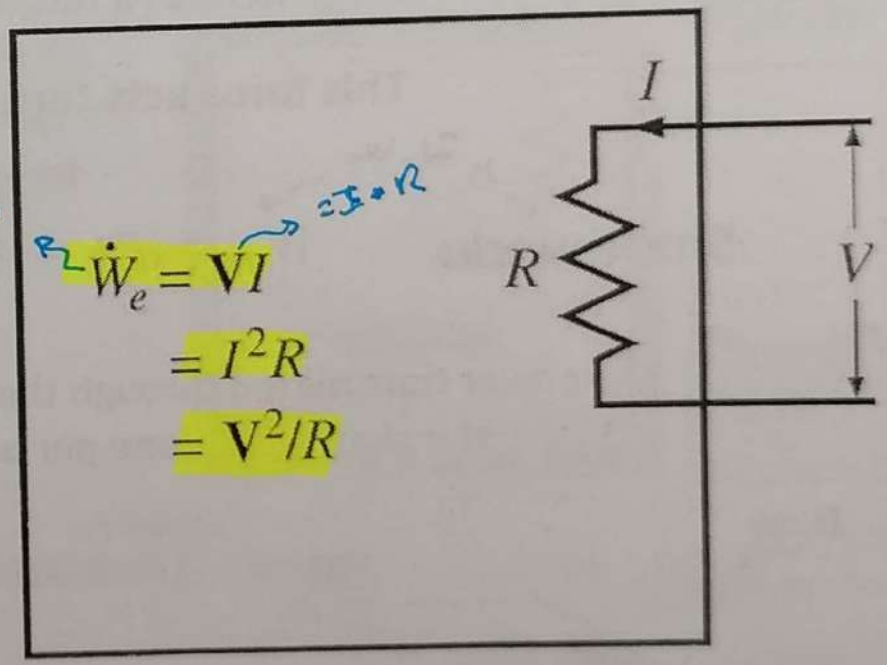
$$W_e = VN$$

V: voltage (volt)

Electrical power

$$\dot{W}_e = VI \quad (W)$$

I: current (A)



$\dot{W}_e = VI = I \cdot R$

$= I^2R$

$= V^2/R$

قسمنا على الزمن

When potential difference and current change with time

$$W_e = \int_1^2 VI\, dt \quad (kJ)$$

t: In second

When potential difference and current remain constant

$$W_e = VI\, \Delta t \quad (kJ)$$

Electrical power in terms of resistance *R*, current *I*, and potential difference V.

N = coulombs of electrons move through a potential difference V

$N = I \cdot \Delta t$

1 coulomb = 1 Ampere * 1 second

ohm's law: $V = I \cdot R$

1 Joule = 1 Volt * 1 coulomb

قاس بالكولوم

كمية الكهرباء = التيار * الزمن

$Q = I \cdot t$ كمية

[Colomb] : A * Sec

الممسوحة ضوئيا بـ CamScanner

MECHANICAL FORMS OF WORK

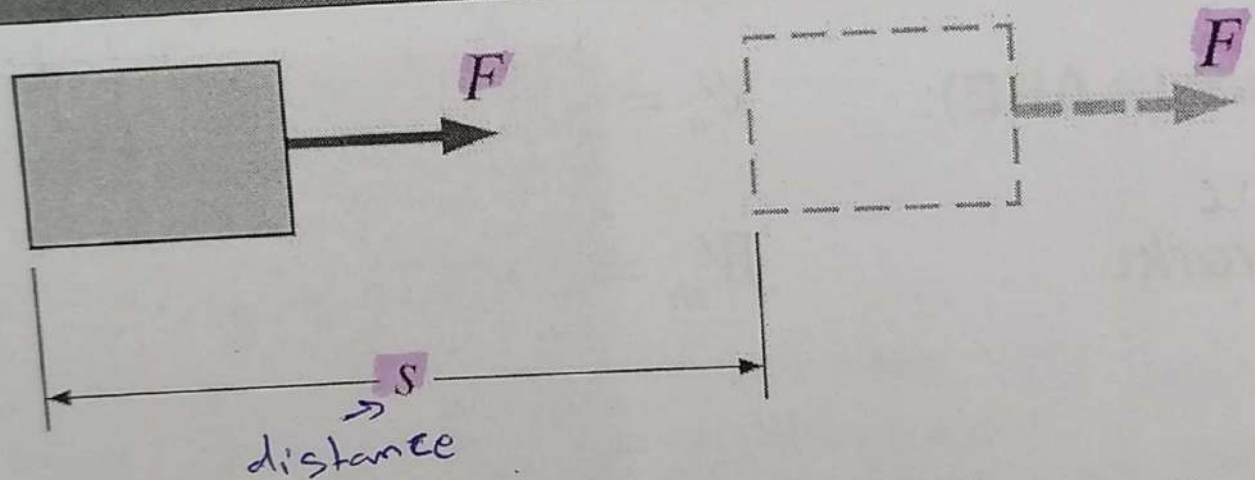
- There are two requirements for a work interaction between a system and its surroundings to exist:
  - there must be a ***force*** acting on the boundary.
  - the boundary must ***move***.

Work = Force × Distance

$$W = Fs \qquad \text{(kJ)}$$

When force is not constant

$$W = \int_1^2 F\, ds \qquad \text{(kJ)}$$



The work done is proportional to the force applied (*F*) and the distance traveled (*s*).

CamScanner الممسوحة ضوئيا بـ

قانون أوم: التيار يتناسب طردياً مع فرق الجهد أي يعني ← طاقة كهربائية

$V = IR$ ∴

Electrical Work

Electrical work — كمية الكهرباء

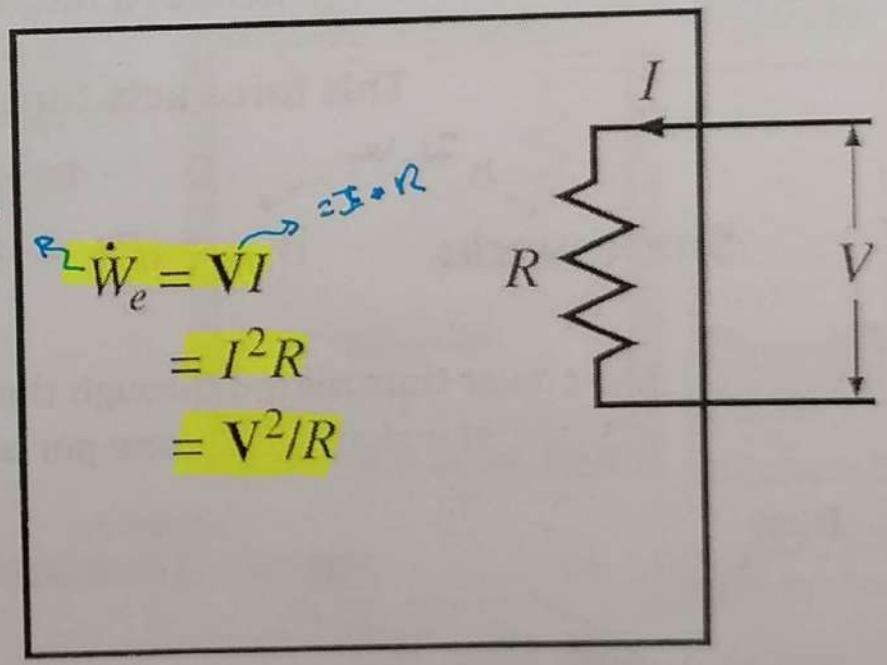
$$W_e = VN$$

V: voltage (volt)

Electrical power

$$\dot{W}_e = VI \quad (W)$$

I: current (A)



$\dot{W}_e = VI = I \cdot R$

$= I^2R$

$= V^2/R$

قسمنا على الزمن

When potential difference and current change with time

$$W_e = \int_1^2 VI\, dt \quad (kJ)$$

t: In second

When potential difference and current remain constant

$$W_e = VI\, \Delta t \quad (kJ)$$

Electrical power in terms of resistance *R*, current *I*, and potential difference V.

N = coulombs of electrons move through a potential difference V

$N = I \cdot \Delta t$

1 coulomb = 1 Ampere * 1 second

ohm's law: $V = I \cdot R$

1 Joule = 1 Volt * 1 coulomb

قاس بالكولوم

كمية الكهرباء = التيار * الزمن

$Q = I \cdot t$ كمية

[Colomb] : A * Sec

الممسوحة ضوئيا بـ CamScanner

Shaft Work

A force F acting through a moment arm r generates a torque T

$$T = Fr \quad \rightarrow \quad F = \frac{T}{r}$$

This force acts through a distance s

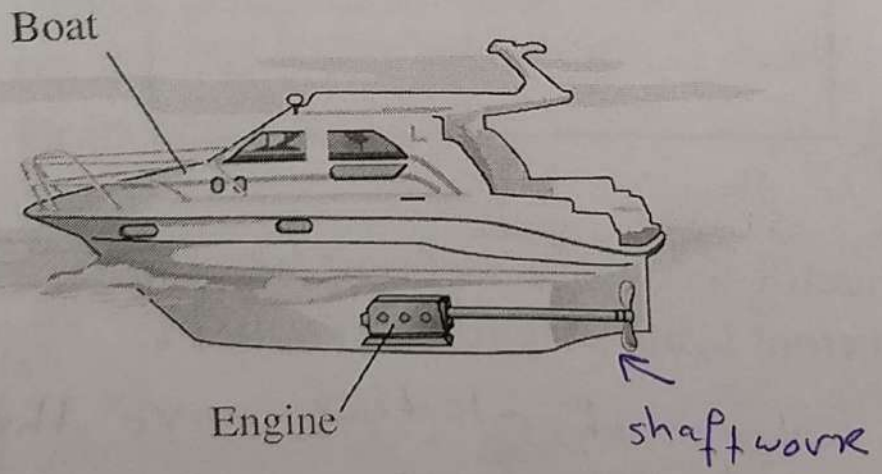
$$s = (2\pi r)n$$

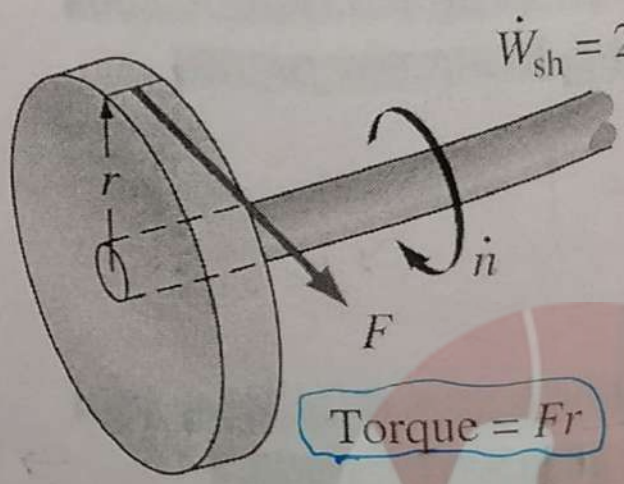
Shaft work:

$$W_{sh} = Fs = \left(\frac{T}{r}\right)(2\pi rn) = 2\pi nT \quad \text{(kJ)}$$

The power transmitted through the shaft is the shaft work done per unit time

$$\dot{W}_{sh} = 2\pi \dot{n} T \quad \text{(kW)}$$





Energy transmission through rotating shafts is commonly encountered in practice.

Shaft work is proportional to the torque applied and the number of revolutions of the shaft.

CamScanner الممسوحة ضوئيا بـ

THE FIRST LAW OF THERMODYNAMICS

- The *first law of thermodynamics* (***the conservation of energy principle***) provides a sound basis for studying the relationships among the various forms of energy and energy interactions.
- The first law states that ***energy can be neither created nor destroyed during a process; it can only change forms.***
- The *First Law*: For all adiabatic processes between two specified states of a closed system, the net work done is the same regardless of the nature of the closed system and the details of the process.

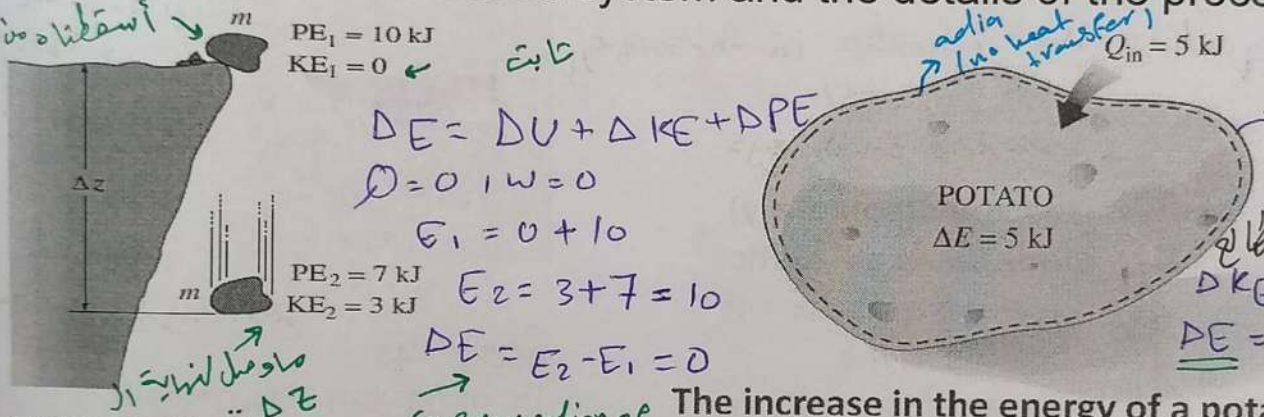
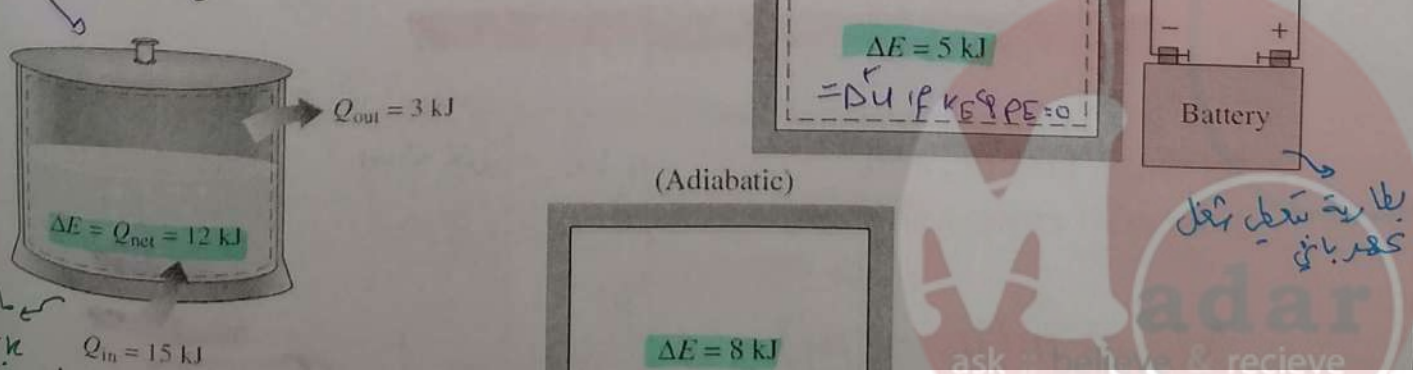


FIGURE 2–39
Energy cannot be created or destroyed; it can only change forms.

The increase in the energy of a potato in an oven is equal to the amount of heat transferred to it.

THE FIRST LAW OF THERMODYNAMICS

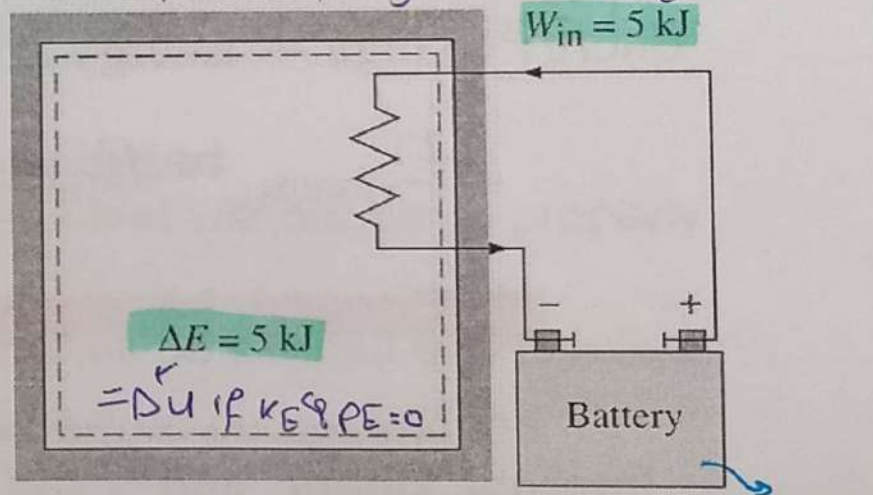
The work (electrical) done on an adiabatic system is equal to the increase in the energy of the system.



CamScanner الممسوحة ضوئيا بـ

THE FIRST LAW OF THERMODYNAMICS

The work (electrical) done on an adiabatic system is equal to the increase in the energy of the system.



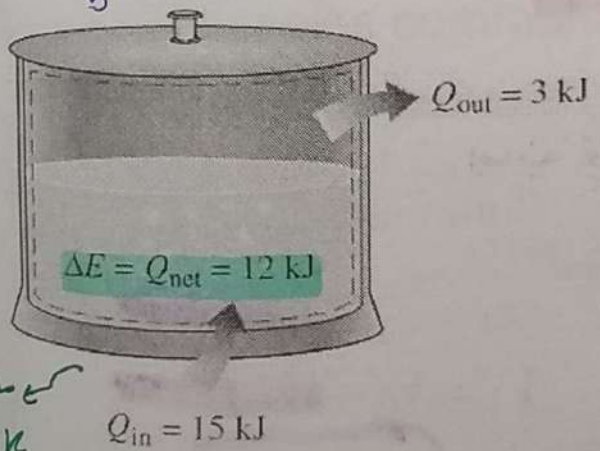
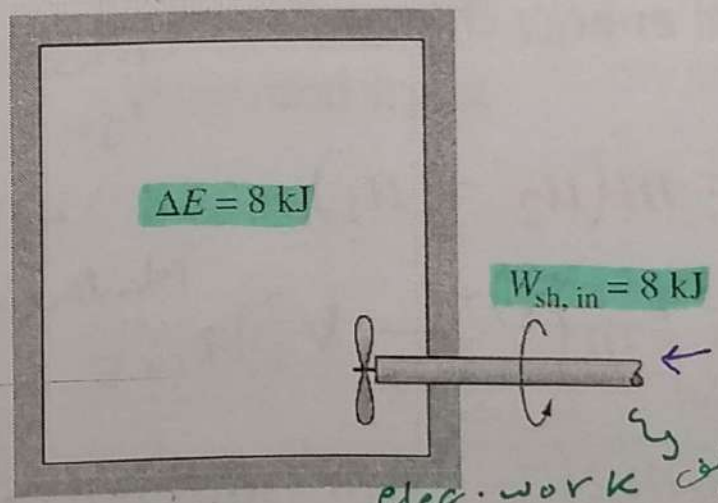


FIGURE 2–41
In the absence of any work interactions, the energy change of a system is equal to the net heat transfer.



The work (shaft) done on an adiabatic system is equal to the increase in the energy of the system.

CamScanner الممسوحة ضوئيا بـ

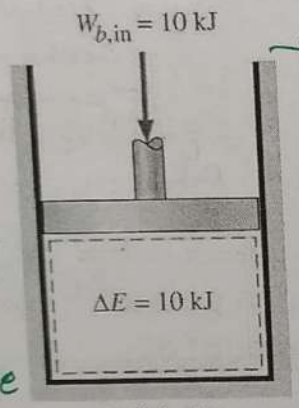
Energy Balance

*The net change (increase or decrease) in the **total energy** of the system during a process is equal to the difference between the total energy entering and the total energy leaving the system during that process.*

$$\begin{pmatrix}\text{Total energy}\\ \text{entering the system}\end{pmatrix} - \begin{pmatrix}\text{Total energy}\\ \text{leaving the system}\end{pmatrix} = \begin{pmatrix}\text{Change in the total}\\ \text{energy of the system}\end{pmatrix}$$

$$E_{in} - E_{out} = \Delta E_{system}$$

The boundary work done on an adiabatic sys is equal to the increase in the energy of the system



work done on the sys

The work (boundary) done on an adiabatic system is equal to the increase in the energy of the system.

$\Delta E = \Delta U = Q - W$

$0 - (-10) = 10$

OR: $\Delta E = \Delta U = W_{in} - W_{out}$

$= 10 - 0$

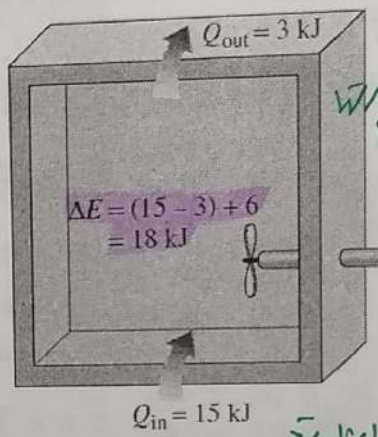


FIGURE 2–45
The energy change of a system during a process is equal to the *net* work and heat transfer between the system and its surroundings.

Energy Change of a System, ΔE_{system}

Energy change = Energy at final state − Energy at initial state

$$\Delta E_{system} = E_{final} - E_{initial} = E_2 - E_1$$

$$\Delta E = \Delta U + \Delta KE + \Delta PE$$

Internal, kinetic, and potential energy changes

$$\Delta U = m(u_2 - u_1)$$

$$\Delta KE = \frac{1}{2}m(V_2^2 - V_1^2)$$

Stationary Systems

$z_1 = z_2 \rightarrow \Delta PE = 0$

$V_1 = V_2 \rightarrow \Delta KE = 0$

$\Delta E = \Delta U$

ask recieve

الممسوحة ضوئيا بـ CamScanner

Energy Change of a System, ΔE_{system}

Energy change = Energy at final state − Energy at initial state

$$\Delta E_{system} = E_{final} - E_{initial} = E_2 - E_1$$

$$\Delta E = \Delta U + \Delta KE + \Delta PE$$

Internal, kinetic, and potential energy changes

$$\Delta U = m(u_2 - u_1)$$

$$\Delta KE = \frac{1}{2}m(V_2^2 - V_1^2)$$

$$\Delta PE = mg(z_2 - z_1)$$

Stationary Systems

$z_1 = z_2 \rightarrow \Delta PE = 0$

$V_1 = V_2 \rightarrow \Delta KE = 0$

$\Delta E = \Delta U$

Nadar ask · believe & recieve

الممسوحة ضوئيا بـ CamScanner

$\Delta = In - out$ ... energy balance

$\Delta T = T_2 - T_1$

$\Delta P = P_2 - P_1$

Mechanisms of Energy Transfer, E_{in} and E_{out}

1) Heat transfer
2) Work transfer
3) Mass flow

just for open sys

A closed mass involves only *heat transfer* and work.

$$E_{in} - E_{out} = (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass,in} - E_{mass,out}) = \Delta E_{system}$$

energy balance

$$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic, potential, etc., energies}} \quad \text{(kJ)}$$

الطاقة المخزنة بالجسم ونتاجة بسبب الحركة

energy balance لنظام ال In - out

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} \quad \text{(kW)}$$

$$Q = \dot{Q}\,\Delta t \ \text{(kJ)} \qquad W = \dot{W}\,\Delta t \qquad \Delta E = (dE/dt)\,\Delta t$$

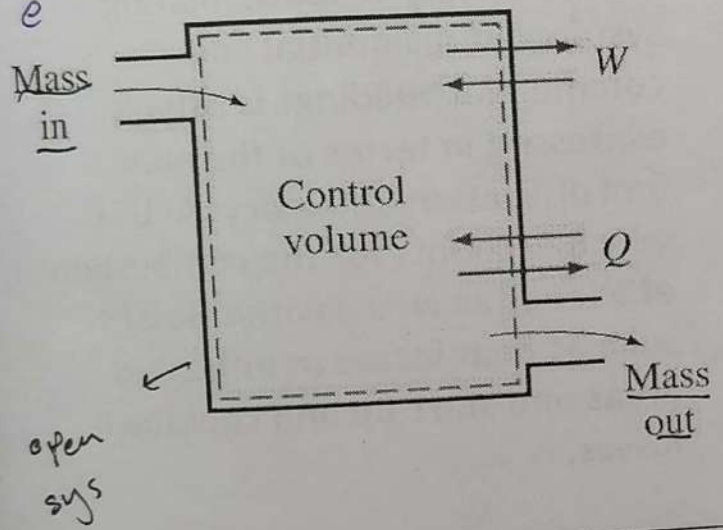
معدل تغير الـ energy

$$e_{in} - e_{out} = \Delta e_{system} \quad \text{(kJ/kg)}$$

energy per unit mass

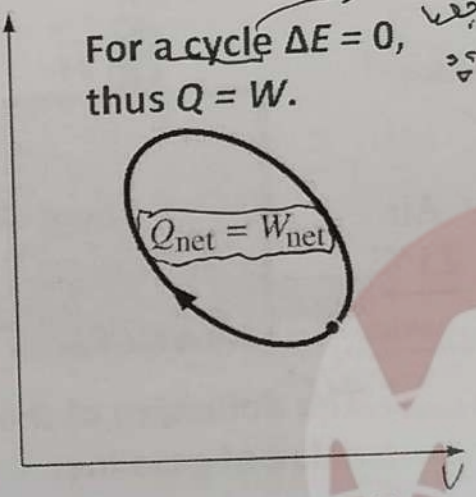
$$\delta E_{in} - \delta E_{out} = dE_{system} \qquad \delta e_{in} - \delta e_{out} = de_{system}$$

$$\dot{W}_{net,out} = \dot{Q}_{net,in} \quad \text{(for a cycle)}$$



open sys

The energy content of a control volume can be changed by mass flow as well as heat and work interactions.



For a cycle $\Delta E = 0$, thus $Q = W$.

كنا عند نقطة درجة عندما ...

Qadar ask ... recieve

الممسوحة ضوئيا بـ CamScanner

ENERGY CONVERSION EFFICIENCIES

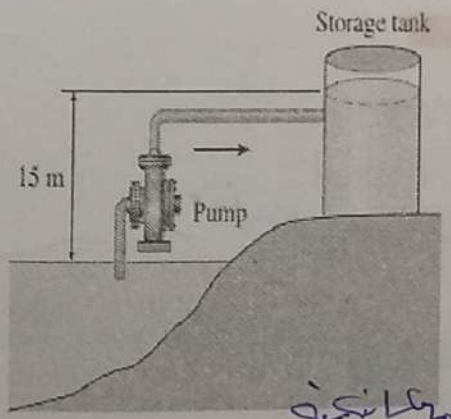
- *Efficiency* is one of the most frequently used terms in thermo-dynamics, and it indicates how well an energy conversion or transfer process is accomplished.
- *Efficiency* is also one of the most frequently misused terms in thermodynamics, because it is often used without being properly defined first.
- Some efficiencies commonly used in practice will be defined and clarified.
- *Efficiency* can be expressed in terms of the desired output and the required input as:

(In general equation) →

$$\text{Efficiency} = \frac{\text{Desired output}}{\text{Required input}}$$

← عم حطت مقارنة بالي حطيتيه

Example:



← رفعت الي من مكان لمكان عن طريق طاقة ميكانيكية

$$\eta_{pump} = \frac{\Delta \dot{E}_{mech,fluid}}{\dot{W}_{shaft,in}} = \frac{\dot{W}_{pump,u}}{\dot{W}_{pump}}$$

useful

الـ shaftwork تحولت إلى طاقة ميكانيكية مخزنة بالي

ask & believe & recieve
CamScanner الممسوحة ضوئيا بـ

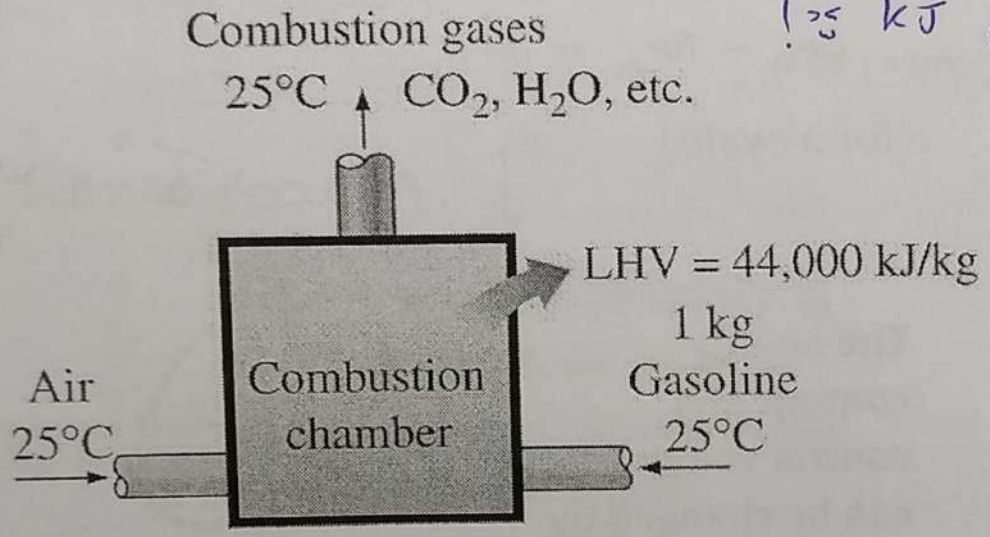
Combustion

$$\eta_{combustion} = \frac{Q}{HV} = \frac{\text{Amount of heat released during combustion}}{\text{Heating value of the fuel burned}}$$

Heating value of the fuel: The amount of heat released when a unit amount of fuel at room temperature is completely burned, and the combustion products are cooled to the room temperature.

Lower heating value (LHV): When the water leaves as a vapor.

Higher heating value (HHV): When the water in the combustion gases is completely condensed and thus the heat of vaporization is also recovered.

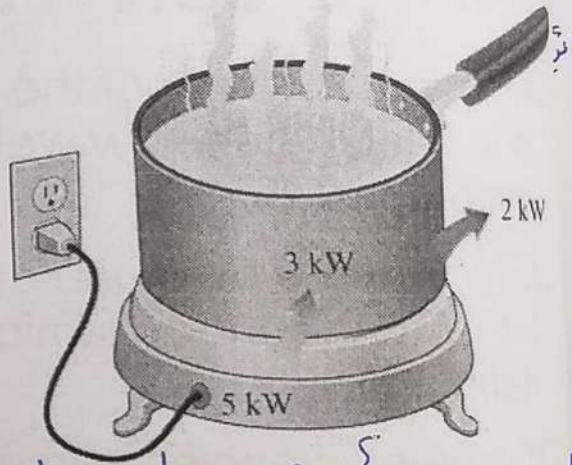


The definition of the heating value of gasoline.

The efficiency of space heating systems of residential and commercial buildings is usually expressed in terms of the annual fuel utilization efficiency (AFUE), which accounts for the combustion efficiency as well as other losses such as heat losses to unheated areas and start-up and cooldown losses.

CamScanner الممسوحة ضوئيا بـ

The efficiency of a **cooking appliance** represents the fraction of the energy supplied to the appliance that is transferred to the food.



$$\text{Efficiency} = \frac{\text{Energy utilized}}{\text{Energy supplied to appliance}}$$

$$= \frac{3\ \text{kWh}}{5\ \text{kWh}} = 0.60$$

Power Plants

- **Generator:** A device that converts mechanical energy to electrical energy.
- **Generator efficiency:** The ratio of the electrical power output to the mechanical power input.
- **Thermal efficiency of a power plant:**

  The ratio of the net electrical power output to the rate of fuel energy input:

$$\eta_{overall} = \eta_{combustion}\,\eta_{thermal}\,\eta_{generator} = \frac{\dot{W}_{net,electric}}{HHV \times \dot{m}_{fuel}}$$

$$\dot{W}_{net,mech} \times \frac{\dot{W}_{net,elect}}{\dot{W}_{net,mech}} =$$

CamScanner المسوحة ضوئيا بـ

Efficiencies of Mechanical and Electrical Devices

Mechanical efficiency

$$\eta_{mech} = \frac{\text{Mechanical energy output}}{\text{Mechanical energy input}} = \frac{E_{mech,out}}{E_{mech,in}} = 1 - \frac{E_{mech,loss}}{E_{mech,in}}$$

The effectiveness of the conversion process between the mechanical work supplied or extracted and the mechanical energy of the fluid is expressed by the pump efficiency and turbine efficiency:

$$\eta_{pump} = \frac{\text{Mechanical energy increase of the fluid}}{\text{Mechanical energy input}} = \frac{\Delta \dot{E}_{mech,fluid}}{\dot{W}_{shaft,in}} = \frac{\dot{W}_{pump,u}}{\dot{W}_{pump}}$$

$$\Delta \dot{E}_{mech,fluid} = \dot{E}_{mech,out} - \dot{E}_{mech,in}$$

$$\eta_{turbine} = \frac{\text{Mechanical energy output}}{\text{Mechanical energy decrease of the fluid}} = \frac{\dot{W}_{shaft,out}}{|\Delta \dot{E}_{mech,fluid}|} = \frac{\dot{W}_{turbine}}{\dot{W}_{turbine,e}}$$

$$|\Delta \dot{E}_{mech,fluid}| = \dot{E}_{mech,in} - \dot{E}_{mech,out}$$

25

$$\eta_{motor} = \frac{\text{Mechanical power output}}{\text{Electric power input}} = \frac{\dot{W}_{shaft,out}}{\dot{W}_{elect,in}}$$

$$\eta_{generator} = \frac{\text{Electric power output}}{\text{Mechanical power input}} = \frac{\dot{W}_{elect,out}}{\dot{W}_{shaft,in}}$$

Pump-Motor overall efficiency

$$\eta_{pump-motor} = \eta_{pump}\eta_{motor} = \frac{\dot{W}_{pump,u}}{\dot{W}_{elect,in}} = \frac{\Delta \dot{E}_{mech,fluid}}{\dot{W}_{elect,in}}$$

Turbine-Generator overall efficiency

$$\eta_{turbine-gen} = \eta_{turbine}\eta_{generator} = \frac{\dot{W}_{elect,out}}{\dot{W}_{turbine,e}} = \frac{\dot{W}_{elect,out}}{|\Delta \dot{E}_{mech,fluid}|}$$

$\eta_{turbine} = 0.75 \quad \eta_{generator} = 0.97$

CamScanner الممسوحة ضوئيا بـ

$$\eta_{\text{motor}} = \frac{\text{Mechanical power output}}{\text{Electric power input}} = \frac{\dot{W}_{\text{shaft,out}}}{\dot{W}_{\text{elect,in}}}$$

Pump efficiency

$$\eta_{\text{pump}} = \frac{\Delta \dot{E}_{\text{mech,fluid}}}{\dot{W}_{\text{shaft}}}$$

Generator efficiency

$$\eta_{\text{generator}} = \frac{\text{Electric power output}}{\text{Mechanical power input}} = \frac{\dot{W}_{\text{elect,out}}}{\dot{W}_{\text{shaft,in}}}$$

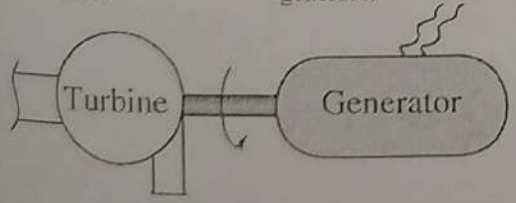
Pump-Motor overall efficiency

$$\eta_{\text{pump-motor}} = \eta_{\text{pump}}\eta_{\text{motor}} = \frac{\dot{W}_{\text{pump},u}}{\dot{W}_{\text{elect,in}}} = \frac{\Delta \dot{E}_{\text{mech,fluid}}}{\dot{W}_{\text{elect,in}}}$$

Turbine-Generator overall efficiency

$$\eta_{\text{turbine-gen}} = \eta_{\text{turbine}}\eta_{\text{generator}} = \frac{\dot{W}_{\text{elect,out}}}{\dot{W}_{\text{turbine},e}} = \frac{\dot{W}_{\text{elect,out}}}{|\Delta \dot{E}_{\text{mech,fluid}}|}$$

$\eta_{\text{turbine}} = 0.75$ $\eta_{\text{generator}} = 0.97$



$$\eta_{\text{turbine-gen}} = \eta_{\text{turbine}}\eta_{\text{generator}} = 0.75 \times 0.97 = 0.73$$

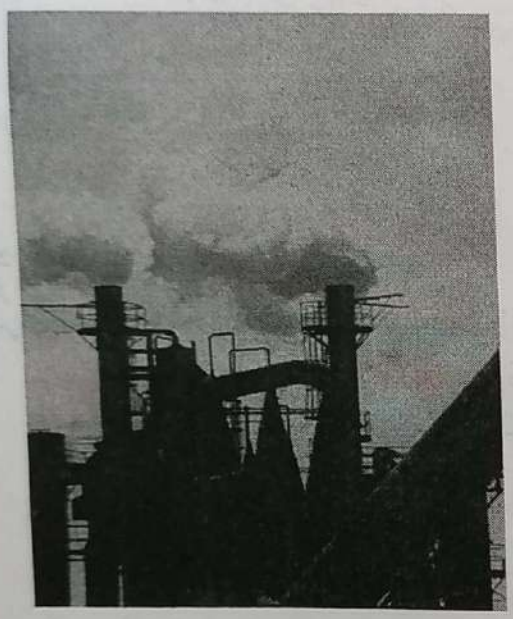
The overall efficiency of a turbine–generator is **the product of** the efficiency of the turbine and the efficiency of the generator and represents the fraction of the mechanical energy of the fluid converted to electric energy.

ask & receive
CamScanner المسوحة ضوئيا بـ

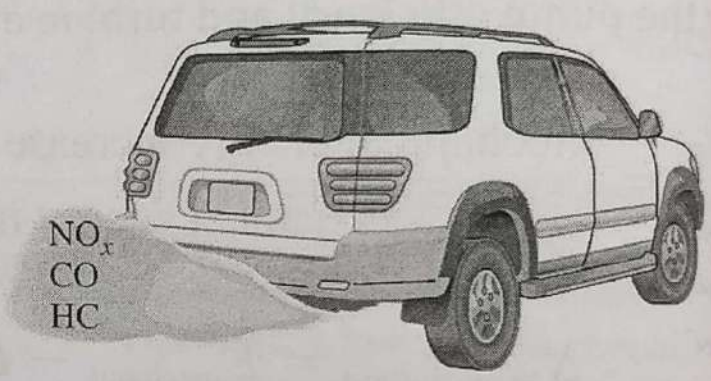
ENERGY AND ENVIRONMENT

Reading

- The conversion of energy from one form to another often affects the environment and the air we breathe in many ways, and thus the study of energy is not complete without considering its impact on the environment.
- Pollutants emitted during the combustion of fossil fuels are responsible for **smog**, **acid rain**, and **global warming**.
- The environmental pollution has reached such high levels that it became a serious threat to **vegetation**, **wildlife**, and **human health**.



Energy conversion processes are often accompanied by environmental pollution.



Motor vehicles are the largest source of air pollution.

EXAMPLE 2–2 **Wind Energy**

A site evaluated for a wind farm is observed to have steady winds at a speed of 8.5 m/s (Fig. 2–13). Determine the wind energy (*a*) per unit mass, (*b*) for a mass of 10 kg, and (*c*) for a flow rate of 1154 kg/s for air.

SOLUTION A site with a specified wind speed is considered. Wind energy per unit mass, for a specified mass, and for a given mass flow rate of air are to be determined.

Assumptions Wind flows steadily at the specified speed.

Analysis The only harvestable form of energy of atmospheric air is the kinetic energy, which is captured by a wind turbine.

(a) Wind energy per unit mass of air is

$$e = \text{ke} = \frac{V^2}{2} = \frac{(8.5\ \text{m/s})^2}{2}\left(\frac{1\ \text{J/kg}}{1\ \text{m}^2/\text{s}^2}\right) = 36.1\ \text{J/kg}$$

(b) Wind energy for an air mass of 10 kg is

EXAMPLE 2–2 Wind Energy

A site evaluated for a wind farm is observed to have steady winds at a speed of 8.5 m/s (Fig. 2–13). Determine the wind energy (*a*) per unit mass, (*b*) for a mass of 10 kg, and (*c*) for a flow rate of 1154 kg/s for air.

SOLUTION A site with a specified wind speed is considered. Wind energy per unit mass, for a specified mass, and for a given mass flow rate of air are to be determined.

Assumptions Wind flows steadily at the specified speed.

Analysis The only harvestable form of energy of atmospheric air is the kinetic energy, which is captured by a wind turbine.

(a) Wind energy per unit mass of air is

$$e = \text{ke} = \frac{V^2}{2} = \frac{(8.5\ \text{m/s})^2}{2}\left(\frac{1\ \text{J/kg}}{1\ \text{m}^2/\text{s}^2}\right) = 36.1\ \text{J/kg}$$

(b) Wind energy for an air mass of 10 kg is

$$E = me = (10\ \text{kg})(36.1\ \text{J/kg}) = 361\ \text{J}$$

(c) Wind energy for a mass flow rate of 1154 kg/s is

$$\dot{E} = \dot{m}e = (1154\ \text{kg/s})(36.1\ \text{J/kg})\left(\frac{1\ \text{kW}}{1000\ \text{J/s}}\right) = 41.7\ \text{kW}$$



ask recieve
الممسوحة ضوئيا بـ CamScanner

EXAMPLE 2–10 Cooling of a Hot Fluid in a Tank

A rigid tank contains a hot fluid that is cooled while being stirred by a paddle wheel. Initially, the internal energy of the fluid is 800 kJ. During the cooling process, the fluid loses 500 kJ of heat, and the paddle wheel does 100 kJ of work on the fluid. Determine the final internal energy of the fluid. Neglect the energy stored in the paddle wheel.

SOLUTION A fluid in a rigid tank looses heat while being stirred. The final internal energy of the fluid is to be determined.

Assumptions 1 The tank is stationary and thus the kinetic and potential energy changes are zero, $\Delta KE = \Delta PE = 0$. Therefore, $\Delta E = \Delta U$ and internal energy is the only form of the system's energy that may change during this process. 2 Energy stored in the paddle wheel is negligible.

Analysis Take the contents of the tank as the system (Fig. 2–49). This is a *closed system* since no mass crosses the boundary during the process.

We observe that the volume of a rigid tank is constant, and thus there is no moving boundary work. Also, heat is lost from the system and shaft work is done on the system. Applying the energy balance on the system gives

$$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic, potential, etc., energies}}$$

$$W_{sh,in} - Q_{out} = \Delta U = U_2 - U_1$$

$$100 \text{ kJ} - 500 \text{ kJ} = U_2 - 800 \text{ kJ}$$

$$U_2 = 400 \text{ kJ}$$

Therefore, the final internal energy of the system is 400 kJ.

EXAMPLE 2–15 Power Generation from a Hydroelectric Plant

Electric power is to be generated by installing a hydraulic turbine–generator at a site 70 m below the free surface of a large water reservoir that can supply water at a rate of 1500 kg/s steadily (Fig. 2–60). If the mechanical power output of the turbine is 800 kW and the electric power generation is 750 kW, determine the turbine efficiency and the combined turbine–generator efficiency of this plant. Neglect losses in the pipes.

SOLUTION A hydraulic turbine-generator installed at a large reservoir is to generate electricity. The combined turbine–generator efficiency and the turbine efficiency are to be determined.

Assumptions 1 The water elevation in the reservoir remains constant. 2 The mechanical energy of water at the turbine exit is negligible.

Analysis We take the free surface of water in the reservoir to be point 1

CamScanner الممسوحة ضوئيا بـ

EXAMPLE 2–15 Power Generation from a Hydroelectric Plant

Electric power is to be generated by installing a hydraulic turbine–generator at a site 70 m below the free surface of a large water reservoir that can supply water at a rate of 1500 kg/s steadily (Fig. 2–60). If the mechanical power output of the turbine is 800 kW and the electric power generation is 750 kW, determine the turbine efficiency and the combined turbine–generator efficiency of this plant. Neglect losses in the pipes.

SOLUTION A hydraulic turbine-generator installed at a large reservoir is to generate electricity. The combined turbine–generator efficiency and the turbine efficiency are to be determined.

Assumptions 1 The water elevation in the reservoir remains constant. 2 The mechanical energy of water at the turbine exit is negligible.

Analysis We take the free surface of water in the reservoir to be point 1 and the turbine exit to be point 2. We also take the turbine exit as the reference level ($z_2 = 0$) so that the potential energies at 1 and 2 are $pe_1 = gz_1$ and $pe_2 = 0$. The flow energy P/ρ at both points is zero since both 1 and 2 are open to the atmosphere ($P_1 = P_2 = P_{atm}$). Further, the kinetic energy at both points is zero ($ke_1 = ke_2 = 0$) since the water at point 1 is essentially motionless, and the kinetic energy of water at turbine exit is assumed to be negligible. The potential energy of water at point 1 is

CamScanner الممسوحة ضوئيا بـ

$$pe_1 = gz_1 = (9.81\ \text{m/s}^2)(70\ \text{m})\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = 0.687\ \text{kJ/kg}$$

Then the rate at which the mechanical energy of water is supplied to the turbine becomes

$$|\Delta \dot{E}_{\text{mech, fluid}}| = \dot{m}(e_{\text{mech, in}} - e_{\text{mech, out}}) = \dot{m}(pe_1 - 0) = \dot{m}pe_1$$
$$= (1500\ \text{kg/s})(0.687\ \text{kJ/kg})$$
$$= 1031\ \text{kW}$$

The combined turbine–generator and the turbine efficiency are determined from their definitions to be

$$\eta_{\text{turbine-gen}} = \frac{\dot{W}_{\text{elect, out}}}{|\Delta \dot{E}_{\text{mech, fluid}}|} = \frac{750\ \text{kW}}{1031\ \text{kW}} = 0.727 \text{ or } 72.7\%$$

$$\eta_{\text{turbine}} = \frac{\dot{W}_{\text{elect, out}}}{|\dot{E}_{\text{mech, fluid}}|} = \frac{800\text{kW}}{1031\text{kW}} = 0.776 \text{ or } 77.6\%$$

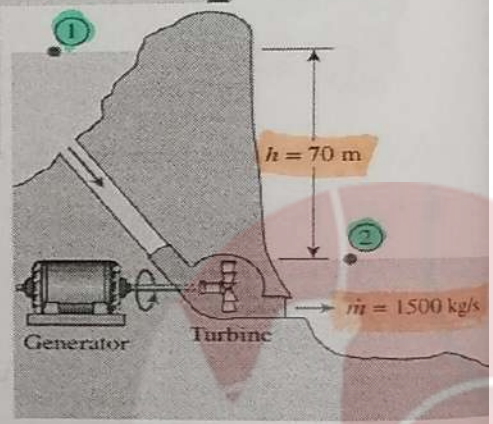


FIGURE 2–60
Schematic for Example 2–15

ask & believe & recieve
CamScanner الممسوحة ضوئيا بـ



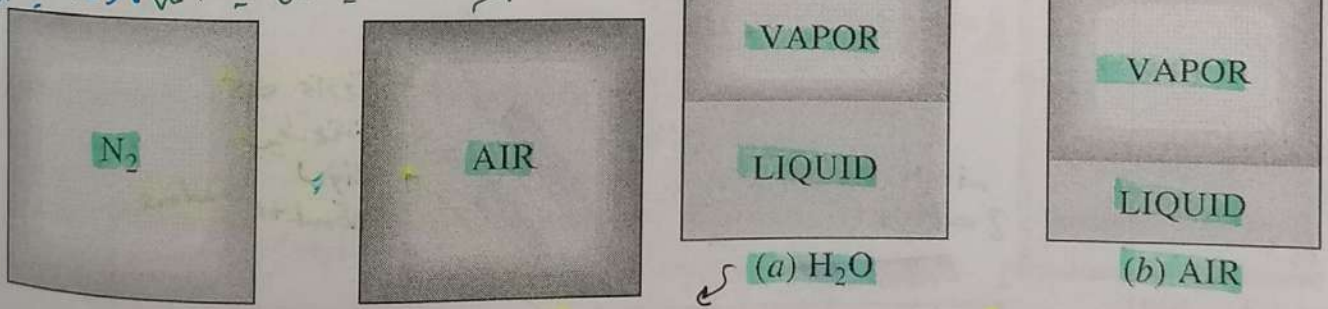
SUBSTANCES

Thermodynamics: An Engineering Approach
Yunus A. Cengel, Michael A. Boles, Mehmet Kanoglu
McGraw-Hill

Dr. Ahmad M. AbuYaghi
October 2023

PURE SUBSTANCE

- **Pure substance**: A substance that has a fixed chemical composition throughout.
- Air is a mixture of several gases, but it is considered to be a pure substance.

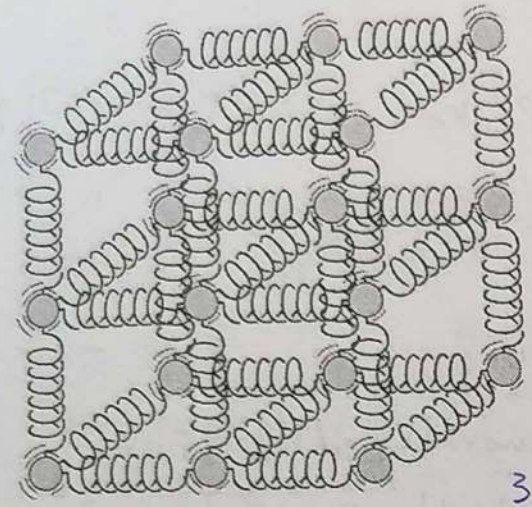


Nitrogen and gaseous air are pure substances.

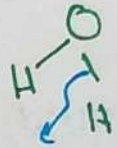
A mixture of liquid and gaseous water is a pure substance, but a mixture of liquid and gaseous air is not.

* PHASES OF A PURE SUBSTANCE *

Inter & Intra molecular



The molecules in a solid are kept at their positions by the large springlike inter-molecular forces.



→ If we break it will get :-

Intramolecular $H_2O \rightarrow H_2 + \frac{1}{2} O_2$

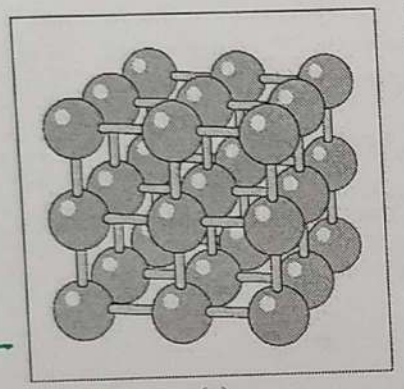
$H_2O - H_2O$ → If we break it will get s → L → g

Intermolecular

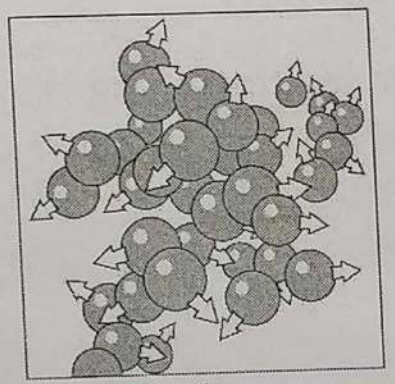
3 Types of substance :-

(3 phase change)

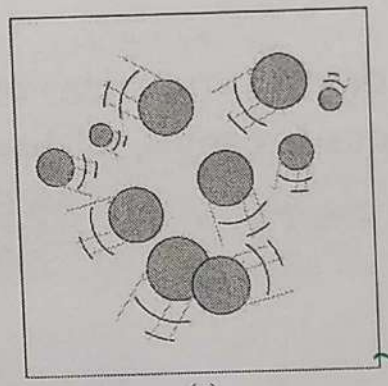
In a solid, the attractive and repulsive forces between the molecules tend to maintain them at relatively constant distances from each other.



Solid (a)



(b) liq



(c) gas

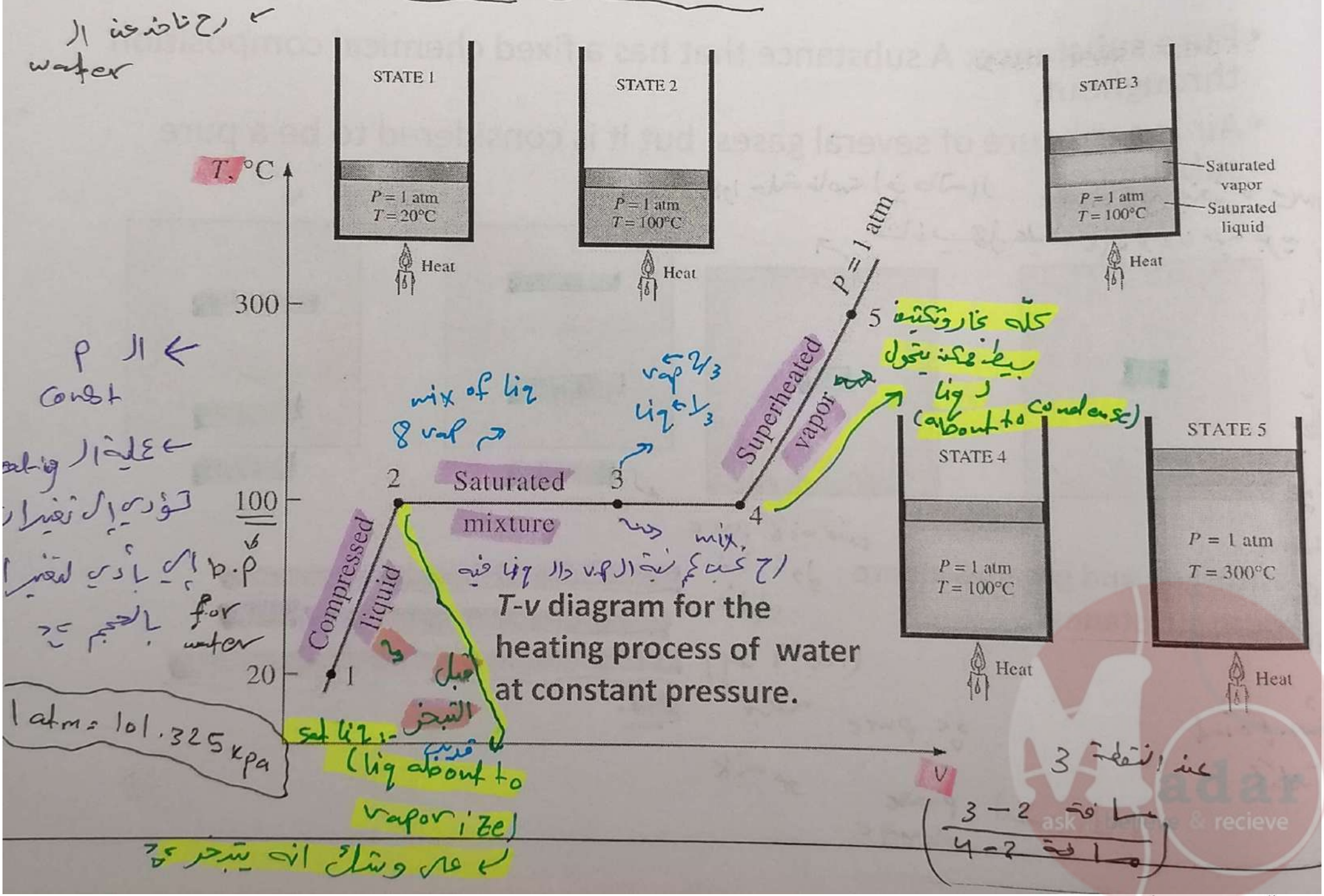
كل ما نعطي حرارة للمادة كل molecule بياخدها طاقة حركة ف بتبعد عن بعض وبتكسر الـ Intermolecular forces وبتتحول لـ liq وبعدين لـ gas

The arrangement of atoms in different phases: (*a*) molecules are at relatively fixed positions in a solid, (*b*) groups of molecules move about each other in the liquid phase, and (*c*) molecules move about at random in the gas phase.

Madar ask - believe & recieve

الممسوحة ضوئيا بـ CamScanner

PHASE-CHANGE PROCESSES OF PURE SUBSTANCES

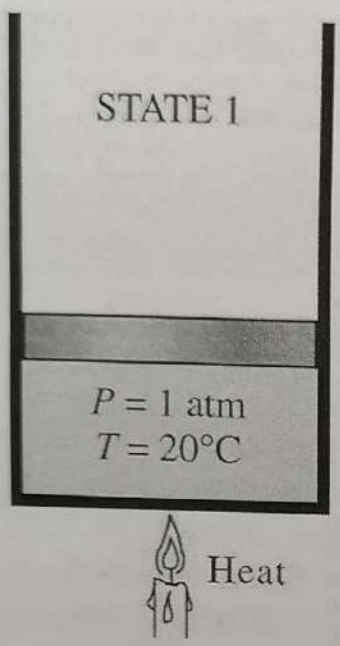


T-v diagram for the heating process of water at constant pressure.

الممسوحة ضوئيا بـ CamScanner

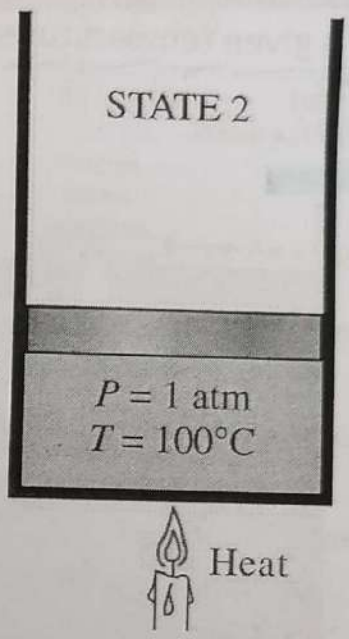
PHASE-CHANGE PROCESSES OF PURE SUBSTANCES

- **Compressed liquid (subcooled liquid)**: A substance that it is *not about to vaporize.*
- **Saturated liquid**: A liquid that is *about to vaporize.*

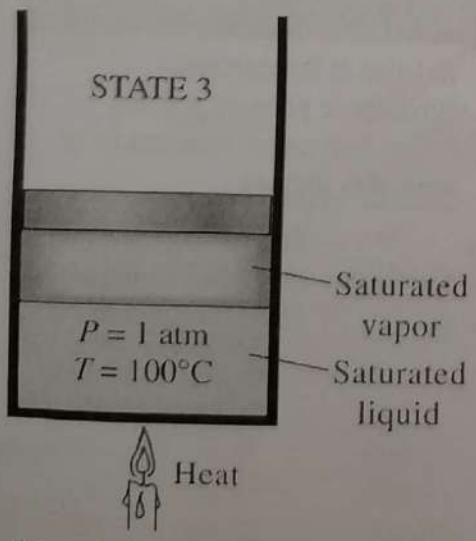


At 1 atm and 20°C, water exists in the liquid phase (***compressed liquid***).

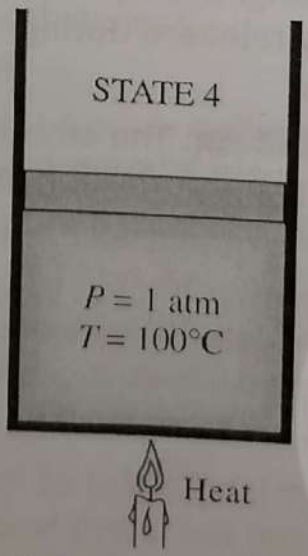
At 1 atm pressure and 100°C, water exists as a liquid that is ready to vaporize (***saturated liquid***).



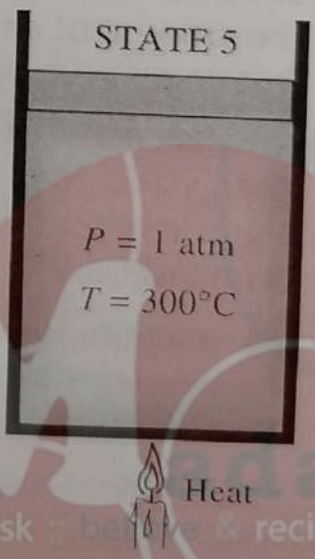
- **Saturated vapor**: A vapor that is *about to condense.*
- **Saturated liquid–vapor mixture**: The state at which the *liquid and vapor phases coexist* in equilibrium.
- **Superheated vapor**: A vapor that is *not about to condense* (i.e., not a saturated vapor).



As more heat is transferred, part of the saturated liquid vaporizes



At 1 atm pressure, the temperature remains constant

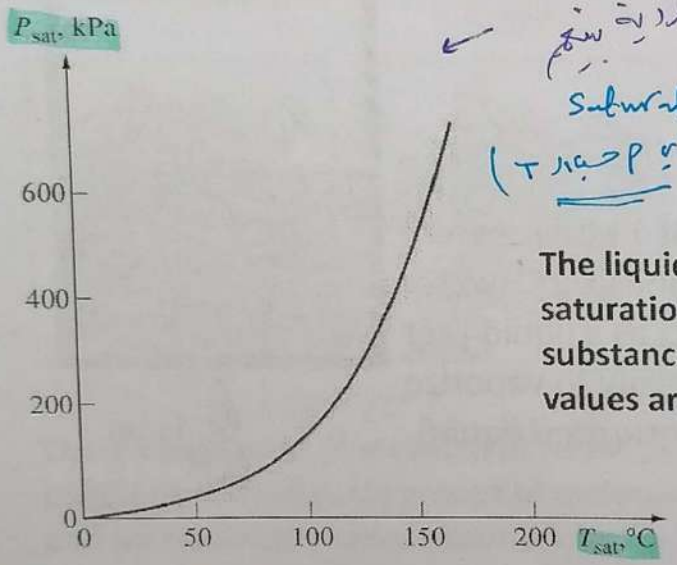


As more heat is transferred, the

ask & believe & recieve
الممسوحة ضوئيا بـ CamScanner

Saturation Temperature and Saturation Pressure

- The temperature at which water starts boiling depends on the pressure; therefore, if the pressure is fixed, so is the boiling temperature.
- Water boils at 100°C at 1 atm pressure.
- **Saturation temperature T_{sat}**: The temperature at which a pure substance changes phase at a given pressure.
- **Saturation pressure P_{sat}**: The pressure at which a pure substance changes phase at a given temperature.



The liquid–vapor saturation curve of a pure substance (numerical values are for water).

TABLE 3–1

Saturation (boiling) pressure of water at various temperatures

Temperature, T, °C	Saturation pressure, P_{sat}, kPa
−10	0.26
−5	0.40
0	0.61
5	0.87
10	1.23
15	1.71
20	2.34
25	3.17
30	4.25
40	7.39
50	12.35
100	101.4
150	476.2
200	1555
250	3976
300	8588

- **Latent heat**: The amount of energy absorbed or released during a phase-change process.
- **Latent heat of fusion**: The amount of energy absorbed during melting. It is equivalent to the amount of energy released during freezing.
- **Latent heat of vaporization**: The amount of energy absorbed during vaporization, and it is equivalent to the energy released during condensation.
- The magnitudes of the latent heats depend on the temperature or pressure at which the phase change occurs.
- At 1 atm pressure, the latent heat of fusion of water is 333.7 kJ/kg and the latent

TABLE 3–2

Variation of the standard atmospheric pressure and the boiling (saturation) temperature of water with altitude

Elevation, m	Atmospheric pressure, kPa	Boiling temperature, °C
0	101.33	100.0
1,000	89.55	96.5
2,000		

CamScanner الممسوحة ضوئيا بـ

- **Latent heat**: The amount of energy absorbed or released during a phase-change process.
- **Latent heat of fusion**: The amount of energy absorbed during melting. It is equivalent to the amount of energy released during freezing.
- **Latent heat of vaporization**: The amount of energy absorbed during vaporization, and it is equivalent to the energy released during condensation.
- The magnitudes of the latent heats depend on the temperature or pressure at which the phase change occurs.
- At 1 atm pressure, the latent heat of fusion of water is 333.7 kJ/kg and the latent heat of vaporization is 2256.5 kJ/kg.
- The atmospheric pressure, and thus the boiling temperature of water, decreases with elevation.

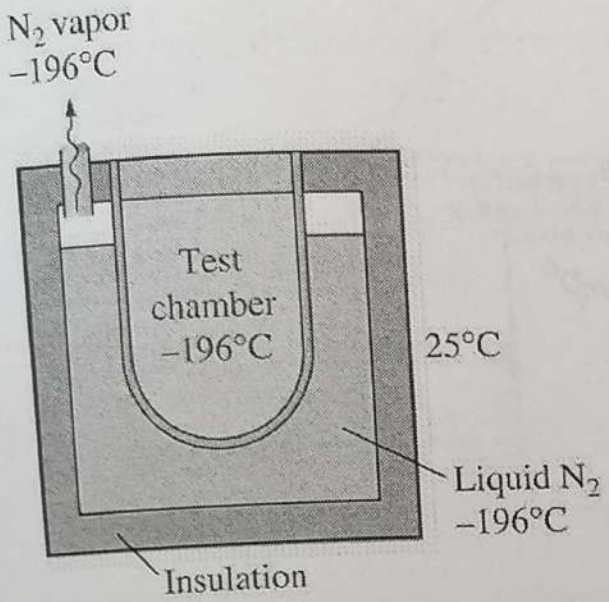
TABLE 3–2

Variation of the standard atmospheric pressure and the boiling (saturation) temperature of water with altitude

Elevation, m	Atmospheric pressure, kPa	Boiling temperature, °C
0	101.33	100.0
1,000	89.55	96.5
2,000	79.50	93.3
5,000	54.05	83.3
10,000	26.50	66.3
20,000	5.53	34.7

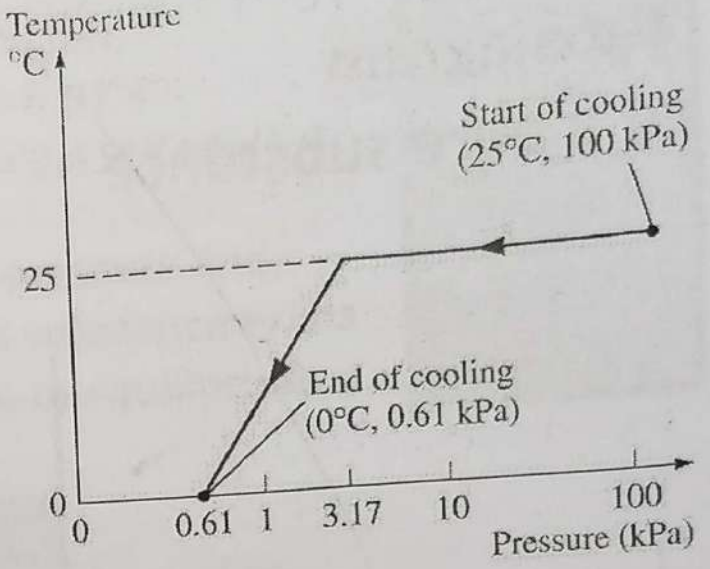
CamScanner الممسوحة ضوئيا بـ

Some Consequences of T_{sat} and P_{sat} Dependence

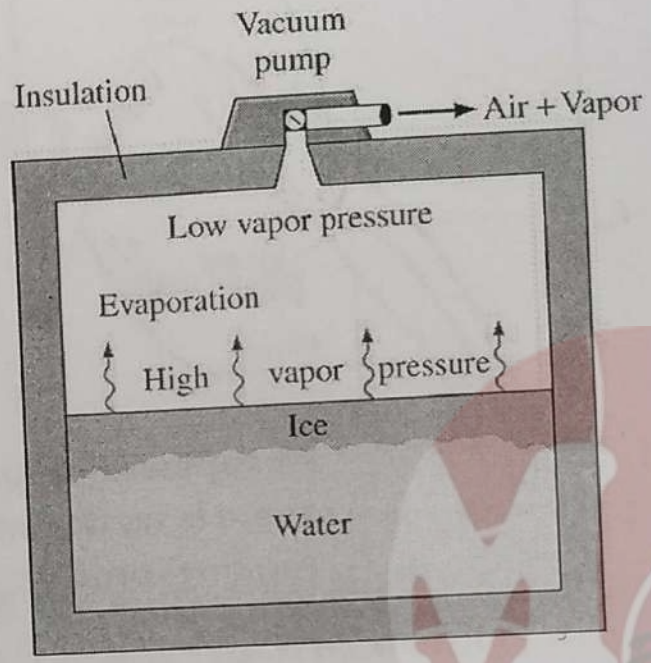


The temperature of liquid nitrogen exposed to the atmosphere remains constant at 196°C, and thus it maintains the test chamber at 196°C.

The variation of the temperature of fruits and vegetables with pressure during vacuum cooling from 25°C to 0°C.



In 1775, ice was made by evacuating the air space in a water tank.

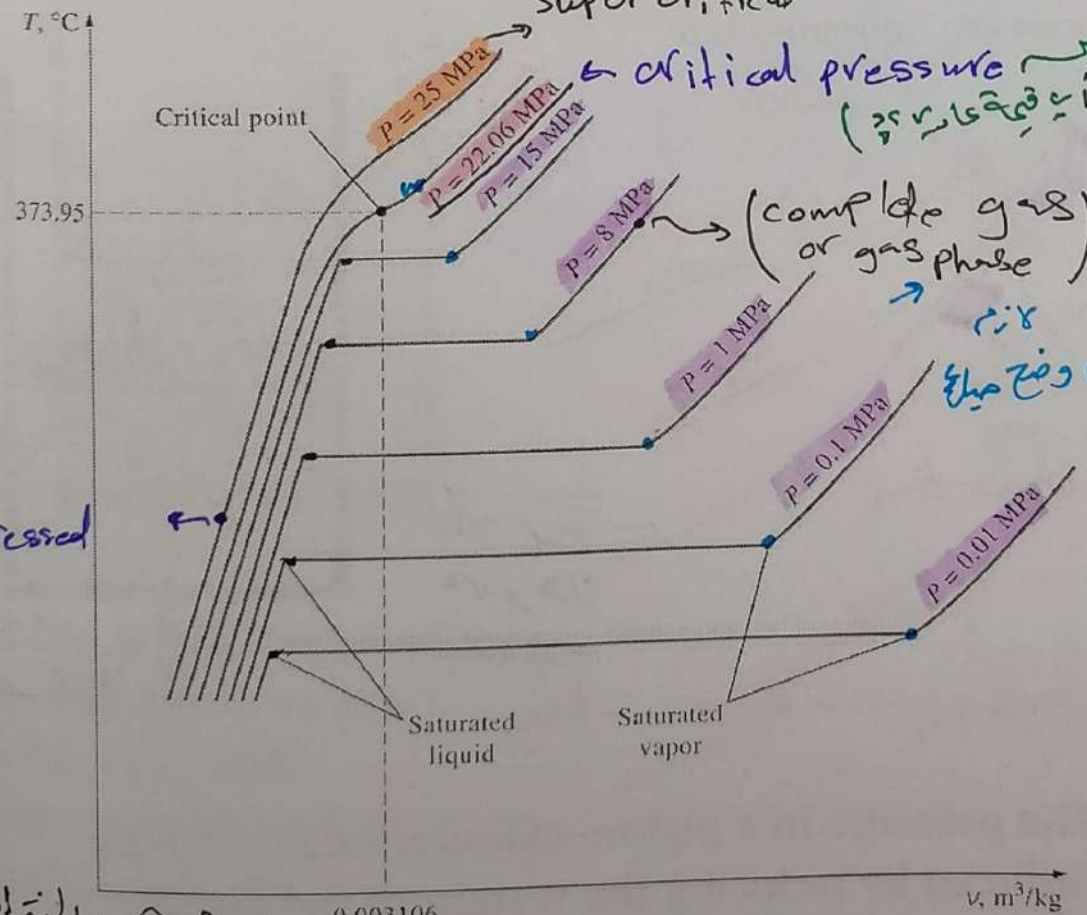


CamScanner الممسوحة ضوئيا بـ

PROPERTY DIAGRAMS FOR PHASE-CHANGE PROCESSES

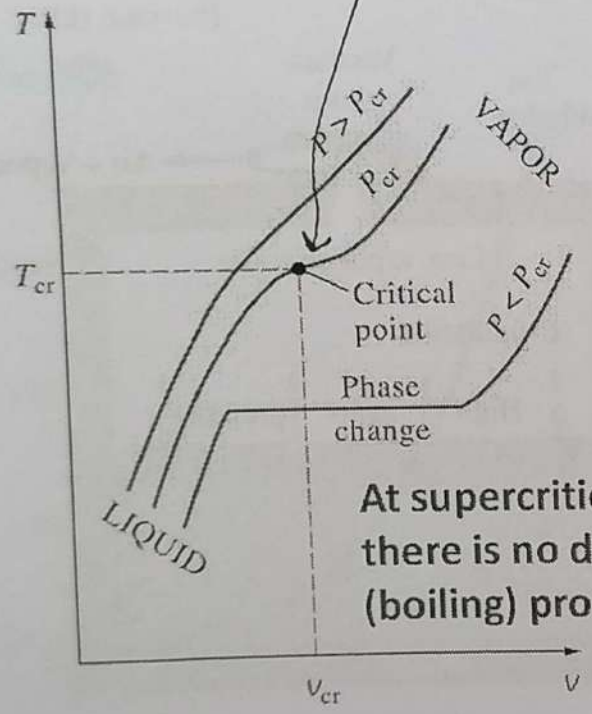
- The variations of properties during phase-change processes are best studied and understood with the help of property diagrams such as the

T-v, P-v, and P-T diagrams for pure substances.

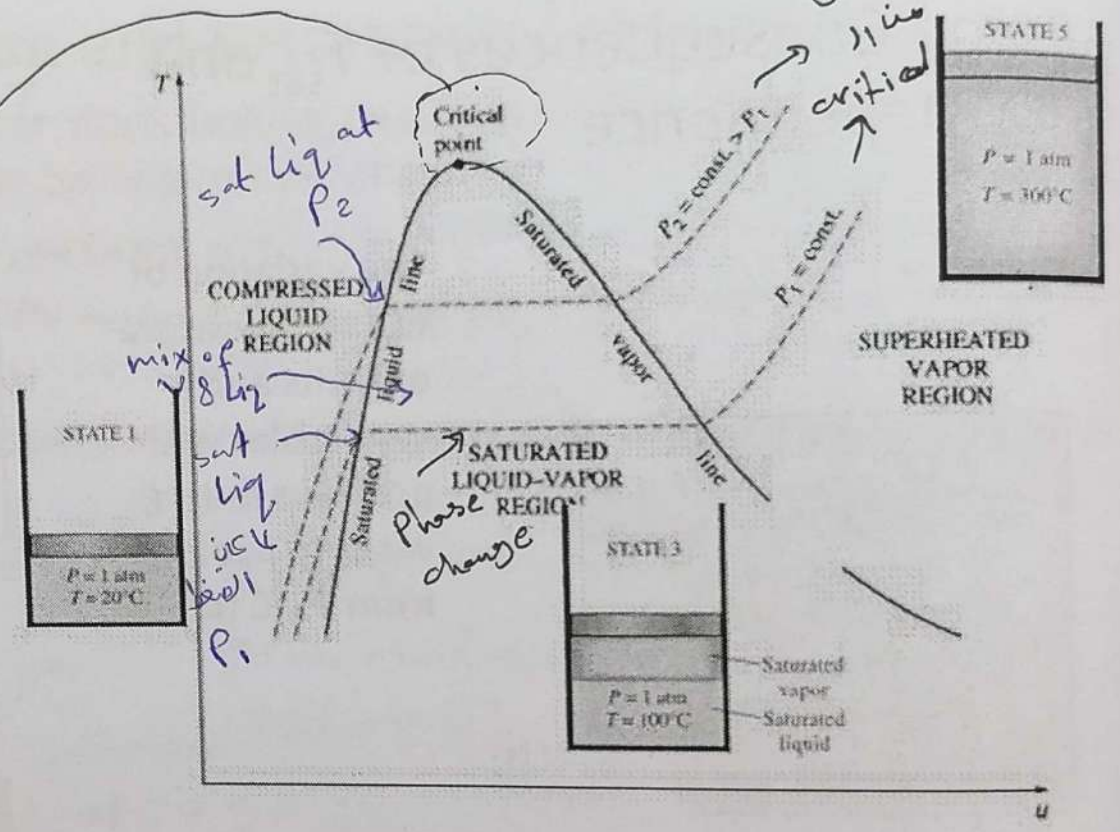


T-v diagram of constant-pressure phase-change processes of a pure substance at various pressures (numerical values are for water).

T-*v* diagram of a pure substance



At supercritical pressures ($P > P_{cr}$), there is no distinct phase-change (boiling) process.



Critical point: The point at which the saturated liquid and saturated vapor states are identical.

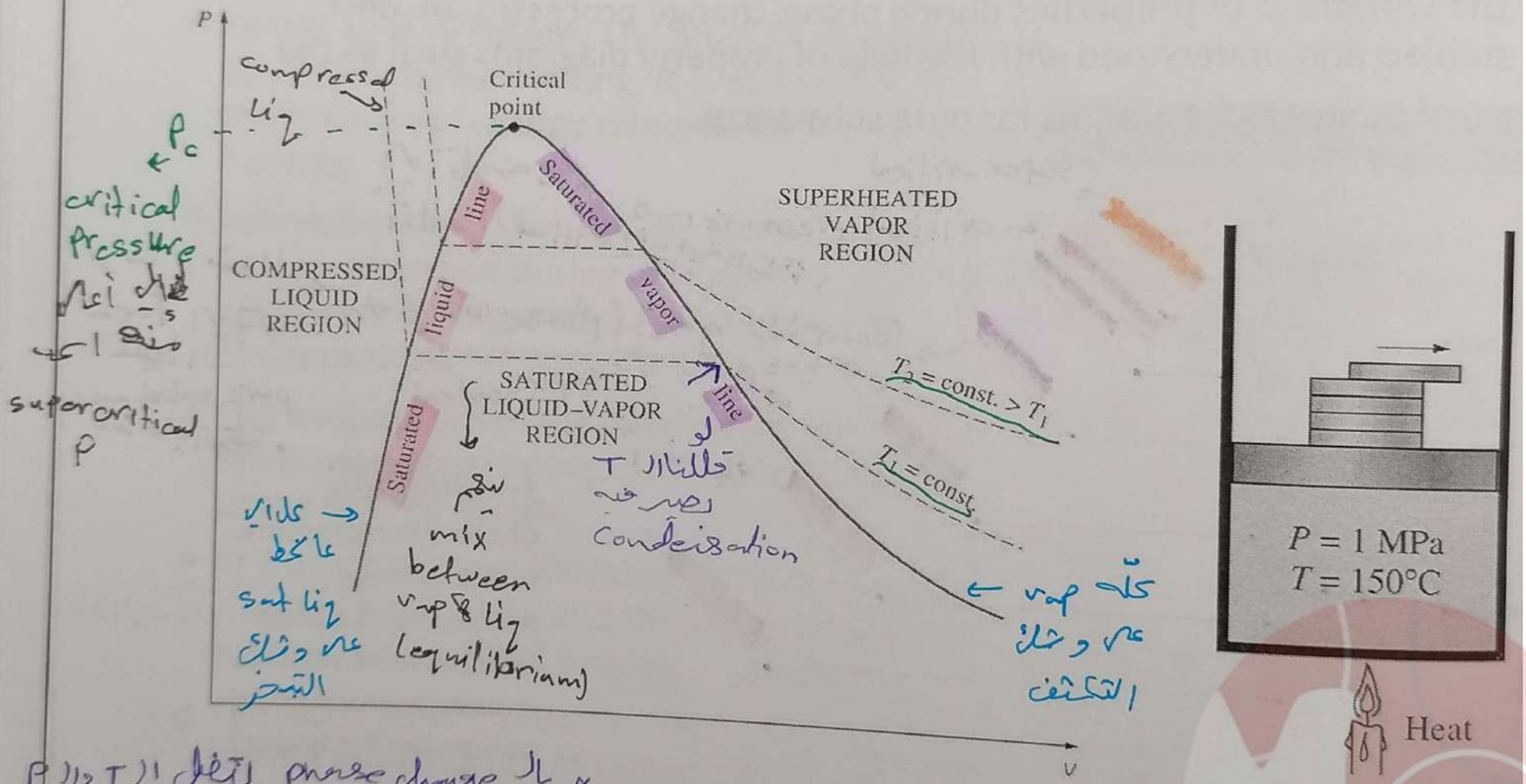
For water

$T_c = 374\ c^\circ$

$P_c = 22.06\ MPa \simeq 22000\ KPa$

CamScanner الممسوحة ضوئيا بـ

P-v diagram of a pure substance.

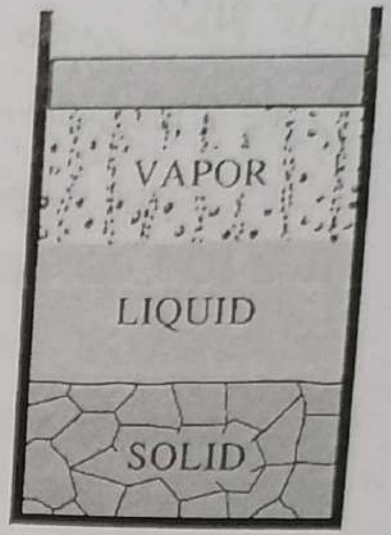


The pressure in a piston–cylinder device can be reduced by reducing the weight of the piston.

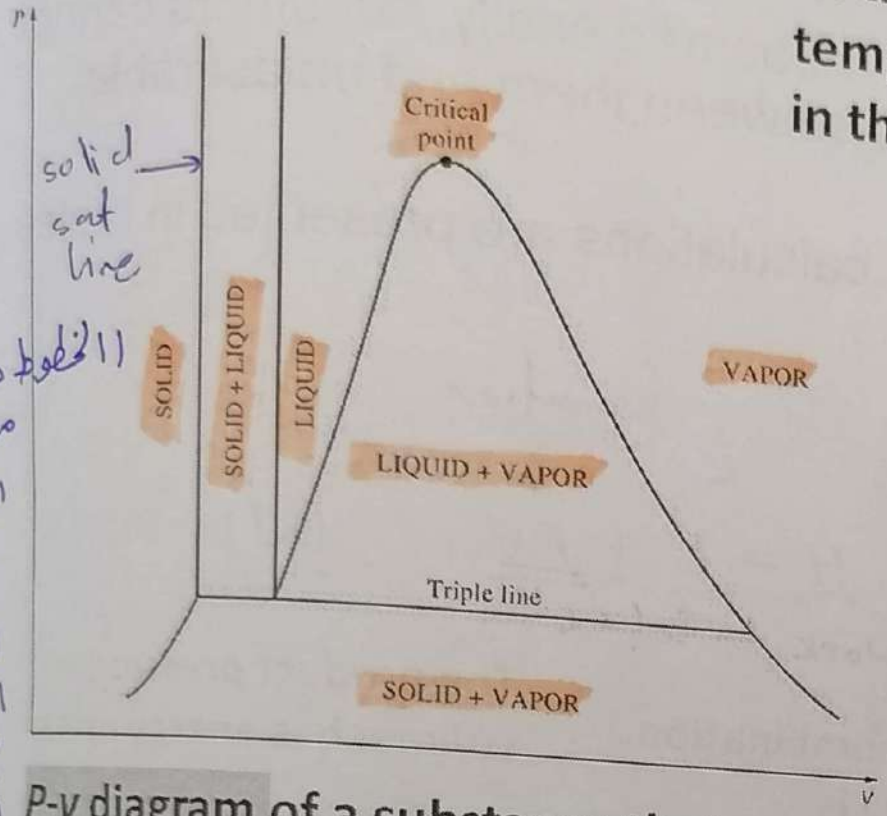
الممسوحة ضوئيا بـ CamScanner

Extending Diagrams to Include Solid Phase

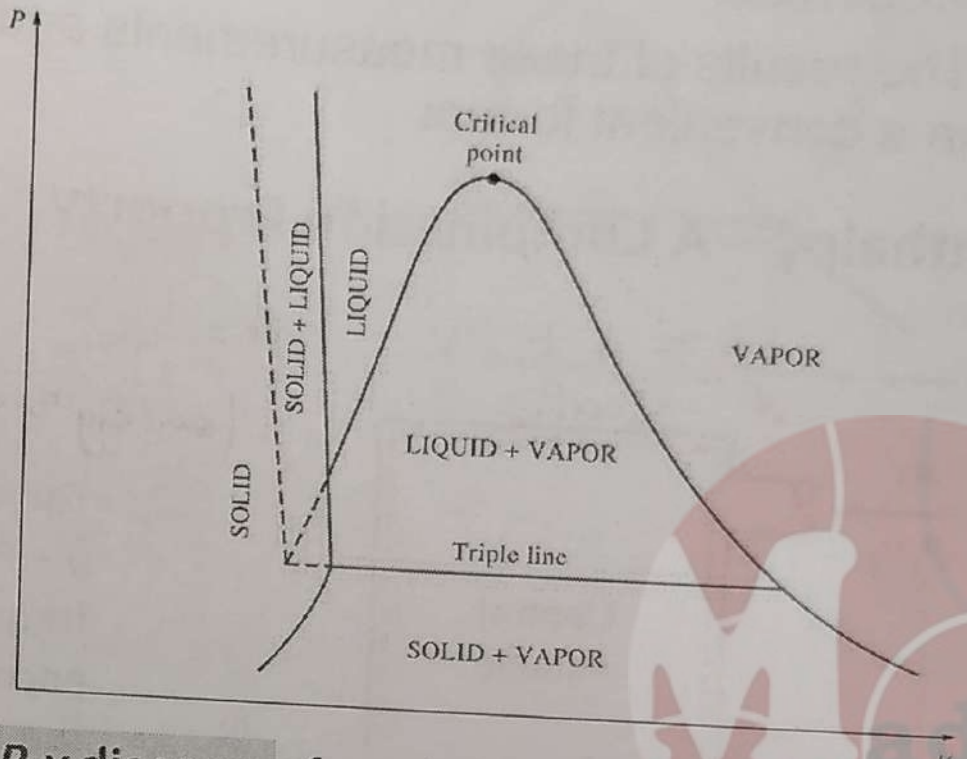
For water,
$T_{tp} = 0.01°C$
$P_{tp} = 0.6117$ kPa



At triple-point pressure and temperature, a substance exists in three phases in equilibrium.



P-v diagram of a substance that contracts on freezing.

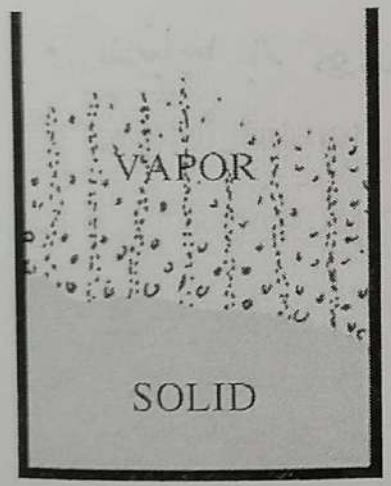


P-v diagram of a substance that expands on freezing (such as water).

CamScanner الممسوحة ضوئيا بـ

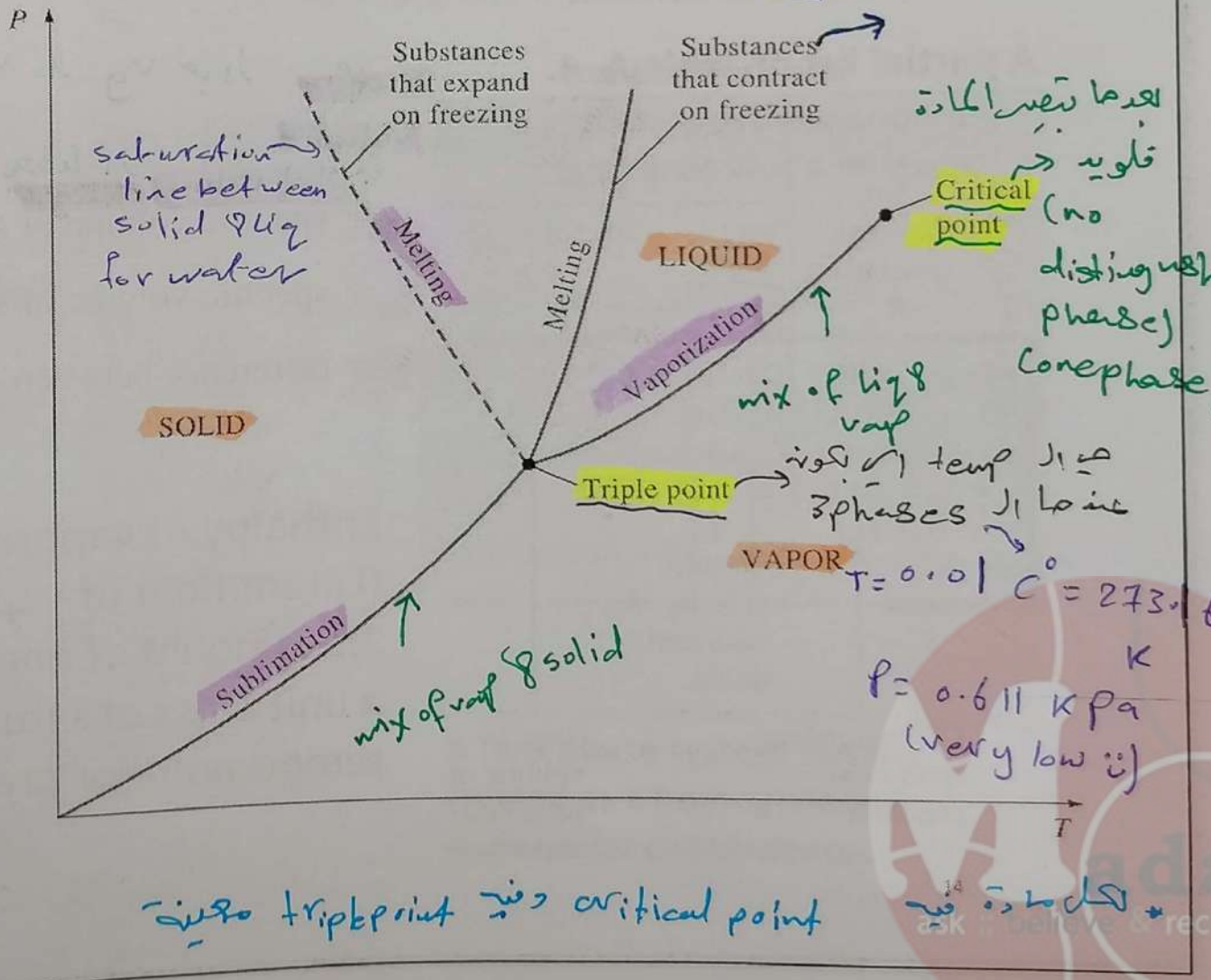
the first graph for study

Sublimation:
Passing from the solid phase directly into the vapor phase.



At low pressures (**below the triple-point value**), solids evaporate without melting first (*sublimation*).

P-T diagram of pure substances



H2O حالة الخط لمعظم المواد ما عدا ال

saturation line between solid & liq for water

بعدها بتصير المادة غازية (no distinguish phase/ one phase)

mix of liq & vap

عند ال temp اللي بتكون عندها ال 3 phases

T = 0.01 C° = 273.16 K

P = 0.611 kPa (very low)

mix of vap & solid

triple point و critical point معينة

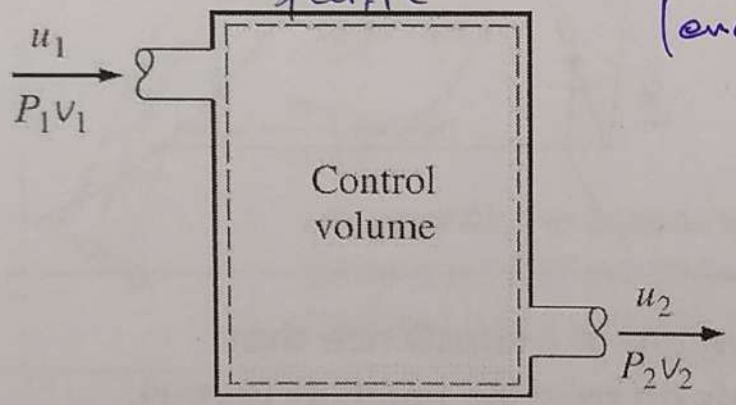
المادة في

PROPERTY TABLES

- For most substances, the relationships among thermodynamic properties are too complex to be expressed by simple equations.
- Therefore, properties are frequently presented in the form of tables.
- Some thermodynamic properties can be measured easily, but others cannot and are calculated by using the relations between them and measurable properties.
- The results of these measurements and calculations are presented in tables in a convenient format.

Enthalpy—A Combination Property

$$h = u + Pv \quad (\text{kJ/kg}) \qquad H = U + PV \quad (\text{kJ})$$



The combination *u + Pv* is frequently encountered in the analysis of control volumes.

The product *pressure* × *volume* has energy units.

$$\text{kPa} \cdot \text{m}^3 \equiv \text{kJ}$$
$$\text{kPa} \cdot \text{m}^3/\text{kg} \equiv \text{kJ/kg}$$
$$\text{bar} \cdot \text{m}^3 \equiv 100\ \text{kJ}$$
$$\text{MPa} \cdot \text{m}^3 \equiv 1000\ \text{kJ}$$

CamScanner الممسوحة ضوئيا بـ

24/10

Saturated Liquid and Saturated Vapor States

- **Table A–4**: Saturation properties of water under temperature.
- **Table A–5**: Saturation properties of water under pressure.

A partial list of Table A–4.

Temp. T °C	Sat. press. P_{sat} kPa	Specific volume m^3/kg Sat. liquid v_f	Sat. vapor v_g
85	57.868	0.001032	2.8261
90	70.183	0.001036	2.3593
95	84.609	0.001040	1.9808

Specific temperature

Corresponding saturation pressure

Specific volume of saturated liquid

Specific volume of saturated vapor

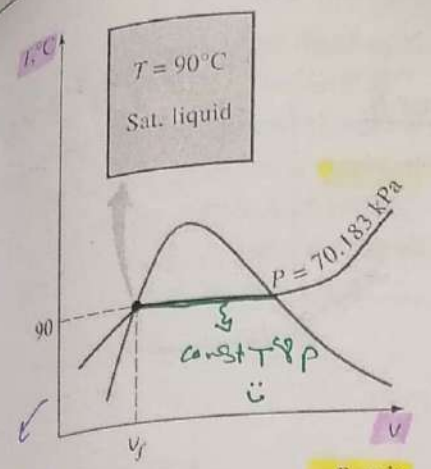
v_f = specific volume of saturated liquid

v_g = specific volume of saturated vapor

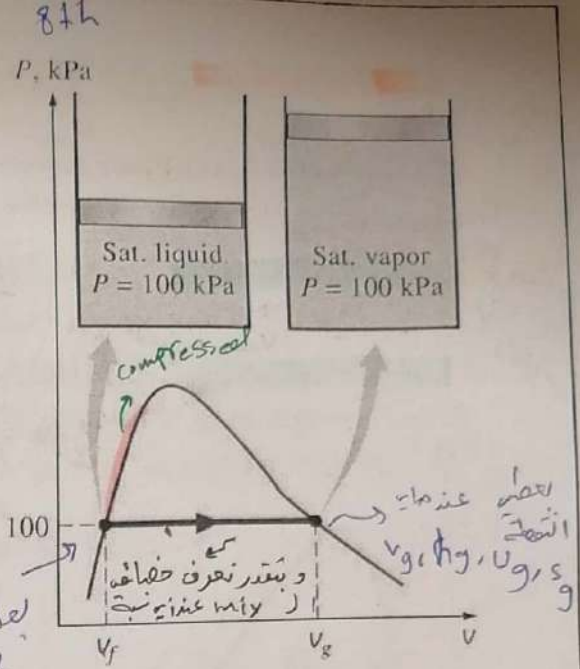
v_{fg} = difference between v_g and v_f (that is, $v_{fg} = v_g - v_f$)

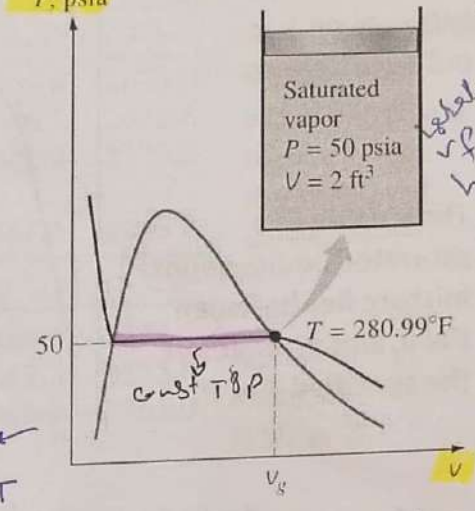
Enthalpy of vaporization, h_{fg} (Latent heat of vaporization): The amount of energy needed to vaporize a unit mass of saturated liquid at a given temperature or pressure.

CamScanner الممسوحة ضوئيا بـ



Examples: Saturated liquid and saturated vapor states of water on *T-v* and *P-v* diagrams.





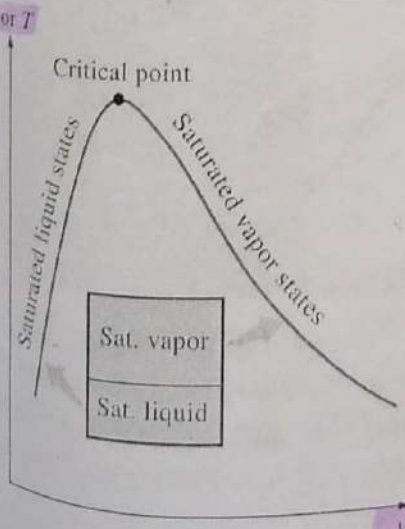
Saturated Liquid–Vapor Mixture

Quality, x : The ratio of the mass of vapor to the total mass of the mixture. Quality is between 0 and 1 **0: sat. liquid, 1: sat. vapor.**

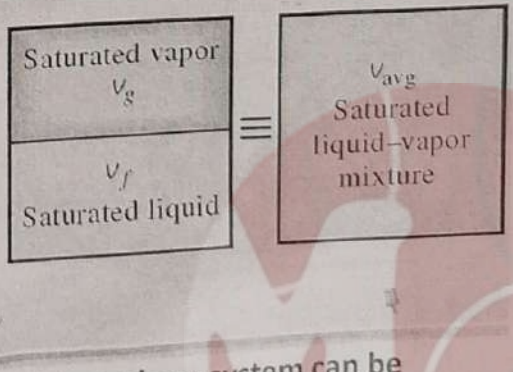
The properties of the saturated liquid are the same whether it exists alone or in a mixture with saturated vapor.

$$x = \frac{m_{\text{vapor}}}{m_{\text{total}}} \qquad m_{\text{total}} = m_{\text{liquid}} + m_{\text{vapor}} = m_f + m_g$$

Temperature and pressure are dependent properties for a mixture.



The relative amounts of liquid and vapor phases in a saturated mixture are specified by the *quality x*.



A two-phase system can be treated as a homogeneous mixture for convenience.

CamScanner الممسوحة ضوئيا بـ

$$v_{avg} = v_f + x v_{fg} \quad (m^3/kg)$$

$$x = m_g/m_t \qquad x = \frac{v_{avg} - v_f}{v_{fg}}$$

fraction of vap

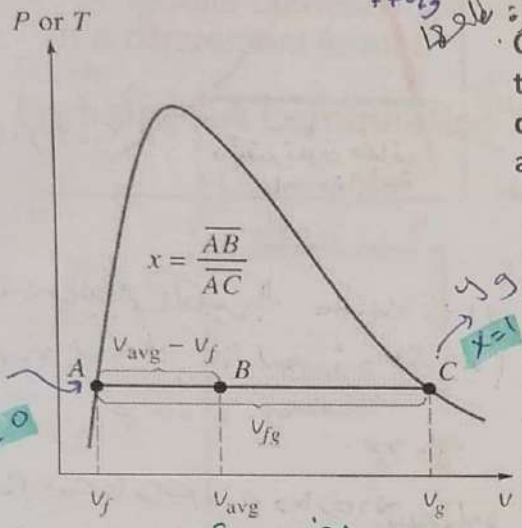
$$u_{avg} = u_f + x u_{fg} \quad (kJ/kg)$$

$$h_{avg} = h_f + x h_{fg} \quad (kJ/kg)$$

$y \rightarrow v, u, \text{ or } h.$

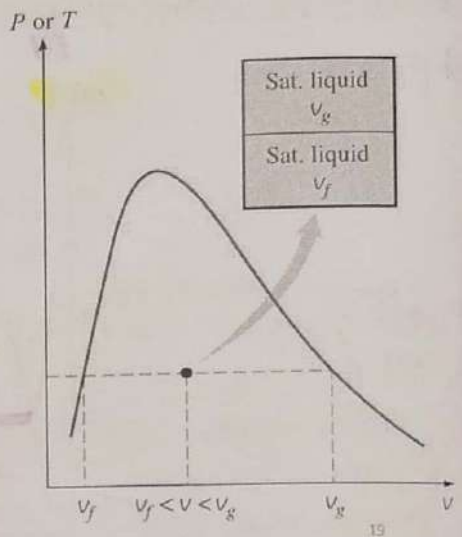
$$y_{avg} = y_f + x y_{fg}$$

$$y_f \le y_{avg} \le y_g$$



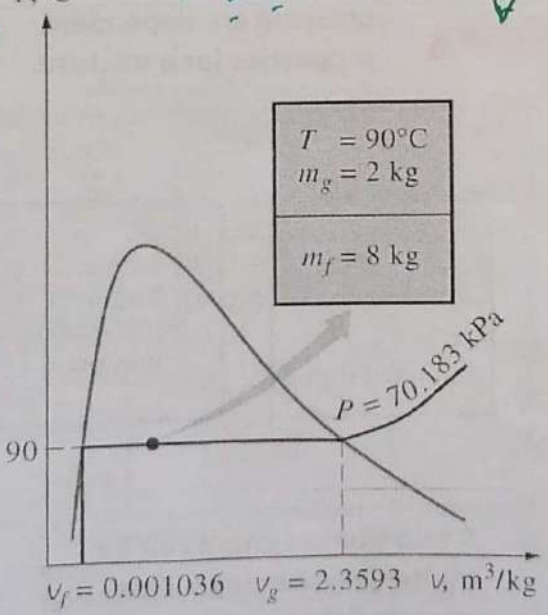
Quality is related to the horizontal distances on *P-v* and *T-v* diagrams.

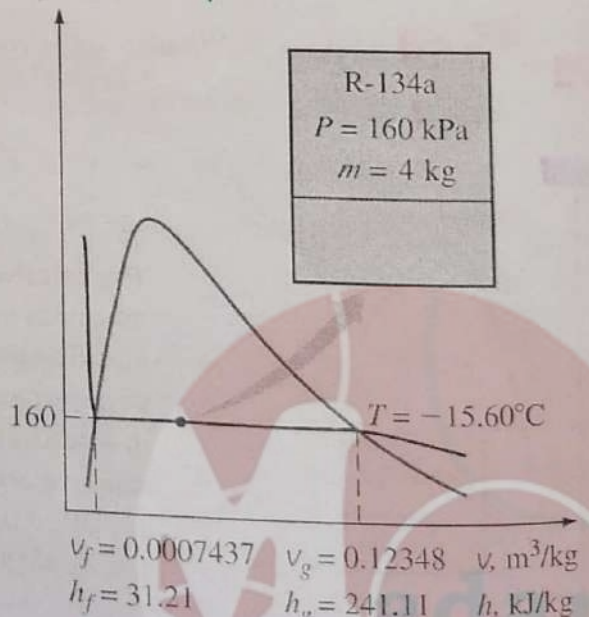
The *v* value of a saturated liquid–vapor mixture lies between the v_f and v_g values at the specified *T* or *P*.



Examples:

Saturated liquid-vapor mixture states on *T-v* and *P-v* diagrams.





CamScanner الممسوحة ضوئيا بـ

Superheated Vapor

In the region to the right of the saturated vapor line and at temperatures above the critical point temperature, a substance exists as superheated vapor. In this region, temperature and pressure are independent properties.

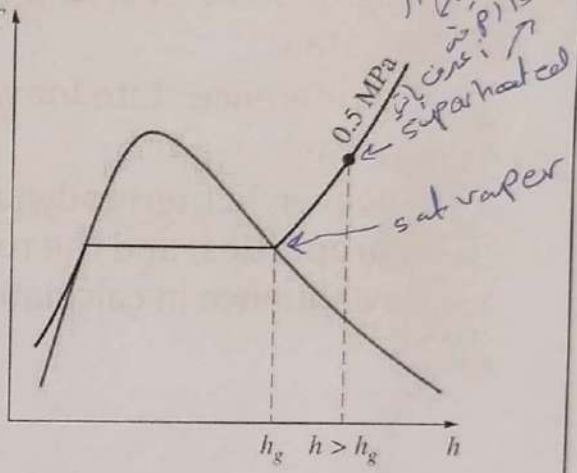
Compared to saturated vapor, superheated vapor is characterized by

- Lower pressures ($P < P_{sat}$ at a given T)
- Higher tempreatures ($T > T_{sat}$ at a given P)
- Higher specific volumes ($v > v_g$ at a given P or T)
- Higher internal energies ($u > u_g$ at a given P or T)
- Higher enthalpies ($h > h_g$ at a given P or T)

T, °C	v m³/kg	u kJ/kg	h kJ/kg
	$P = 0.1$ MPa (99.61°C)		
Sat.	1.6941	2505.6	2675.0
100	1.6959	2506.2	2675.8
150	1.9367	2582.9	2776.6
⋮	⋮	⋮	⋮
1300	7.2605	4687.2	5413.3
	$P = 0.5$ MPa (151.83°C)		
Sat.	0.37483	2560.7	2748.1
200	0.42503	2643.3	2855.8
250	0.47443	2723.8	2961.0

A partial listing of Table A–6.

At a specified P, superheated vapor exists at a higher h than the saturated vapor.



Compressed Liquid

The compressed liquid properties depend on temperature much more strongly than they do on pressure.

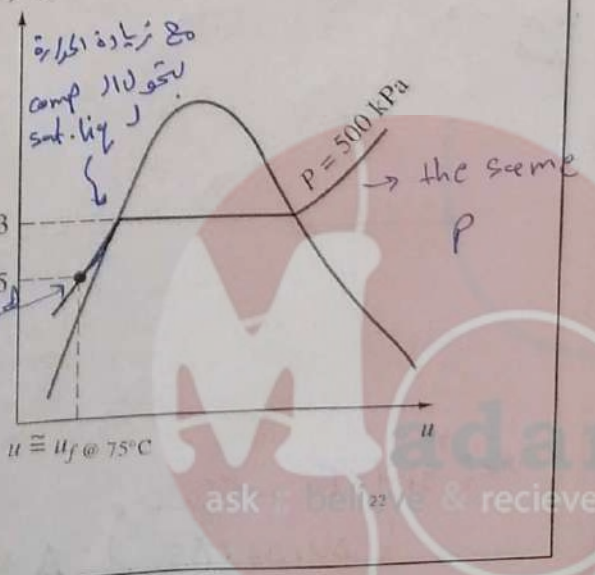
$y \cong y_{f\,@\,T}$ $\quad y \rightarrow v, u,$ or h

A more accurate relation for h

$$h \cong h_{f\,@\,T} + v_{f\,@\,T}(P - P_{sat\,@\,T})$$

Compressed liquid is characterized by

Higher pressures ($P > P_{sat}$ at a given T)
Lower tempreatures ($T < T_{sat}$ at a given P)
Lower specific volumes ($v < v_f$ at a given P or T)
Lower internal energies ($u < u_f$ at a given P or T)
Lower enthalpies ($h < h_f$ at a given P or T)



Given: P and T

$v \cong v_{f\,@T}$
$u \cong u_{f\,@T}$
$h \cong h_{f\,@T}$

A compressed liquid may be approximated as a saturated liquid at the given temperature.

At a given P and T, a pure substance will exist as a compressed liquid if $T < T_{sat\,@\,P}$

CamScanner الممسوحة ضوئيا بـ

13th

Reference State and Reference Values

- The values of ***u***, ***h***, and ***s*** cannot be measured directly, and they are calculated from measurable properties using the relations between properties.
- Those relations give the ***changes* in properties**, not the values of properties at specified states.
- Therefore, we need to choose a convenient ***reference state*** and assign a value of ***zero*** for a convenient property or properties at that state.
- The reference state for water is 0.01°C and for R-134a is -40°C in tables.
- However, In thermodynamics we are concerned with the ***changes* in properties,** and the reference state chosen is of no consequence in calculations.

14th

Reference State and Reference Values

Saturated water—Temperature table

Temp., T °C	Sat. press., P_{sat} kPa	Specific volume, m³/kg: Sat. liquid, v_f	Specific volume, m³/kg: Sat. vapor, v_g	Internal energy, kJ/kg: Sat. liquid, u_f	Internal energy, kJ/kg: Evap., u_{fg}	Internal energy, kJ/kg: Sat. vapor, u_g	Enthalpy, kJ/kg: Sat. liquid, h_f	Enthalpy, kJ/kg: Evap., h_{fg}	Enthalpy, kJ/kg: Sat. vapor, h_g	Entropy, kJ/kg · K: Sat. liquid, s_f	Entropy, kJ/kg · K: Evap., s_{fg}	Entropy, kJ/kg · K: Sat. vapor, s_g
0.01	0.6117	0.001000	206.00	0.000	2374.9	2374.9	0.001	2500.9	2500.9	0.0000	9.1556	9.1556
5	0.8725	0.001000	147.03	21.019	2360.8	2381.8	21.020	2489.1	2510.1	0.0763	8.9487	9.0249

triple point

Saturated refrigerant-134a—Temperature table

Temp., T °C	Sat. press., P_{sat} kPa	Specific volume, m³/kg: Sat. liquid, v_f	Specific volume, m³/kg: Sat. vapor, v_g	Internal energy, kJ/kg: Sat. liquid, u_f	Internal energy, kJ/kg: Evap., u_{fg}	Internal energy, kJ/kg: Sat. vapor, u_g	Enthalpy, kJ/kg: Sat. liquid, h_f	Enthalpy, kJ/kg: Evap., h_{fg}	Enthalpy, kJ/kg: Sat. vapor, h_g	Entropy, kJ/kg · K: Sat. liquid, s_f	Entropy, kJ/kg · K: Evap., s_{fg}	Entropy, kJ/kg · K: Sat. vapor, s_g
−40	51.25	0.0007054	0.36081	−0.036	207.40	207.37	0.000	225.86	225.86	0.00000	0.96866	0.96866

Ref state for reffrence

(ΔU، ΔH، ΔS) Δ بعضنا الدنيا reff في وحنا لو ما كانة

بالنيرو state

CamScanner الممسوحة ضوئيا بـ

THE IDEAL-GAS EQUATION OF STATE

- Equation of state: Any equation that relates the pressure, temperature, and specific volume of a substance.
- The simplest and best-known equation of state for substances in the gas phase is the ideal-gas equation of state. This equation predicts the *P-v-T* behavior of a gas quite accurately within some properly selected region.

$$P = R\left(\frac{T}{v}\right) \quad \text{or} \quad Pv = RT$$

Ideal gas equation of state

$$R = \frac{R_u}{M} \qquad (\text{kJ/kg} \cdot \text{K or kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})$$

R: gas constant
M: molar mass (kg/kmol)
R_u: universal gas constant

$R_u =$
- 8.31447 kJ/kmol · K
- 8.31447 kPa · m³/kmol · K
- 0.0831447 bar · m³/kmol · K
- 1.98588 Btu/lbmol · R
- 10.7316 psia · ft³/lbmol · R
- 1545.37 ft · lbf/lbmol · R

Substance	R, kJ/kg·K
Air	0.2870
Helium	2.0769
Argon	0.2081
Nitrogen	0.2968

Different substances have different gas constants.

$$w = \int_{v_1}^{v_2} P\,dv$$

Mass = Molar mass × Mole number

$$m = MN \quad (\text{kg})$$

$$V = mv \longrightarrow \boxed{PV = mRT}$$

$$mR = (MN)R = NR_u \longrightarrow PV = NR_uT$$

$$V = N\bar{v} \longrightarrow P\bar{v} = R_uT$$

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

Ideal gas equation at two states for a fixed mass

$$PV = NR_uT \qquad (\text{kJ/(kmol} \cdot \text{K)})$$

Various expressions of ideal gas equation

Per unit mass	Per unit mole
v, m³/kg	$\bar{v}$, m³/kmol
u, kJ/kg	$\bar{u}$, kJ/kmol
h, kJ/kg	$\bar{h}$, kJ/kmol

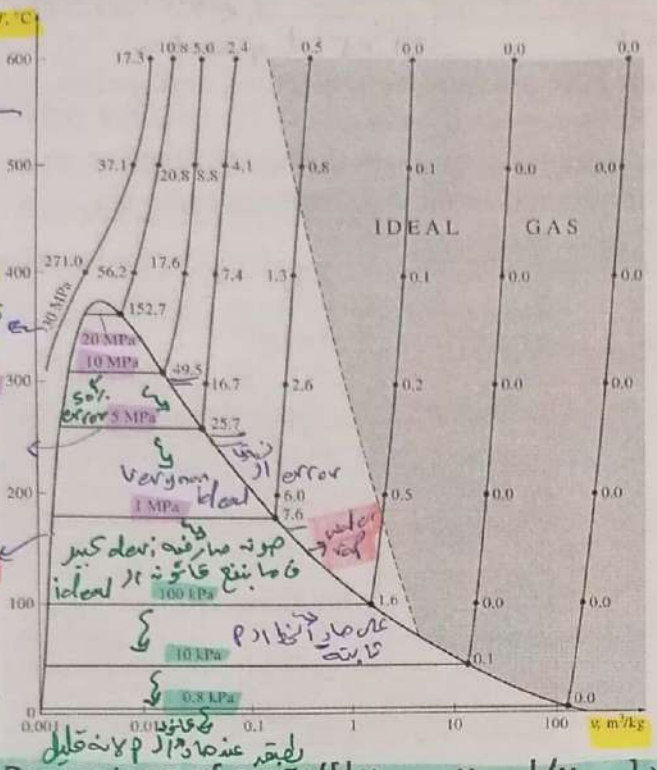
Properties per unit mole are denoted with a bar on the top.

- Real gases behave as an ideal gas at low densities (i.e., low pressure, high temperature).
- The ideal-gas relation often is not applicable to real gases; thus, care should be exercised when using it.

CamScanner الممسوحة ضوئيا بـ

17th

Is Water Vapor an Ideal Gas?



- At pressures below 10 kPa, water vapor can be treated as an ideal gas, regardless of its temperature, with negligible error (less than 0.1 percent).
- At higher pressures, however, the ideal gas assumption yields unacceptable errors, particularly in the vicinity of the critical point and the saturated vapor line.
- In air-conditioning applications, the water vapor in the air can be treated as an ideal gas. Why?
- In steam power plant applications, however, the pressures involved are usually very high; therefore, ideal-gas relations should not be used.

Percentage of error ($[|v_{table} - v_{ideal}|/v_{table}] \times 100$) involved in assuming steam to be an ideal gas, and the region where steam can be treated as an ideal gas with less than 1 percent error.

27

18th

COMPRESSIBILITY FACTOR—A MEASURE OF DEVIATION FROM IDEAL-GAS BEHAVIOR

Compressibility factor Z A factor that accounts for the deviation of real gases from ideal-gas behavior at a given temperature and pressure.

$$Pv = ZRT$$

$$Z = \frac{Pv}{RT} \qquad Z = \frac{v_{actual}}{v_{ideal}}$$

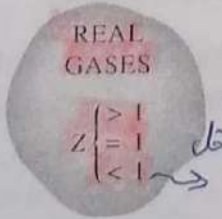
The farther away Z is from unity, the more the gas deviates from ideal-gas behavior.

Gases behave as an ideal gas at low densities (i.e., low pressure, high temperature).

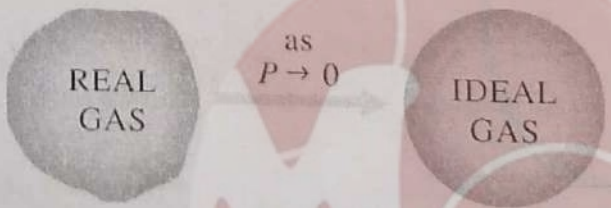
Question: What is the criteria for low pressure and high temperature?

Answer: The pressure or temperature of a gas is high or low relative to its critical temperature or pressure.





The compressibility factor is unity for ideal gases.



At very low pressures, all gases approach ideal-gas behavior (regardless of their temperature).

CamScanner الممسوحة ضوئيا بـ

Reduced Properties

Reduced pressure

$$P_R = \frac{P}{P_{cr}}$$

P_{cr} ← critical point pressure

Reduced temperature

$$T_R = \frac{T}{T_{cr}}$$

T ← actual condition point

T_{cr} ← critical point temp

Pseudo-reduced specific volume

$$v_R = \frac{v_{actual}}{RT_{cr}/P_{cr}}$$

- The Z factor is approximately the same for all gases at the same reduced temperature and reduced pressure, which are defined as

$$T_R = \frac{T}{T_{cr}} \quad \text{and} \quad P_R = \frac{P}{P_{cr}}$$

where P_{cr} and T_{cr} are the critical pressure and temperature, respectively.

- This is known as the *principle of corresponding states*.

Compressibility factor

The pvT properties of a component are expressed in terms of compressibility factor (Z) and Z can be related to p, T, and v (or V) as below:

$$Z = \frac{pV}{nRT} \qquad Z = \frac{pv}{RT} \quad (n = 1)$$

For ideal gas: $Z = 1.0$

For liquids: $Z = 0.01$ to 0.2 [9]

Z at the critical point is usually in the range of 0.27 to 0.29. For most substances, Z_c is 0.27.

$$\left.\begin{aligned} P_R &= \frac{P}{P_{cr}} \\ v_R &= \frac{v}{RT_{cr}/P_{cr}} \end{aligned}\right\} Z = \ldots \text{ (Fig. A–15)}$$

Z can also be determined from a knowledge of P_R and v_R.

Comparison of Z Factors for Various Gases

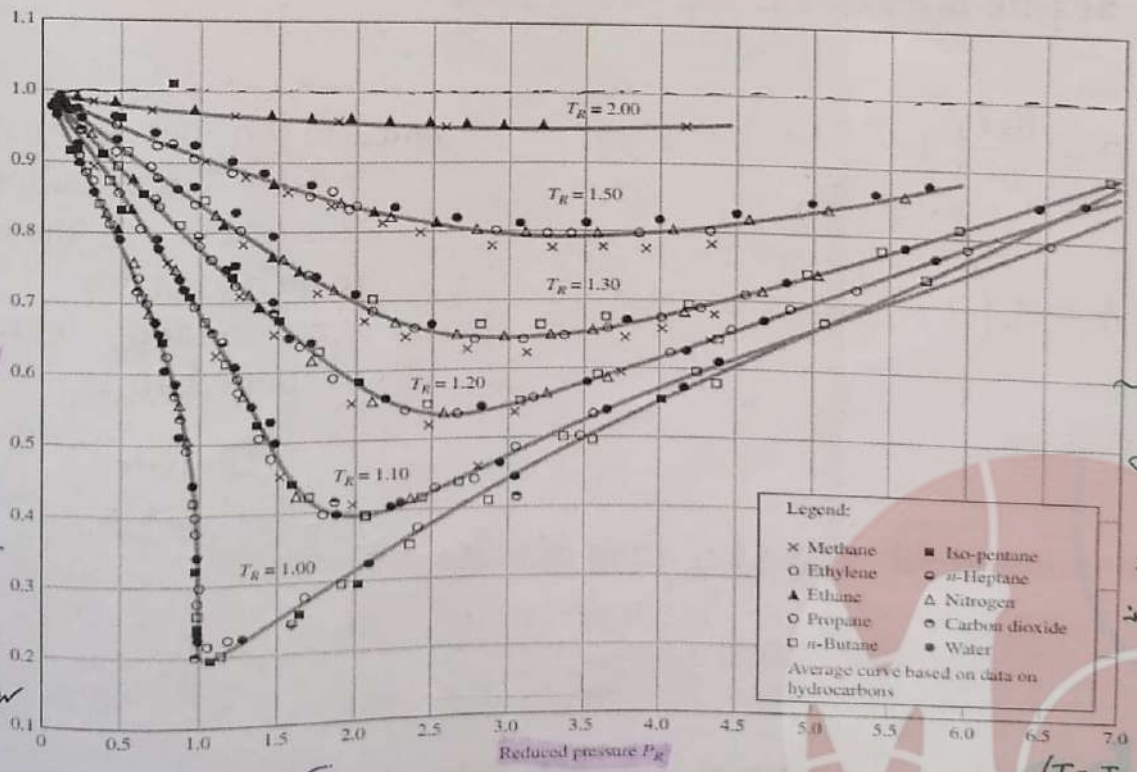


FIGURE 3–47
Comparison of Z factors for various gases.
Source: Gour-Jen Su, "Modified Law of Corresponding States," Ind. Eng. Chem. (International ed.) 38 (1946), p. 803.

CamScanner الممسوحة ضوئيا بـ

OTHER EQUATIONS OF STATE

Several equations have been proposed to represent the ***P-v-T*** behavior of substances accurately over a larger region with no limitations.

van der Waals
Berthelet
Redlich-Kwang
Beattie-Bridgeman
Benedict-Webb-Rubin
Strobridge
Virial

Van der Waals Equation of State

$$\left(P + \frac{a}{v^2}\right)(v - b) = RT$$

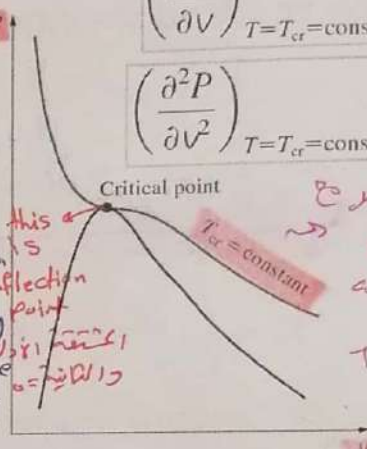
$$a = \frac{27R^2T_{cr}^2}{64P_{cr}} \qquad b = \frac{RT_{cr}}{8P_{cr}}$$

This model includes two effects not considered in the ideal-gas model: the *intermolecular attraction forces* and the *volume occupied by the molecules themselves*. The accuracy of the van der Waals equation of state is often inadequate.

Critical isotherm of a pure substance has an inflection point at the critical state.

$$\left(\frac{\partial P}{\partial v}\right)_{T=T_{cr}=\text{const}} = 0$$

$$\left(\frac{\partial^2 P}{\partial v^2}\right)_{T=T_{cr}=\text{const}} = 0$$



Beattie-Bridgeman Equation of State

$$P = \frac{R_u T}{\bar{v}^2}\left(1 - \frac{c}{\bar{v}T^3}\right)(\bar{v} + B) - \frac{A}{\bar{v}^2}$$

$$A = A_0\left(1 - \frac{a}{\bar{v}}\right) \qquad B = B_0\left(1 - \frac{b}{\bar{v}}\right)$$

The constants are given in Table 3–4 for various substances. It is known to be reasonably accurate for densities up to about $0.8\rho_{cr}$.

Benedict-Webb-Rubin Equation of State

$$P = \frac{R_u T}{\bar{v}} + \left(B_0 R_u T - A_0 - \frac{C_0}{T^2}\right)\frac{1}{\bar{v}^2} + \frac{bR_u T - a}{\bar{v}^3} + \frac{a\alpha}{\bar{v}^6} + \frac{c}{\bar{v}^3 T^2}\left(1 + \frac{\gamma}{\bar{v}^2}\right)e^{-\gamma/\bar{v}^2}$$

The constants are given in Table 3–4. This equation can handle substances at densities up to about 2.5 ρ_{cr}.

Qadar ask & believe & recieve

الممسوحة ضوئيا بـ CamScanner

Examples

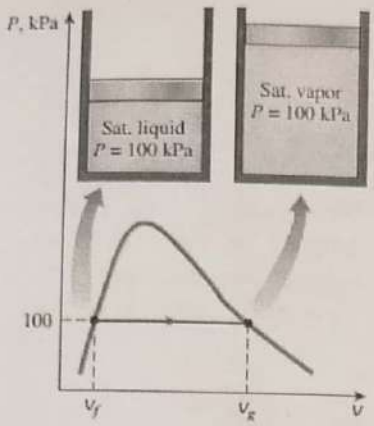


FIGURE 3–30
Schematic and *P-v* diagram for Example 3–3.

EXAMPLE 3–3 Volume and Energy Change during Evaporation

A mass of 200 g of saturated liquid water is completely vaporized at a constant pressure of 100 kPa. Determine (*a*) the volume change and (*b*) the amount of energy transferred to the water.

SOLUTION Saturated liquid water is vaporized at constant pressure. The volume change and the energy transferred are to be determined.

Analysis (*a*) The process described is illustrated on a *P-v* diagram in Fig. 3–30. The volume change per unit mass during a vaporization process is v_{fg}, which is the difference between v_g and v_f. Reading these values from Table A–5 at 100 kPa and substituting yield

$$v_{fg} = v_g - v_f = 1.6941 - 0.001043 = 1.6931 \text{ m}^3/\text{kg}$$

Thus,

$$\Delta V = mv_{fg} = (0.2 \text{ kg})(1.6931 \text{ m}^3/\text{kg}) = 0.3386 \text{ m}^3$$

(*b*) The amount of energy needed to vaporize a unit mass of a substance at a given pressure is the enthalpy of vaporization at that pressure, which is h_{fg} = 2257.5 kJ/kg for water at 100 kPa. Thus, the amount of energy transferred is

$$mh_{fg} = (0.2 \text{ kg})(2257.5 \text{ kJ/kg}) = 451.5 \text{ kJ}$$

Discussion Note that we have considered the first four decimal digits of v_{fg} and disregarded the rest. This is because v_g has significant numbers to the first four decimal places only, and we do not know the numbers in the other decimal places. Copying all the digits from the calculator would mean that we are assuming v_g = 1.694100, which is not necessarily the case. It could very well be that v_g = 1.694138 since this number, too, would truncate to 1.6941. All the digits in our result (1.6931) are significant. But if we did not truncate the result, we would obtain v_{fg} = 1.693057, which falsely implies that our result is accurate to the sixth decimal place.

EXAMPLE 3–4 Pressure and Volume of a Saturated Mixture

A rigid tank contains 10 kg of water at 90°C. If 8 kg of the water is in the liquid form and the rest is in the vapor form, determine (*a*) the pressure in the tank and (*b*) the volume of the tank.

SOLUTION A rigid tank contains saturated mixture. The pressure and the volume of the tank are to be determined.

Analysis (*a*) The state of the saturated liquid–vapor mixture is shown in Fig. 3–35. Since the two phases coexist in equilibrium, we have a saturated mixture, and the pressure must be the saturation pressure at the given temperature:

$$P = P_{\text{sat @ 90°C}} = 70.183 \text{ kPa} \qquad \text{(Table A–4)}$$

(*b*) At 90°C, we have v_f = 0.001036 m³/kg and v_g = 2.3593 m³/kg (Table A–4). One way of finding the volume of the tank is to determine the volume occupied by each phase and then add them:

$$V = V_f + V_g = m_f v_f + m_g v_g$$
$$= (8 \text{ kg})(0.001036 \text{ m}^3/\text{kg}) + (2 \text{ kg})(2.3593 \text{ m}^3/\text{kg})$$
$$= 4.73 \text{ m}^3$$

Another way is to first determine the quality *x*, then the average specific volume *v*, and finally the total volume:

$$x = \frac{m_g}{m_t} = \frac{2 \text{ kg}}{10 \text{ kg}} = 0.2$$

$$v = v_f + xv_{fg}$$
$$= 0.001036 \text{ m}^3/\text{kg} + (0.2)[(2.3593 - 0.001036) \text{ m}^3/\text{kg}]$$
$$= 0.473 \text{ m}^3/\text{kg}$$

and

$$V = mv = (10 \text{ kg})(0.473 \text{ m}^3/\text{kg}) = 4.73 \text{ m}^3$$

Discussion The first method appears to be easier in this case since the masses of each phase are given. In most cases, however, the masses of each phase are not available, and the second method becomes more convenient.

CamScanner الممسوحة ضوئيا بـ

EXAMPLE 3–5 **Properties of Saturated Liquid–Vapor Mixture**

An 80-L vessel contains 4 kg of refrigerant-134a at a pressure of 160 kPa. Determine (*a*) the temperature, (*b*) the quality, (*c*) the enthalpy of the refrigerant, and (*d*) the volume occupied by the vapor phase.

SOLUTION A vessel is filled with refrigerant-134a. Some properties of the refrigerant are to be determined.

Analysis (*a*) The state of the saturated liquid–vapor mixture is shown in Fig. 3–36. At this point we do not know whether the refrigerant is in the compressed liquid, superheated vapor, or saturated mixture region. This can be determined by comparing a suitable property to the saturated liquid and saturated vapor values. From the information given, we can determine the specific volume:

$$v = \frac{V}{m} = \frac{0.080\ \text{m}^3}{4\ \text{kg}} = 0.02\ \text{m}^3/\text{kg}$$

At 160 kPa, we read

$$v_f = 0.0007435\ \text{m}^3/\text{kg}$$
$$v_g = 0.12355\ \text{m}^3/\text{kg} \qquad \text{(Table A–12)}$$

Obviously, $v_f < v < v_g$, and, the refrigerant is in the saturated mixture region. Thus, the temperature must be the saturation temperature at the specified pressure:

$$T = T_{\text{sat @ 160 kPa}} = -15.60°\text{C}$$

(*b*) Quality can be determined from

$$x = \frac{v - v_f}{v_{fg}} = \frac{0.02 - 0.0007435}{0.12355 - 0.0007435} = 0.157$$

(*c*) At 160 kPa, we also read from Table A–12 that $h_f = 31.18$ kJ/kg and $h_{fg} = 209.96$ kJ/kg. Then,

$$h = h_f + xh_{fg}$$
$$= 31.18\ \text{kJ/kg} + (0.157)(209.96\ \text{kJ/kg})$$
$$= 64.1\ \text{kJ/kg}$$

(*d*) The mass of the vapor is

$$m_g = xm_t = (0.157)(4\ \text{kg}) = 0.628\ \text{kg}$$

and the volume occupied by the vapor phase is

$$V_g = m_g v_g = (0.628\ \text{kg})(0.12355\ \text{m}^3/\text{kg}) = 0.0776\ \text{m}^3\ (\text{or } 77.6\ \text{L})$$

The rest of the volume (2.4 L) is occupied by the liquid.

CamScanner الممسوحة ضوئيا بـ

EXAMPLE 3–11 The Use of Generalized Charts

Determine the specific volume of refrigerant-134a at 1 MPa and 50°C, using (a) the ideal-gas equation of state and (b) the generalized compressibility chart. Compare the values obtained to the actual value of 0.021796 m³/kg and determine the error involved in each case.

SOLUTION The specific volume of refrigerant-134a is to be determined assuming ideal- and nonideal-gas behavior.

Analysis The gas constant, the critical pressure, and the critical temperature of refrigerant-134a are determined from Table A–1 to be

$$R = 0.0815 \text{ kPa·m}^3\text{/kg·K}$$
$$P_{cr} = 4.059 \text{ MPa}$$
$$T_{cr} = 374.2 \text{ K}$$

(a) The specific volume of refrigerant-134a under the ideal-gas assumption is

$$v = \frac{RT}{P} = \frac{(0.0815 \text{ kPa·m}^3\text{/kg·K})(323 \text{ K})}{1000 \text{ kPa}} = 0.026325 \text{ m}^3\text{/kg}$$

Therefore, treating the refrigerant-134a vapor as an ideal gas would result in an error of (0.026325 − 0.021796)/0.021796 = 0.208, or 20.8 percent in this case.

(b) To determine the correction factor Z from the compressibility chart, we first need to calculate the reduced pressure and temperature:

$$P_R = \frac{P}{P_{cr}} = \frac{1 \text{ MPa}}{4.059 \text{ MPa}} = 0.246$$
$$T_R = \frac{T}{T_{cr}} = \frac{323 \text{ K}}{374.2 \text{ K}} = 0.863$$
$$\Rightarrow Z = 0.84$$

Thus

$$v = Zv_{ideal} = (0.84)(0.026325 \text{ m}^3\text{/kg}) = 0.022113 \text{ m}^3\text{/kg}$$

Discussion The error in this result is less than 2 percent. Therefore, in the absence of tabulated data, the generalized compressibility chart can be used with confidence.

Exercises

3–23 Complete this table for H_2O:

T, °C	P, kPa	v, m³/kg	Phase description
140		0.05	
	550		Saturated liquid
125	750		
500		0.140	

3–26 Complete this table for refrigerant-134a:

T, °C	P, kPa	v, m³/kg	Phase description
−4	320		
10		0.0065	
	850		Saturated vapor
90	600		

CamScanner الممسوحة ضوئيا بـ

31 + 36 + 37 + 38 + 39 + 40 + 41 + 43

T(°C)	P(kPa)	U(kJ/kg)	phase composition
143.61	400	1450	Sat mix (because $U_f < U < U_g$)
220	2319.6	2801.3	Sat. vap
190	2500	805.05	compressed liq
466.2	4000	3040	superheated

* إذا أعطانا P لحال ← طلع الـ T (إذا كانت sat) والعكس (كلها في sat dependency)
* أما إذا أعطانا (T و P) مع بعض في حال الـ sat يكون (بصور حالة one phase) (مش حالة mix)
↳ Sup or compressed

← بالنوع التالي رح نروح إما لـ super أو compressed.

بنروح على A-6 عند الـ superheated مثال 190 والـ 2.5 ← بناءً إنه الحرارة أكبر من 190 مثال 2.5 MPa
(so not applicable)

← بنروح على A-7 ← بناءً إنه الـ P أكبر من 2.5 بروح في بنقربها (عشوائيا)
لـ compressed الـ P مش كتير بتأثر على الـ T إنها تأثر بشكل كبير)

we interpolate in 3rd one

Radar ask & believe & recieve

الممسوحة ضوئيا بـ CamScanner



Chapter 4

ENERGY ANALYSIS OF CLOSED SYSTEMS (Control Mass)

Thermodynamics: An Engineering Approach
Yunus A. Cengel, Michael A. Boles, Mehmet Kanoglu
McGraw-Hill

شو الفرق بين الـ E_{in} والـ E_{out} والـ ΔE !

Dr. Ahmad M. AbuYaghi
October 2023

MOVING BOUNDARY WORK

صوأ حدأ نواعي الـ work المرتبط بالحركة (moving boundary) زي الغاز لما يتمدد (كل ذرة بتضغط عالذرة اللي جنبها ت)

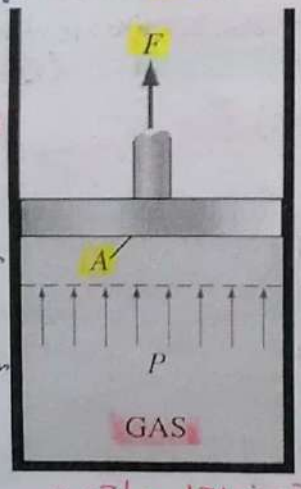
Moving boundary work (*P dV* work):
The expansion and compression work in a piston-cylinder device.

Quasi-equilibrium process:
A process during which the system remains nearly in equilibrium at all times.

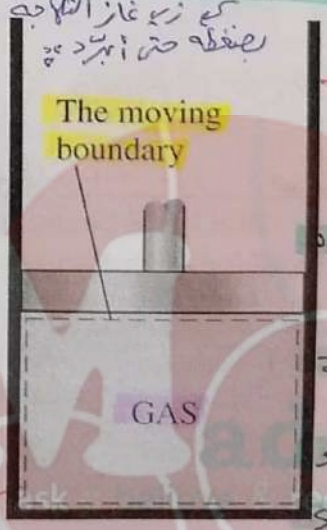
$$\delta W_b = F\,ds = PA\,ds = P\,dV$$

$$W_b = \int_1^2 P\,dV \quad (\text{kJ})$$

W_b is positive → for expansion
W_b is negative → for compression

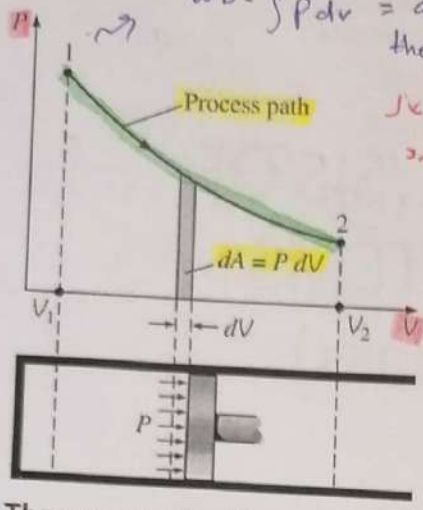


A gas does a differential amount of work δW_b as it forces the piston to move by a differential amount *ds*.



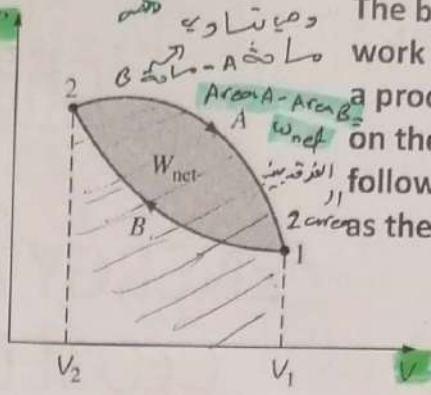
The work associated with a moving boundary is called *boundary work*.

CamScanner الممسوحة ضوئيا بـ

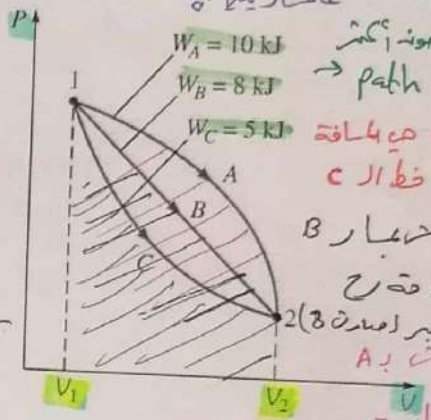


The area under the process curve on a *P-V* diagram represents the boundary work.

$$\text{Area} = A = \int_1^2 dA = \int_1^2 P\,dV$$



The boundary work done during a process depends on the path followed as well as the end states.



The net work done during a cycle is the difference between the work done by the system and the work done on the system.

Polytropic, Isothermal, and Isobaric processes

Polytropic process: C, n (polytropic exponent) constants

$$P = CV^{-n}$$

$$W_b = \int_1^2 P\,dV = \int_1^2 CV^{-n}\,dV = C\frac{V_2^{-n+1} - V_1^{-n+1}}{-n+1} = \frac{P_2V_2 - P_1V_1}{1-n}$$

Polytropic and for ideal gas

$$W_b = \frac{mR(T_2 - T_1)}{1-n}$$

When $n = 1$ (isothermal process)

$$W_b = \int_1^2 P\,dV = \int_1^2 CV^{-1}\,dV = RV\ln\left(\frac{V_2}{V_1}\right)$$

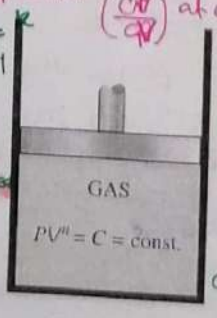
Constant pressure process

$$W_b = \int_1^2 P\,dV = P_0\int_1^2 dV = P_0(V_2 - V_1)$$

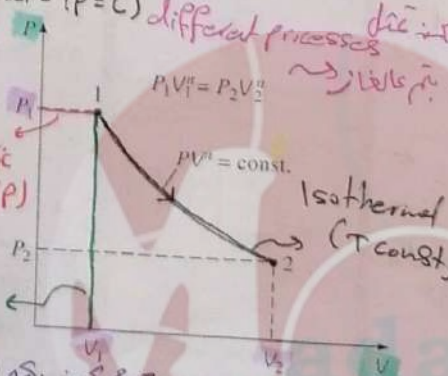
Q: What is the boundary work for a constant-volume process? equal zero

$$W_b = 0$$

because $W_b = \int P\Delta V$



Schematic and *P-V* diagram for a polytropic process.



ENERGY BALANCE FOR CLOSED SYSTEMS

$$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic, potential, etc., energies}} \quad \text{(kJ)}$$

Energy balance for any system undergoing any process

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} \quad \text{(kW)}$$

Energy balance in the rate form

The total quantities are related to the quantities per unit time is:

$$Q = \dot{Q}\Delta t, \quad W = \dot{W}\Delta t, \quad \text{and} \quad \Delta E = (dE/dt)\Delta t \quad \text{(kJ)}$$

$$e_{in} - e_{out} = \Delta e_{system} \quad \text{(kJ/kg)}$$

Energy balance per unit mass basis

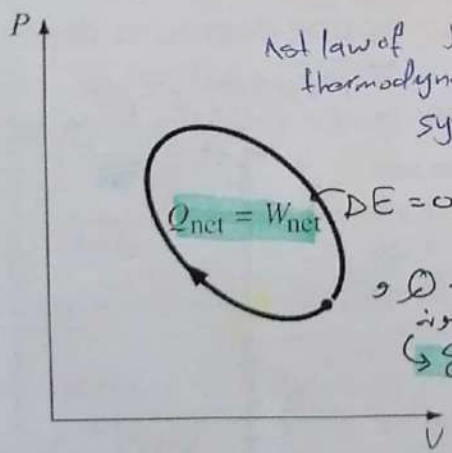
$$W_{net,out} = Q_{net,in} \quad \text{or} \quad \dot{W}_{net,out} = \dot{Q}_{net,in}$$

Energy balance for a cycle

$$Q_{net,in} - W_{net,out} = \Delta E_{system} \quad \text{or} \quad Q - W = \Delta E$$

$$Q = Q_{net,in} = Q_{in} - Q_{out}$$
$$W = W_{net,out} = W_{out} - W_{in}$$

Energy balance when sign convention is used (i.e., heat input and work output are positive; heat output and work input are negative).



For a cycle $\Delta E = 0$, thus $Q = W$.

General	$Q - W = \Delta E$
Stationary systems	$Q - W = \Delta U$
Per unit mass	$q - w = \Delta e$
Differential form	$\delta q - \delta w = de$

Various forms of the first-law relation for closed systems when sign convention is used.

The first law cannot be proven mathematically, but no process in nature is known to have violated the first law, and this should be taken as sufficient proof.

الممسوحة ضوئيا بـ CamScanner

Energy balance for a constant-pressure expansion or compression process

General analysis for a closed system undergoing a quasi-equilibrium constant-pressure process. *Q* is *to* the system and *W* is *from* the system.

For a constant-pressure expansion or compression process:

$$\Delta U + W_b = \Delta H$$

$$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic, potential, etc., energies}}$$

$$Q - W = \Delta U + \Delta KE^{\nearrow 0} + \Delta PE^{\nearrow 0}$$

$$Q - W_{other} - W_b = U_2 - U_1$$

$$Q - W_{other} - P_0(V_2 - V_1) = U_2 - U_1$$

$$Q - W_{other} = (U_2 + P_2V_2) - (U_1 + P_1V_1)$$

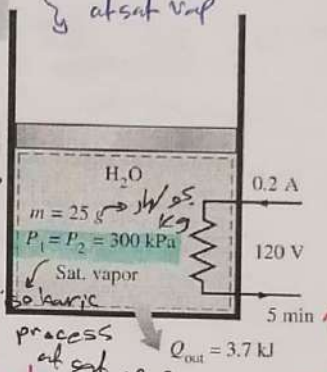
$$H = U + PV$$

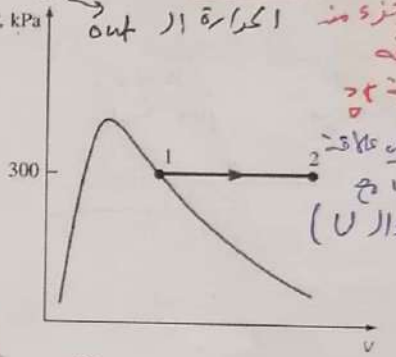
$$Q - W_{other} = H_2 - H_1$$

An example of constant-pressure process

$$W_{e,in} - Q_{out} - W_b = \Delta U \quad \text{(isobaric, const P)}$$

$$W_{e,in} - Q_{out} = \Delta H = m(h_2 - h_1)$$

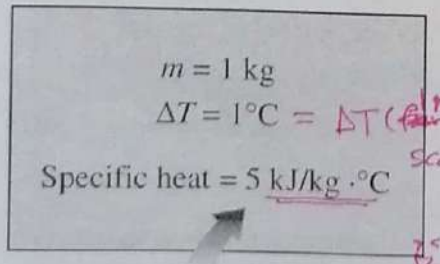




SPECIFIC HEATS

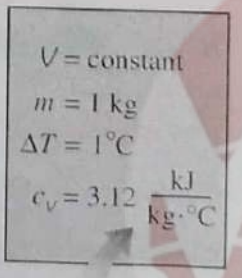
Specific heat at constant volume, c_v: The energy required to raise the temperature of the unit mass of a substance by one degree as the volume is maintained constant.

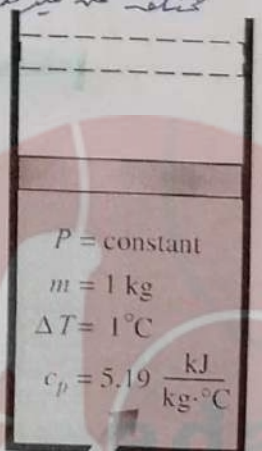
Specific heat at constant pressure, c_p: The energy required to raise the temperature of the unit mass of a substance by one degree as the pressure is maintained constant.



Specific heat is the energy required to raise the temperature of a unit mass of a substance by one degree in a specified way.

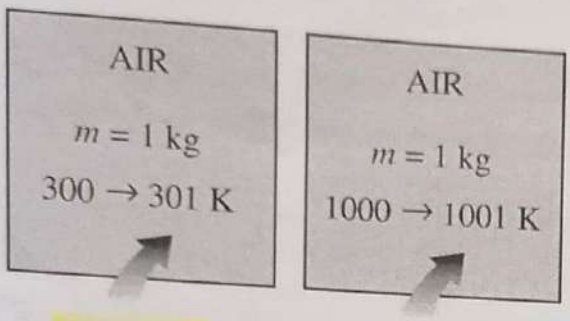
Constant-volume and constant-pressure specific heats c_v and c_p (values are for helium gas).





CamScanner الممسوحة ضوئيا بـ

- The equations in the figure are valid for *any* substance undergoing *any* process.
- c_v and c_p are properties.
- c_v is related to the changes in *internal energy* and c_p to the changes in *enthalpy*.
- A common unit for specific heats is kJ/kg · °C or kJ/kg · K. ***Are these units identical?***



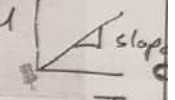
0.718 kJ 0.855 kJ

The specific heat of a substance changes with temperature.

Q: True or False:
c_p is always greater than c_v

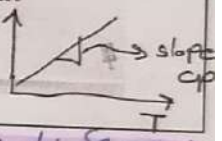
$\Delta U = \int c_v dT$

$c_v = \left(\frac{\partial u}{\partial T}\right)_v$ = the change in internal energy with temperature at constant volume



Formal definitions of c_v and c_p.

$c_p = \left(\frac{\partial h}{\partial T}\right)_p$ = the change in enthalpy with temperature at constant pressure



$c_p > c_v$ always

$R = c_p - c_v$ (only on ideal gas)

because $h = u + pv$, so $h > u$

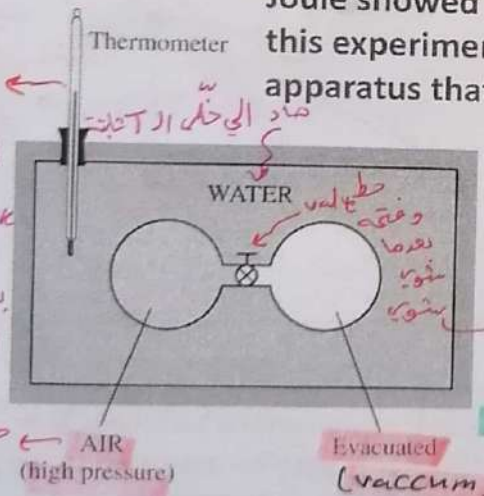
$\frac{dh}{dT} > \frac{du}{dT} \Rightarrow c_p > c_v$

In real gas it differ ;

* In liq & solid $c_p = c_v = c$ (because they are incompressible)

INTERNAL ENERGY, ENTHALPY, and SPECIFIC HEATS OF IDEAL GASES

Joule showed using this experimental apparatus that $u = u(T)$



$$\left.\begin{aligned} h &= u + Pv \\ Pv &= RT \end{aligned}\right\} \quad h = u + RT$$

$u = u(T)$ $h = h(T)$

$du = c_v(T)\,dT$ $dh = c_p(T)\,dT$

also c_v & c_p depend on Temp (not depend on P)

$$\Delta u = u_2 - u_1 = \int_1^2 c_v(T)\,dT$$

$$\Delta h = h_2 - h_1 = \int_1^2 c_p(T)\,dT$$

ΔU & ΔH ← c_v & c_p

$$\Delta H = \int_{T_1}^{T_2} c_p dT = \int_{T_1}^{T_2} (a + bT + cT^2 + dT^3)\,dT$$

$$\Delta H = \left(a\,dT + bT\,dT + cT^2\,dT\right)\Big|_{T_1}^{T_2}$$

$$\Delta H = aT + b\frac{T^2}{2} + c\frac{T^3}{3}\Big|_{T_1}^{T_2}$$

$u = u(T)$
$h = h(T)$
$c_v = c_v(T)$
$c_p = c_p(T)$

For ideal gases, u, h, c_v, and c_p vary with temperature only.

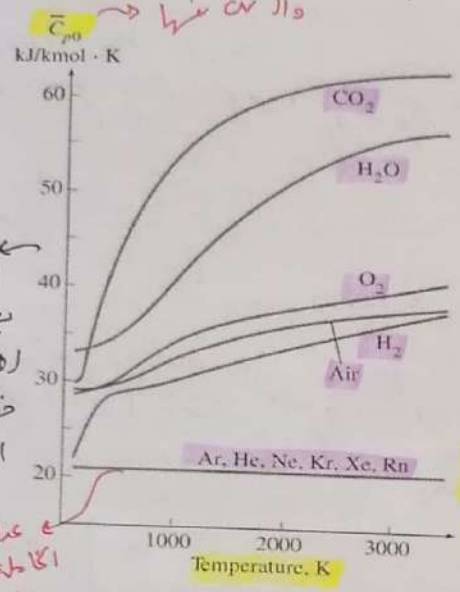
Internal energy and enthalpy change of an ideal gas because they are fun on T

$c_v(T)$

$c_p(T)$

الممسوحة ضوئيا بـ CamScanner

- At low pressures, all real gases approach ideal-gas behavior, and therefore their specific heats depend on temperature only.
- The specific heats of real gases at low pressures are called *ideal-gas specific heats*, or *zero-pressure specific heats*, and are often denoted c_{p0} and c_{v0}.



Ideal-gas constant-pressure specific heats for some gases (see Table A–2c for c_p equations).

- u and h data for a number of gases have been tabulated.
- These tables are obtained by choosing an arbitrary reference point and performing the integrations by treating state 1 as the reference state.

AIR

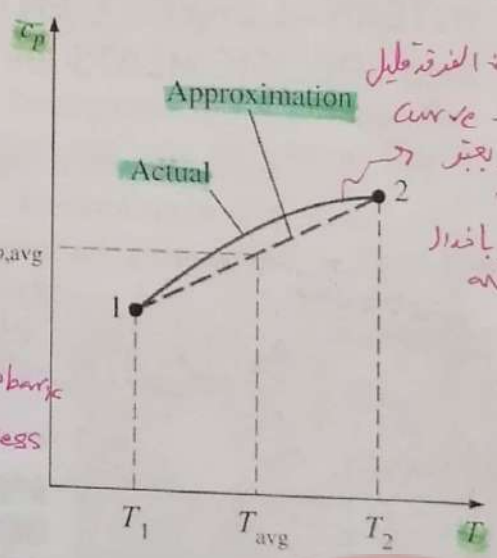
T, K	u, kJ/kg	h, kJ/kg
0	0	0
.	.	.
.	.	.
300	214.07	300.19
310	221.25	310.24
.	.	.
.	.	.

In the preparation of ideal-gas tables, 0 K is chosen as the reference temperature.

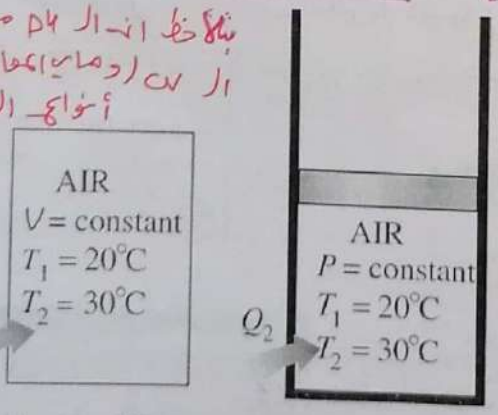
Internal energy and enthalpy change when specific heat is taken constant at an average value:

$$\Delta u = u_2 - u_1 = c_{v,\text{avg}}(T_2 - T_1) \quad \text{(kJ/kg)}$$

$$\Delta h = h_2 - h_1 = c_{p,\text{avg}}(T_2 - T_1)$$



For small temperature intervals, the specific heats may be assumed to vary linearly with temperature.



$\Delta u = c_v \Delta T = 7.18$ kJ/kg

$\Delta u = c_v \Delta T = 7.18$ kJ/kg

The relation $\Delta u = c_v \Delta T$ is valid for any kind of process, constant-volume or not.

CamScanner الممسوحة ضوئيا بـ

Three ways of calculating Δu and Δh

1. By using the tabulated u and h data. This is the easiest and ***most accurate*** way when tables are readily available.
2. By using the c_v or c_p relations (Table A-2c) as a function of temperature and performing the integrations. This is very inconvenient for hand calculations but quite desirable for computerized calculations. The results obtained are ***very accurate.***
3. By using average specific heats. This is very simple and certainly very convenient when property tables are not available. The results obtained are ***reasonably accurate*** if the temperature interval is not very large.

$$\Delta u = u_2 - u_1 \text{ (table)}$$

$$\Delta u = \int_1^2 c_v(T)\, dT$$

$$\Delta u \cong c_{v,\text{avg}}\, \Delta T$$

Three ways of calculating Δu.

13

Specific Heat Relations of Ideal Gases

$$h = u + RT \quad (R = \text{const})$$

$$dh = du + R\,dT$$

$dh = c_p dT$ and $du = c_v dT$

The relationship between c_p, c_v and R

$$c_p = c_v + R \qquad (\text{kJ/kg} \cdot \text{K})$$

On a molar basis

$$\bar{c}_p = \bar{c}_v + R_u \qquad (\text{kJ/kmol} \cdot \text{K})$$

Specific heat ratio:

$$k = \frac{c_p}{c_v}$$

AIR at 300 K

$$\left.\begin{matrix} c_v = 0.718 \text{ kJ/kg} \cdot \text{K} \\ R = 0.287 \text{ kJ/kg} \cdot \text{K} \end{matrix}\right\} c_p = 1.005 \text{ kJ/kg} \cdot \text{K}$$

or

$$\left.\begin{matrix} \bar{c}_v = 20.80 \text{ kJ/kmol} \cdot \text{K} \\ R_u = 8.314 \text{ kJ/kmol} \cdot \text{K} \end{matrix}\right\} \bar{c}_p = 29.114 \text{ kJ/kmol} \cdot \text{K}$$

The c_p of an ideal gas can be determined from a knowledge of c_v and R.

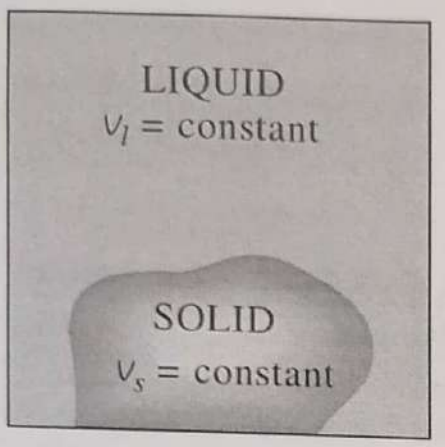
- The specific ratio varies with temperature, but this variation is very mild.
- For monatomic gases (helium, argon, etc.), its value is essentially constant at 1.667.
- Many diatomic gases, including air, have a specific heat ratio of about 1.4 at room temperature.

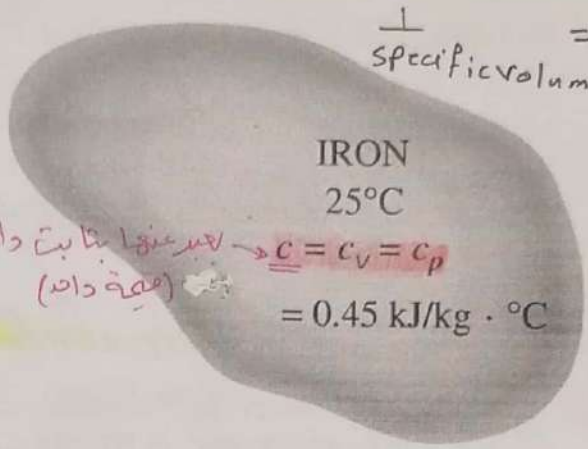
CamScanner الممسوحة ضوئيا بـ

INTERNAL ENERGY, ENTHALPY, and SPECIFIC HEATS OF SOLIDS AND LIQUIDS

Incompressible substance: A substance whose specific volume (or density) is constant. **Solids and liquids** are incompressible substances.

$\frac{1}{\text{specific volume}}$ = density





The specific volumes of incompressible substances remain constant during a process.

The c_v and c_p values of incompressible substances are identical and are denoted by c.

15

Internal Energy Changes

$$du = c_v\,dT = c(T)\,dT$$

$$\Delta u = u_2 - u_1 = \int_1^2 c(T)\,dT \qquad \text{(kJ/kg)}$$

$$\Delta u \cong c_{avg}(T_2 - T_1) \qquad \text{(kJ/kg)}$$

Enthalpy Changes

$$h = u + Pv \quad (Pv \approx 0 \text{ for liq \& solid})$$

$$dh = du + v\,dP + P\,dv = du + v\,dP$$

$$\Delta h = \Delta u + v\,\Delta P \cong c_{avg}\,\Delta T + v\,\Delta P \qquad \text{(kJ/kg)}$$

For *solids*, the term $v\,\Delta P$ is insignificant and thus $\Delta h = \Delta u \cong c_{avg}\Delta T$. For *liquids*, two special cases are commonly encountered:

1. *Constant-pressure processes*, as in heaters ($\Delta P = 0$): $\Delta h = \Delta u \cong c_{avg}\Delta T$
2. *Constant-temperature processes*, as in pumps ($\Delta T = 0$): $\Delta h = v\,\Delta P$

$$h_{@P,T} \cong h_{f@T} + v_{f@T}(P - P_{sat@T})$$

A more accurate relation than

The enthalpy of a compressed liquid

CamScanner الممسوحة ضوئيا بـ

EXAMPLE 4–1 Boundary Work for a Constant-Volume Process

A rigid tank contains air at 500 kPa and 150°C. As a result of heat transfer to the surroundings, the temperature and pressure inside the tank drop to 65°C and 400 kPa, respectively. Determine the boundary work done during this process.

SOLUTION Air in a rigid tank is cooled, and both the pressure and temperature drop. The boundary work done is to be determined.

Analysis A sketch of the system and the *P-V* diagram of the process are shown in Fig. 4–6. The boundary work can be determined from Eq. 4–2 to be

$$W_b = \int_1^2 P\,dV = 0$$

Discussion This is expected since a rigid tank has a constant volume and $dV = 0$ in this equation. Therefore, there is no boundary work done during this process. That is, the boundary work done during a constant-volume process is always zero. This is also evident from the *P-V* diagram of the process (the area under the process curve is zero).

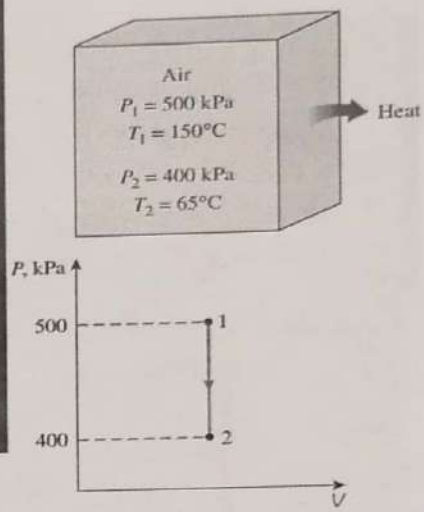


FIGURE 4–6
Schematic and *P-V* diagram for Example 4–1.

EXAMPLE 4–3 Isothermal Compression of an Ideal Gas

A piston–cylinder device initially contains 0.4 m^3 of air at 100 kPa and 80°C. The air is now compressed to 0.1 m^3 in such a way that the temperature inside the cylinder remains constant. Determine the work done during this process.

SOLUTION Air in a piston–cylinder device is compressed isothermally. The boundary work done is to be determined.

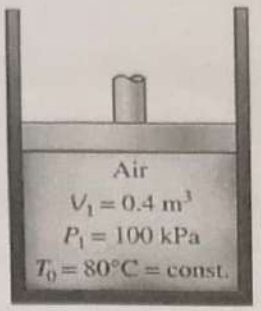
Analysis A sketch of the system and the *P-V* diagram of the process are shown in Fig. 4–8.

Assumptions 1 The compression process is quasi-equilibrium. 2 At specified conditions, air can be considered to be an ideal gas since it is at a high temperature and low pressure relative to its critical-point values.

Analysis For an ideal gas at constant temperature T_0,

$$PV = mRT_0 = C \quad \text{or} \quad P = \frac{C}{V}$$

CamScanner الممسوحة ضوئيا بـ



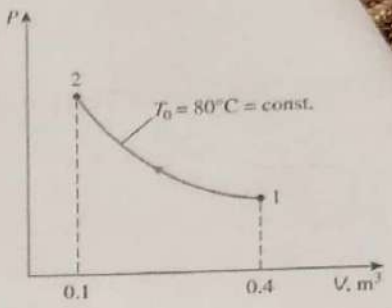


FIGURE 4–8
Schematic and *P-V* diagram for Example 4–3.

where C is a constant. Substituting this into Eq. 4–2, we have

$$W_b = \int_1^2 P\,dV = \int_1^2 \frac{C}{V}\,dV = C\int_1^2 \frac{dV}{V} = C \ln \frac{V_2}{V_1} = P_1V_1 \ln \frac{V_2}{V_1} \qquad (4\text{–}7)$$

In Eq. 4–7, P_1V_1 can be replaced by P_2V_2 or mRT_0. Also, V_2/V_1 can be replaced by P_1/P_2 for this case since $P_1V_1 = P_2V_2$.

Substituting the numerical values into Eq. 4–7 yields

$$W_b = (100\ \text{kPa})(0.4\ \text{m}^3)\left(\ln \frac{0.1}{0.4}\right)\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right)$$

$$= -55.5\ \text{kJ}$$

Discussion The negative sign indicates that this work is done on the system (a work input), which is always the case for compression processes.

EXAMPLE 4–5 Electric Heating of a Gas at Constant Pressure

A piston–cylinder device contains 25 g of saturated water vapor that is maintained at a constant pressure of 300 kPa. A resistance heater within the cylinder is turned on and passes a current of 0.2 A for 5 min from a 120-V source. At the same time, a heat loss of 3.7 kJ occurs. (*a*) Show that for a closed system the boundary work W_b and the change in internal energy ΔU in the first-law relation can be combined into one term, ΔH, for a constant-pressure process. (*b*) Determine the final temperature of the steam.

SOLUTION Saturated water vapor in a piston–cylinder device expands at constant pressure as a result of heating. It is to be shown that $\Delta U + W_b = \Delta H$, and the final temperature is to be determined.

Assumptions 1 The tank is stationary and thus the kinetic and potential energy changes are zero, $\Delta KE = \Delta PE = 0$. Therefore, $\Delta E = \Delta U$ and internal energy is the only form of energy of the system that may change during this process. 2 Electrical wires constitute a very small part of the system, and thus the energy change of the wires can be neglected.

Analysis We take the contents of the cylinder, including the resistance wires, as the *system* (Fig. 4–13). This is a *closed system* since no mass crosses the system boundary during the process. We observe that a piston–cylinder device typically involves a moving boundary and thus boundary work W_b. The pressure remains constant during the process and thus $P_2 = P_1$. Also, heat is lost from the system and electrical work W_e is done on the system.

CamScanner الممسوحة ضوئيا بـ

(*a*) This part of the solution involves a general analysis for a closed system undergoing a quasi-equilibrium constant-pressure process, and thus we consider a general closed system. We take the direction of heat transfer Q to be to the system and the work W to be done by the system. We also express the work as the sum of boundary and other forms of work (such as electrical and shaft). Then, the energy balance can be expressed as

$$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic, potential, etc., energies}}$$

$$Q - W = \Delta U + \Delta KE^{\nearrow 0} + \Delta PE^{\nearrow 0}$$

$$Q - W_{other} - W_b = U_2 - U_1$$

For a constant-pressure process, the boundary work is given as $W_b = P_0(V_2 - V_1)$. Substituting this into the preceding relation gives

$$Q - W_{other} - P_0(V_2 - V_1) = U_2 - U_1$$

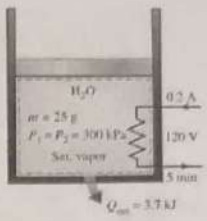
However,

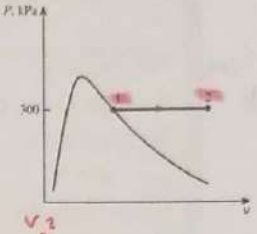
$$P_0 = P_2 = P_1 \rightarrow Q - W_{other} = (U_2 + P_2V_2) - (U_1 + P_1V_1)$$

Also $H = U + PV$, and thus

$$Q - W_{other} = H_2 - H_1 \quad \text{(kJ)} \qquad \textbf{(4–18)}$$

which is the desired relation (Fig. 4–14). This equation is very convenient to use in the analysis of closed systems undergoing a ***constant-pressure quasi-equilibrium process*** since the boundary work is automatically taken care of by the enthalpy terms, and one no longer needs to determine it separately.





$\rightarrow w_b = \int_{v_1}^{v_2} P\,dv = P(v_2 - v_1)$ ln Isobaric

$\rightarrow w_b = \int_{v_1}^{v_2} P\,dv$ (Isothermal)

ln Isothermal Ideal gas law

$PV = mRT \rightarrow$ const $= C$ ($PV = C$)

So $P_1V_1 = P_2V_2 \Rightarrow \frac{V_2}{V_1} = \frac{P_1}{P_2}$

$\rightarrow w_b = \int_{v_1}^{v_2} P\,dv = \int_{v_1}^{v_2} \frac{C}{V}\,dv$

$w_b = C\int \frac{dv}{v}$

$\therefore w_b = P_1V_1 \ln\frac{V_2}{V_1} = P_2V_2 \ln\frac{V_2}{V_1}$

$= \ln\frac{P_1}{P_2}$

(*b*) The only other form of work in this case is the electrical work, which can be determined from

$$W_e = VI\Delta t = (120\text{ V})(0.2\text{ A})(300\text{ s})\left(\frac{1\text{ kJ/s}}{1000\text{ VA}}\right) = 7.2\text{ kJ}$$

State 1: $\left.\begin{matrix} P_1 = 300\text{ kPa} \\ \text{sat. vapor} \end{matrix}\right\} h_1 = h_{g\,@\,300\text{ kPa}} = 2724.9\text{ kJ/kg}$ (Table A–5)

The enthalpy at the final state can be determined directly from Eq. 4–18 by expressing heat transfer from the system and work done on the system as negative quantities (since their directions are opposite to the assumed directions). Alternately, we can use the general energy balance relation with the simplification that the boundary work is considered automatically by replacing ΔU by ΔH for a constant-pressure expansion or compression process:

$$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic, potential, etc., energies}}$$

$$W_{e,in} - Q_{out} - W_b = \Delta U$$

$$W_{e,in} - Q_{out} = \Delta H = m(h_2 - h_1) \quad \text{(since } P = \text{constant)}$$

$$7.2\text{ kJ} - 3.7\text{ kJ} = (0.025\text{ kg})(h_2 - 2724.9)\text{ kJ/kg}$$

$$h_2 = 2864.9\text{ kJ/kg}$$

Now the final state is completely specified since we know both the pressure and the enthalpy. The temperature at this state is

State 2: $\left.\begin{matrix} P_2 = 300\text{ kPa} \\ h_2 = 2864.9\text{ kJ/kg} \end{matrix}\right\} T_2 = 200°\text{C}$ (Table A–6)

Therefore, the steam will be at 200°C at the end of this process.

CamScanner الممسوحة ضوئيا بـ

EXAMPLE 4–7 Evaluation of the Δu of an Ideal Gas

Air at 300 K and 200 kPa is heated at constant pressure (isobaric) to 600 K. Determine the change in internal energy of air per unit mass, using (*a*) data from the air table (Table A–17), (*b*) the functional form of the specific heat (Table A–2*c*), and (*c*) the average specific heat value (Table A–2*b*).

SOLUTION The internal energy change of air is to be determined in three different ways.

Assumptions At specified conditions, air can be considered to be an ideal gas since it is at a high temperature and low pressure relative to its critical-point values.

Analysis The internal energy change Δu of ideal gases depends on the initial and final temperatures only, and not on the type of process. Thus, the following solution is valid for any kind of process.

(*a*) One way of determining the change in internal energy of air is to read the u values at T_1 and T_2 from Table A–17 and take the difference:

$$u_1 = u_{@\,300\,K} = 214.07 \text{ kJ/kg}$$

$$u_2 = u_{@\,600\,K} = 434.78 \text{ kJ/kg}$$

Thus,

$$\Delta u = u_2 - u_1 = (434.78 - 214.07) \text{ kJ/kg} = 220.71 \text{ kJ/kg}$$

(*b*) The $\bar{c}_p(T)$ of air is given in Table A–2*c* in the form of a third-degree polynomial expressed as

$$\bar{c}_p(T) = a + bT + cT^2 + dT^3$$

where $a = 28.11$, $b = 0.1967 \times 10^{-2}$, $c = 0.4802 \times 10^{-5}$, and $d = -1.966 \times 10^{-9}$. From Eq. 4–30,

$$\bar{c}_v(T) = \bar{c}_p - R_u = (a - R_u) + bT + cT^2 + dT^3$$

From Eq. 4–25,

$$\Delta \bar{u} = \int_1^2 \bar{c}_v(T)\, dT = \int_{T_1}^{T_2} [(a - R_u) + bT + cT^2 + dT^3]\, dT$$

Performing the integration and substituting the values, we obtain

$$\Delta \bar{u} = 6447 \text{ kJ/kmol}$$

The change in the internal energy on a unit-mass basis is determined by dividing this value by the molar mass of air (Table A–1):

$$\Delta u = \frac{\Delta \bar{u}}{M} = \frac{6447 \text{ kJ/kmol}}{28.97 \text{ kg/kmol}} = 222.5 \text{ kJ/kg}$$

which differs from the tabulated value by 0.8 percent.

(*c*) The average value of the constant-volume specific heat $c_{v,\text{avg}}$ is determined from Table A–2*b* at the average temperature of $(T_1 + T_2)/2 = 450$ K to be

$$c_{v,\text{avg}} = c_{v\,@\,450\,K} = 0.733 \text{ kJ/kg·K}$$

Thus,

$$\Delta u = c_{v,\text{avg}}(T_2 - T_1) = (0.733 \text{ kJ/kg·K})[(600 - 300)\text{K}]$$
$$= 220 \text{ kJ/kg}$$

CamScanner الممسوحة ضوئيا بـ

EXAMPLE 4–11 **Enthalpy of Compressed Liquid**

Determine the enthalpy of liquid water at 100°C and 15 MPa (*a*) by using compressed liquid tables, (*b*) by approximating it as a saturated liquid, and (*c*) by using the correction given by Eq. 4–38.

SOLUTION The enthalpy of liquid water is to be determined exactly and approximately.

Analysis At 100°C, the saturation pressure of water is 101.42 kPa, and since $P > P_{sat}$, the water exists as a compressed liquid at the specified state.

(*a*) From compressed liquid tables, we read

$$\left.\begin{matrix} P = 15\ \text{MPa} \\ T = 100°\text{C} \end{matrix}\right\} \quad h = 430.39\ \text{kJ/kg} \qquad \text{(Table A–7)}$$

This is the exact value.

(*b*) Approximating the compressed liquid as a saturated liquid at 100°C, as is commonly done, we obtain

$$h \cong h_{f\,@\,100°\text{C}} = 419.17\ \text{kJ/kg}$$

This value is in error by about 2.6 percent.

(*c*) From Eq. 4–38,

$$h_{@P,T} \cong h_{f\,@\,T} + v_{f\,@\,T}(P - P_{sat\,@\,T})$$

$$= (419.17\ \text{kJ/kg}) + (0.001\ \text{m}^3/\text{kg})[(15{,}000 - 101.42)\ \text{kPa}]\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right)$$

$$= 434.07\ \text{kJ/kg}$$

Discussion Note that the correction term reduced the error from 2.6 to about 1 percent in this case. However, this improvement in accuracy is often not worth the extra effort involved.

CamScanner الممسوحة ضوئيا بـ



Chapter 5

MASS AND ENERGY ANALYSIS OF OPEN SYSTEMS (Control Volumes)

Thermodynamics: An Engineering Approach
Yunus A. Cengel, Michael A. Boles, Mehmet Kanoglu
McGraw-Hill

Dr. Ahmad M. AbuYaghi
October 2023

CONSERVATION OF MASS

Conservation of mass: Mass, like energy, is a conserved property, and it cannot be created or destroyed during a process.

Closed systems: The mass of the system remain constant during a process.

Control volumes: Mass can cross the boundaries, and so we must keep track of the amount of mass entering and leaving the control volume.

2 kg H_2	+	16 kg O_2	→	18 kg H_2O

Mass is conserved even during chemical reactions.

Mass m and energy E can be converted to each other according to

$$E = mc^2$$

where c is the speed of light in a vacuum, which is $c = 2.9979 \times 10^8$ m/s.

The mass change due to energy change is absolutely negligible.

CamScanner الممسوحة ضوئيا بـ

Mass and Volume Flow Rates

$$\delta \dot{m} = \rho V_n \, dA_c$$

$$\dot{m} = \int_{A_c} \delta \dot{m} = \int_{A_c} \rho V_n \, dA_c$$

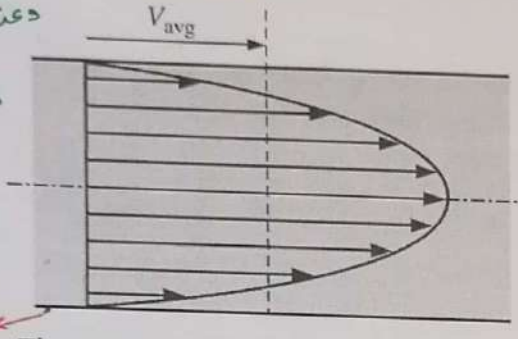
$$\dot{m} = \rho V_{\text{avg}} A_c \quad \text{(kg/s)}$$

$$\dot{m} = \rho \dot{V} = \frac{\dot{V}}{v}$$ Mass flow rate

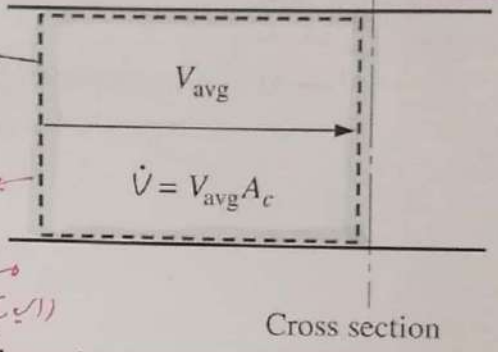
$$V_{\text{avg}} = \frac{1}{A_c} \int_{A_c} V_n \, dA_c$$ Definition of average velocity

Volume flow rate

$$\dot{V} = \int_{A_c} V_n \, dA_c = V_{\text{avg}} A_c = \boxed{VA_c} \quad \text{(m}^3\text{/s)}$$



The average velocity V_{avg} is defined as the average speed through a cross section.



The volume flow rate is the volume of fluid flowing through a cross section per unit time.

Conservation of Mass Principle

The conservation of mass principle for a control volume: **The net mass transfer to or from a control volume during a time interval Δt is equal to the net change (increase or decrease) in the total mass within the control volume during Δt.**

$$\begin{pmatrix}\text{Total mass entering}\\ \text{the CV during } \Delta t\end{pmatrix} - \begin{pmatrix}\text{Total mass leaving}\\ \text{the CV during } \Delta t\end{pmatrix} = \begin{pmatrix}\text{Net change in mass}\\ \text{within the CV during } \Delta t\end{pmatrix}$$

$$m_{\text{in}} - m_{\text{out}} = \Delta m_{\text{CV}} \quad \text{(kg)}$$

$$\dot{m}_{\text{in}} - \dot{m}_{\text{out}} = dm_{\text{CV}}/dt \quad \text{(kg/s)}$$

General conservation of mass

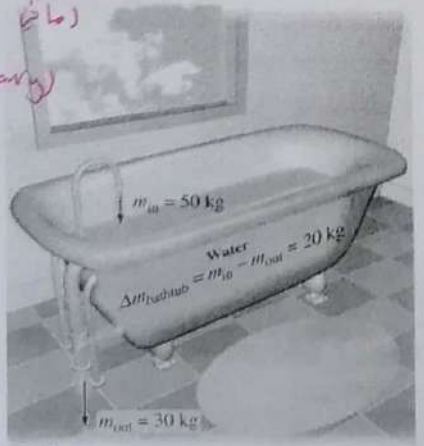
$$\frac{d}{dt}\int_{\text{CV}} \rho \, dV + \int_{\text{CS}} \rho(\vec{V} \cdot \vec{n}) \, dA = 0$$

General conservation of mass in rate form

$$\frac{d}{dt}\int_{\text{CV}} \rho \, dV = \sum_{\text{in}} \dot{m} - \sum_{\text{out}} \dot{m}$$

or

$$\frac{dm_{\text{CV}}}{dt} = \sum_{\text{in}} \dot{m} - \sum_{\text{out}} \dot{m}$$

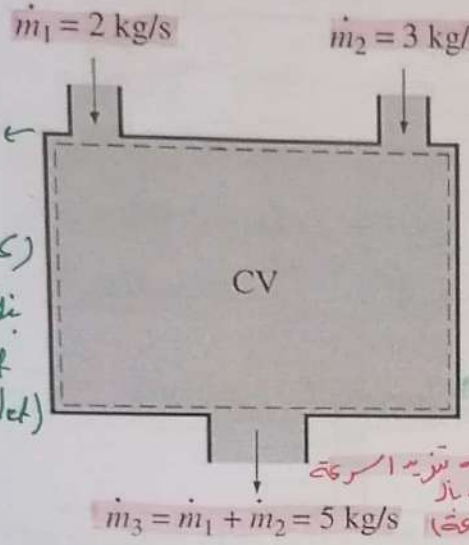


Conservation of mass principle for an ordinary bathtub.

Mass Balance for Steady-Flow Processes

During a steady-flow process, the total amount of mass contained within a control volume does not change with time (m_{CV} = constant).

Then the conservation of mass principle requires that the total amount of mass entering a control volume equal the total amount of mass leaving it.



Conservation of mass principle for a two-inlet–one-outlet steady-flow system.

For steady-flow processes, we are interested in the amount of mass flowing per unit time, that is, *the mass flow rate.*

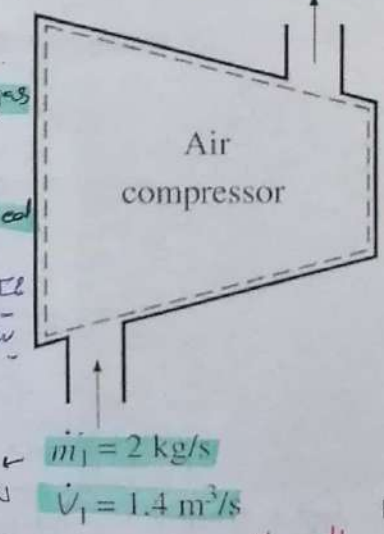
$$\sum_{in} \dot{m} = \sum_{out} \dot{m} \quad (kg/s)$$ Multiple inlets and exits

$$\dot{m}_1 = \dot{m}_2 \rightarrow \rho_1 V_1 A_1 = \rho_2 V_2 A_2$$ Single stream

Many engineering devices such as nozzles, diffusers, turbines, compressors, and pumps involve a single stream (only one inlet and one outlet).

Special Case: Incompressible Flow

The conservation of mass relations can be simplified even further when the fluid is incompressible, which is usually the case for liquids.



$$\sum_{in} \dot{V} = \sum_{out} \dot{V} \quad (m^3/s)$$ Steady, incompressible

$$\dot{V}_1 = \dot{V}_2 \rightarrow V_1 A_1 = V_2 A_2$$ Steady, incompressible flow (single stream)

- **There is no such thing as a "conservation of volume" principle.**
- **However, for steady flow of liquids, the volume flow rates, as well as the mass flow rates, remain constant since liquids are essentially incompressible substances.**

During a steady-flow process, volume flow rates are not necessarily conserved although mass flow rates are.

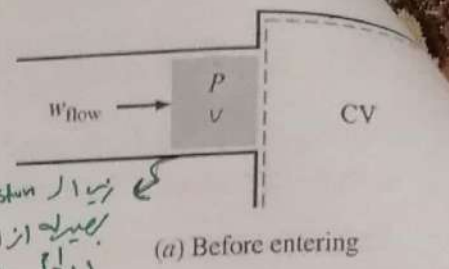
CamScanner الممسوحة ضوئيا بـ

flow work: هو موضوع الـ closed sys — أي خلي الـ open sys كأنه عنده

FLOW WORK AND THE ENERGY OF A FLOWING FLUID

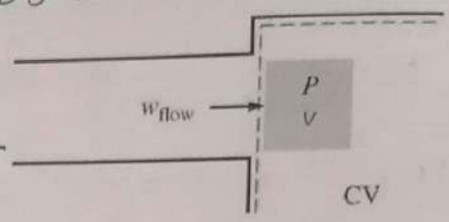
الشغل المطلوب ليتمرر الجسم من داخل الـ sys لخارجه (أو العكس بالإزاحة)

Flow work, or flow energy: The work (or energy) required to push the mass into or out of the control volume. This work is necessary for maintaining a continuous flow through a control volume.



Piston زيال بعيله ازاحة (داخل حال الـ sys)

(a) Before entering



(b) After entering

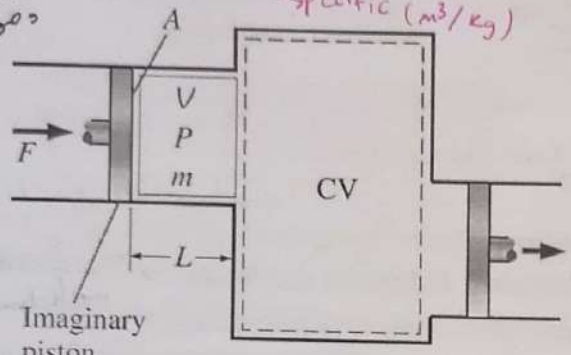
بره بطلع من الـ sys

$$F = PA$$

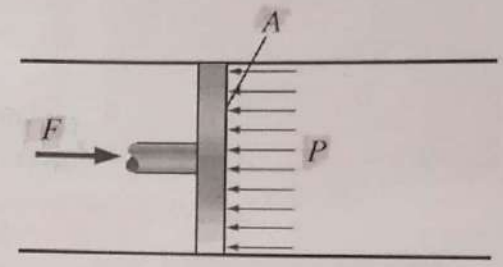
$$W_{flow} = FL = PAL = PV \quad \text{(kJ)}$$ (volume)

$$w_{flow} = Pv \quad \text{(kJ/kg)}$$ (distance)

flow work or (Pv) work — عشان عدل الكلمة — (specific m^3/kg)



Schematic for flow work.



In the absence of acceleration, the force applied on a fluid by a piston is equal to the force applied on the piston by the fluid.

$H = U + pv$ — enth — wb — وهو جزء من الـ flow work اللي رح نضيفها لـ h

بعض المادة بتتحرك وبترفع الـ piston لفوق

Total Energy of a Flowing Fluid

wb في الـ closed sys لما في انتقال للمادة فقط ! — wflow في الـ open sys لما المادة بتتحرك

الفرق بين الـ wb و الـ wflow: أما الـ wb فهو عشان حيك سبب الـ v هو الحركة

moving boundary / boundary volume / work = 0 (fixed boundary) / rigid / enclosed

$$e = \underline{u} + \underline{ke} + \underline{pe} = u + \frac{V^2}{2} + gz \quad \text{(kJ/kg)}$$

الطاقة الكلية — nonflowing fluid ما بتحرك

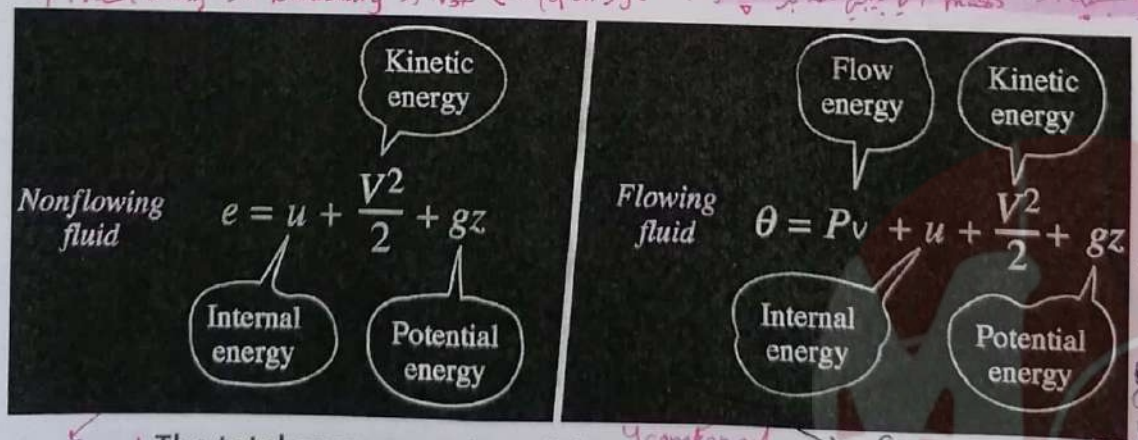
$$\theta = Pv + e = \underline{Pv} + (\underline{u} + \underline{ke} + \underline{pe}) \qquad h = u + Pv$$

flowing fluid

$$\theta = h + ke + pe = h + \frac{V^2}{2} + gz \quad \text{(kJ/kg)}$$

The flow energy is automatically taken care of by enthalpy. In fact, this is the main reason for defining the property enthalpy.

open sys ← boundary ثابتة (fixed boundary) — أما الـ mass اللي بتخش وبتطلع من الـ flow



3 components (الـ sys) — 4 components

The total energy consists of three parts for a nonflowing fluid and four parts for a flowing fluid.

$\theta = e + Pv$ — total flowing energy for flowing sys per unit mass of fluid

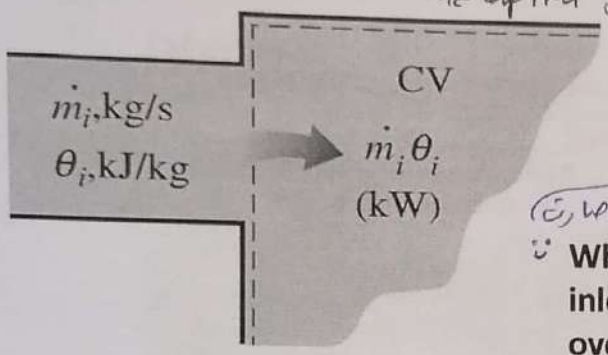
الـ wb بالـ closed sys جزء من الطاقة اللي بتكونها الـ sys أو الطلوبة ← هي اللي بتخش وبتطلع عبر الـ boundary

الممسوحة ضوئيا بـ CamScanner

Energy Transport by Mass

Amount of energy transport: $E_{\text{mass}} = m\theta = m\left(h + \frac{V^2}{2} + gz\right)$ (kJ)

Rate of energy transport: $\dot{E}_{\text{mass}} = \dot{m}\theta = \dot{m}\left(h + \frac{V^2}{2} + gz\right)$ (kW)



When the kinetic and potential energies of a fluid stream are negligible

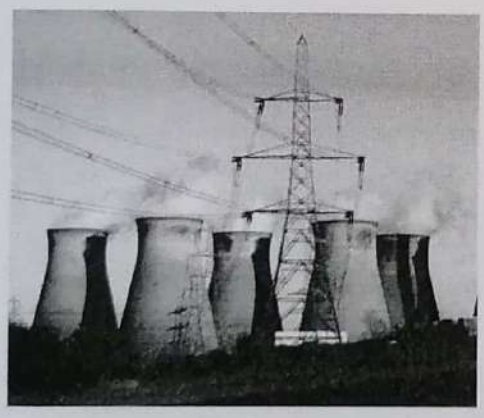
$$E_{\text{mass}} = mh \qquad \dot{E}_{\text{mass}} = \dot{m}h$$

When the properties of the mass at each inlet or exit change with time as well as over the cross section

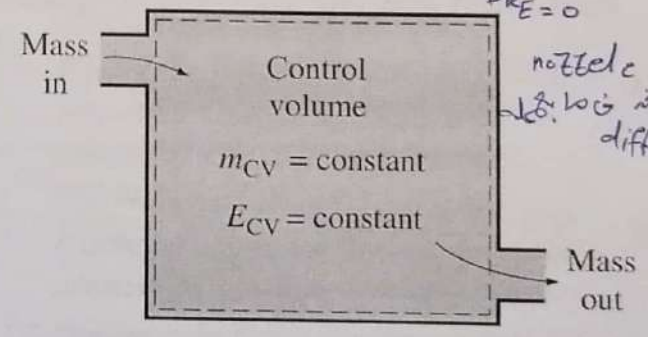
$$E_{\text{in,mass}} = \int_{m_i} \theta_i\, \delta m_i = \int_{m_i} \left(h_i + \frac{V_i^2}{2} + gz_i\right) \delta m_i$$

The product $\dot{m}_i\theta_i$ is the energy transported into control volume by mass per unit time.

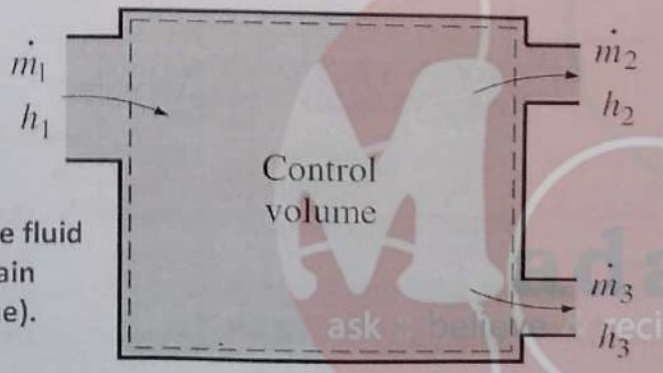
ENERGY ANALYSIS OF STEADY-FLOW SYSTEMS



Many engineering systems such as power plants operate under steady conditions.



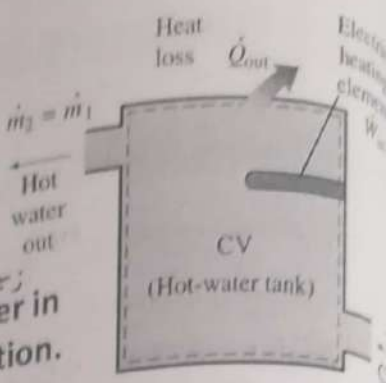
Under steady-flow conditions, the mass and energy contents of a control volume remain constant.



Under steady-flow conditions, the fluid properties at an inlet or exit remain constant (do not change with time).

CamScanner الممسوحة ضوئيا بـ

Mass and Energy balances for a steady-flow process



A water heater in steady operation.

$$\sum_{in} \dot{m} = \sum_{out} \dot{m} \quad (kg/s)$$

Mass balance

$$\dot{m}_1 = \dot{m}_2 \quad \text{(single in \& out)}$$

$$\rho_1 V_1 A_1 = \rho_2 V_2 A_2$$

Energy balance

$$\dot{E}_{in} - \dot{E}_{out} = \underbrace{dE_{system}/dt}_{\text{0 (steady)}} = 0$$

$\dot{E}_{in}$: Rate of net energy transfer by heat, work, and mass

dE_{system}/dt: Rate of change in internal, kinetic, potential, etc., energies

$$\dot{E}_{in} = \dot{E}_{out} \quad (kW)$$

$\dot{E}_{in}$: Rate of net energy transfer in by heat, work, and mass

$\dot{E}_{out}$: Rate of net energy transfer out by heat, work, and mass

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m}\left(h + \frac{V^2}{2} + gz\right) = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m}\left(h + \frac{V^2}{2} + \right.$$

for each inlet → energy carried by the mass

for each exit

Energy balance relations with sign conventions (i.e., heat input and work output are positive)

$$\dot{Q} - \dot{W} = \sum_{out} \dot{m}\left(h + \frac{V^2}{2} + gz\right) - \sum_{in} \dot{m}\left(h + \frac{V^2}{2} + gz\right)$$

for each exit — for each inlet

$$\dot{Q} - \dot{W} = \dot{m}\left[h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right] \quad \text{(for single In \& out)}$$

$\dot{Q}$: kJ/s — $\dot{W}$: kJ/s — $\dot{m}$: kg/s

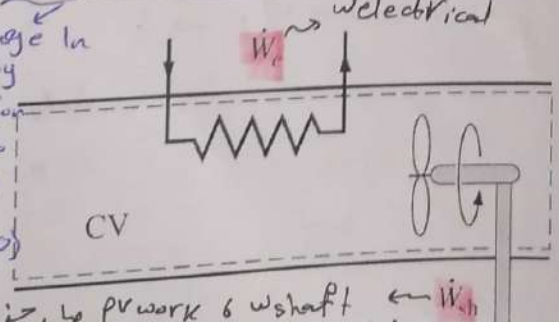
$$q - w = h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$

q: kJ/kg — w: kJ/kg

$$q - w = h_2 - h_1 \quad q = \dot{Q}/\dot{m} \quad w = \dot{W}/\dot{m}$$

$$\frac{J}{kg} \equiv \frac{N \cdot m}{kg} \equiv \left(kg\frac{m}{s^2}\right)\frac{m}{kg} \equiv \frac{m}{s}$$

$$\left(\text{Also, } \frac{Btu}{lbm} \equiv 25{,}037\ \frac{ft^2}{s^2}\right)$$



no change in velocity, elevation, KE = PE = 0

when kinetic and potential energy changes are negligible

Under steady operation, shaft work and electrical work are the only forms of work a simple compressible system may involve.

Some energy unit equivale

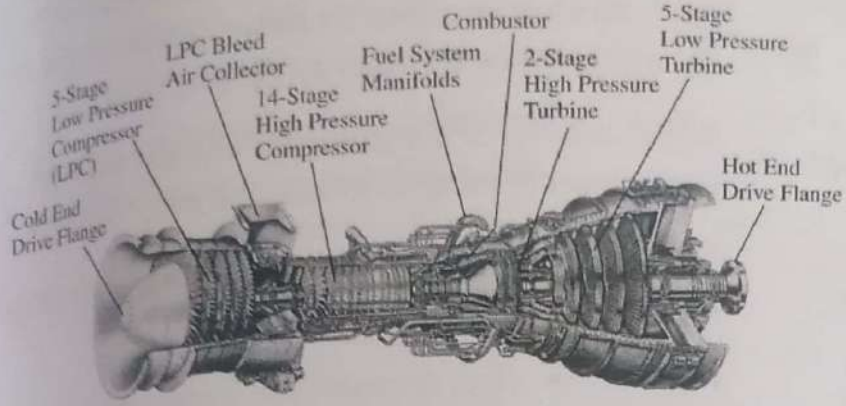
St.st applications: turbines, power plant, pipes, nozzles, compress, throttling, mixing ch

St.st conditions → overall energy balance → equation

Open sys → St.st

SOME STEADY-FLOW ENGINEERING DEVICES

Many engineering devices operate essentially under the same conditions for long periods of time. The components of a steam power plant (turbines, compressors, heat exchangers, and pumps), for example, operate nonstop for months before the system is shut down for maintenance. Therefore, these devices can be conveniently analyzed as steady-flow devices.

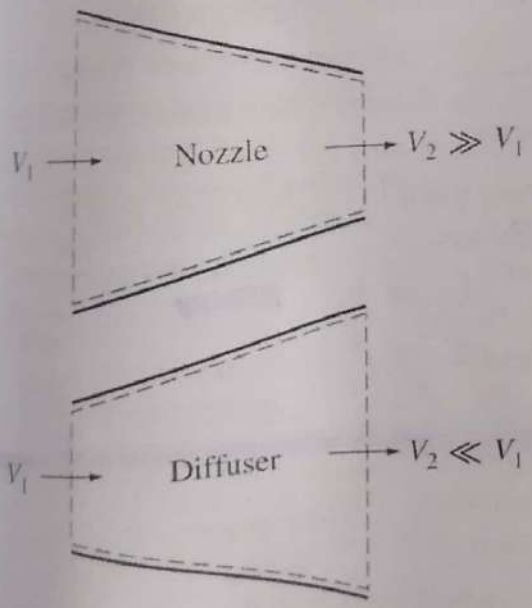


A modern land-based gas turbine used for electric power production. This is a General Electric LM5000 turbine. It has a length of 6.2 m, it weighs 12.5 tons, and produces 55.2 MW at 3600 rpm with steam injection.

V_1 m/s	V_2 m/s	Δke kJ/kg
0	45	1
50	67	1
100	110	1
200	205	1
500	502	1

At very high velocities, even small changes in velocities can cause significant changes in the kinetic energy of the fluid.

Nozzles and Diffusers



Nozzles and diffusers are shaped so that they cause large changes in fluid velocities and thus kinetic energies.

Nozzles and diffusers are commonly utilized in jet engines, rockets, spacecraft, and even garden hoses.

A nozzle is a device that *increases the velocity of a fluid* at the expense of pressure.

A diffuser is a device that *increases the pressure of a fluid* by slowing it down.

The cross-sectional area of a nozzle decreases in the flow direction for subsonic flows and increases for supersonic flows. The reverse is true for diffusers.

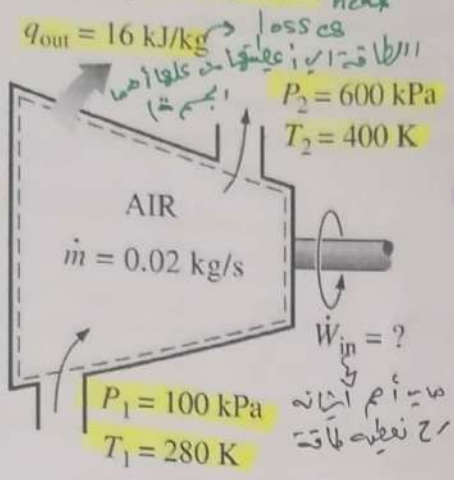
Energy balance for a nozzle or diffuser:

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}\left(h_1 + \frac{V_1^2}{2}\right) = \dot{m}\left(h_2 + \frac{V_2^2}{2}\right)$$

(since $\dot{Q} \cong 0$, $\dot{W} = 0$, and $\Delta pe \cong 0$)

Turbines and Compressors



Energy balance for the compressor in this figure:

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{W}_{in} + \dot{m}h_1 = \dot{Q}_{out} + \dot{m}h_2$$

(since $\Delta ke = \Delta pe \cong 0$)

Turbine drives the electric generator In s
gas, or hydroelectric power plants.

As the fluid passes through the turbine, wo
done against the blades, which are attache
the shaft. As a result, the shaft rotates, and
turbine produces work.

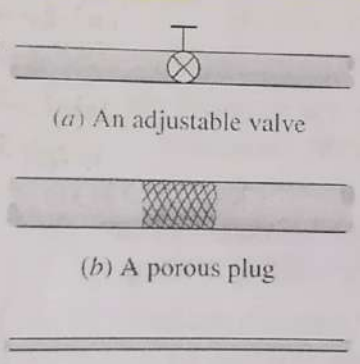
Compressors, as well as **pumps** and f
are devices used to increase the pressure o
fluid. Work is supplied to these devices fro
external source through a rotating shaft.

A ***fan*** increases the pressure of a gas slight
and is mainly used to mobilize a gas.

A ***compressor*** is capable of compressing
gas to very high pressures.

Pumps work very much like compressors
except that they handle liquids instead of ga

Throttling valves



Throttling valves are *any kind of flow-restricting devic*
that cause a significant pressure drop in the fluid.

What is the difference between a turbine and a throttling valve?

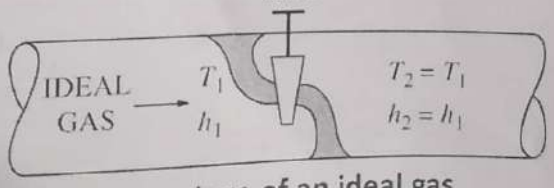
The pressure drop in the fluid is often accompanied b
large drop in temperature, and for that reason throttli
devices are commonly used in refrigeration and air-
conditioning applications.

Energy balance

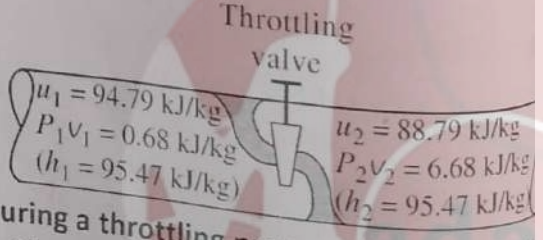
$$h_2 \cong h_1$$

$$u_1 + P_1v_1 = u_2 + P_2v_2$$

Internal energy + Flow energy = Consta



The temperature of an ideal gas does not change during a throttling (h = constant) process since $h = h(T)$.



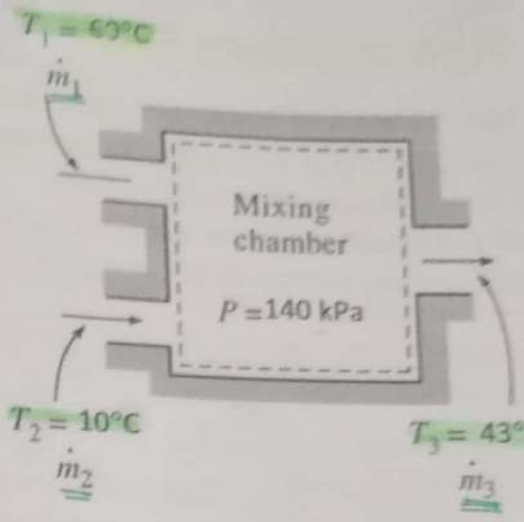
During a throttling process, the enthalpy o
fluid remains constant. But internal and flo
energies may be converted to each other.

الممسوحة ضوئيا بـ CamScanner

Mixing chambers

to mix 2 fluids

- In engineering applications, the section where the mixing process takes place is commonly referred to as a mixing chamber.



Energy balance for the adiabatic mixing chamber in the figure is:

we have 2 inlets & one outlet

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$$

$\dot{m}_1 + \dot{m}_2 = \dot{m}_3$ ← mass balance

Then, $Q_1 = mc_p \Delta T \rightarrow = T_3 - T_1$

$Q_2 = mc_p \Delta T \rightarrow = T_3 - T_2$

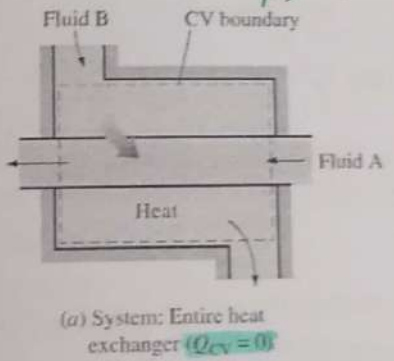
Then, $h = c_p \Delta T$

Assumption (insulated) (since $\dot{Q} \cong 0$, $\dot{W} = 0$, ke $\cong$ pe $\cong 0$)

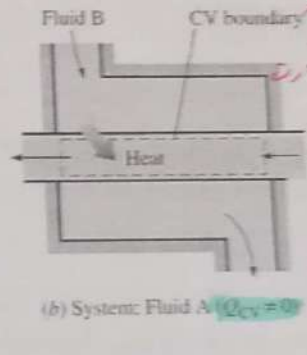
↳ no electrical or fans

Heat exchangers

Heat exchangers are devices where two moving fluid streams exchange heat without mixing. Heat exchangers are widely used in various industries, and they come in various designs.

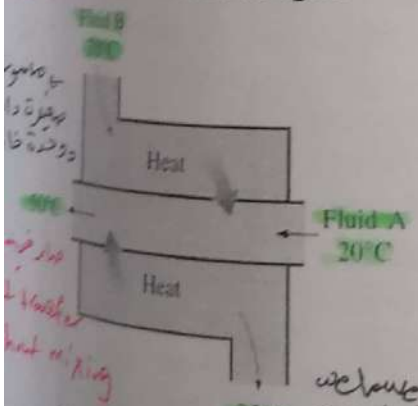


(a) System: Entire heat exchanger ($Q_{CV} = 0$)



(b) System: Fluid A ($Q_{CV} \neq 0$)

The heat transfer associated with a heat exchanger may be zero or nonzero depending on how the control volume is selected.



A heat exchanger can be as simple as two concentric pipes.

Mass and energy balances for the adiabatic heat exchanger in the figure is:

we have 2 inlet & 2 outlet

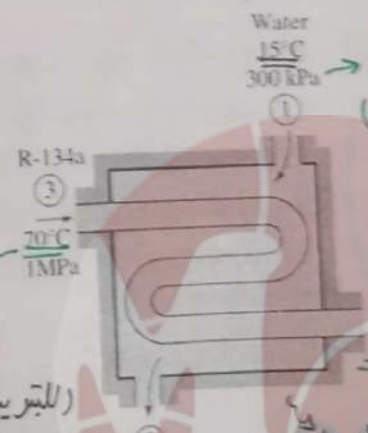
$$\dot{m}_1 = \dot{m}_2 = \dot{m}_w \quad \text{for water}$$

$$\dot{m}_3 = \dot{m}_4 = \dot{m}_R \quad \text{for refrigerant}$$

for st.st ← $\dot{E}_{in} = \dot{E}_{out}$

$$\dot{m}_1 h_1 + \dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_4 h_4$$

input = outlet



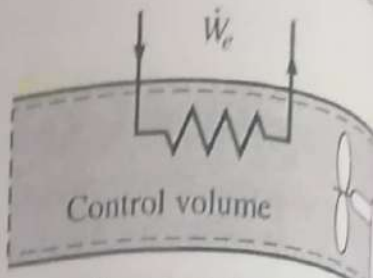
Shell & tube H.E

for sys → Q = 0 = KE = PE = 0

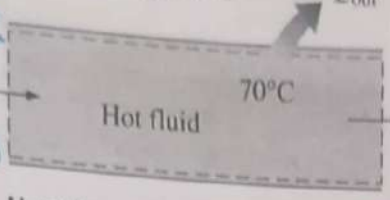
الممسوحة ضوئيا بـ CamScanner

Pipe and duct fow

The transport of liquids or gases in pipes and ducts is of great importance in many engineering applications. Flow through a pipe or a duct usually satisfies the steady-flow conditions.



Pipe or duct flow may involve more than one form of work at the same time.



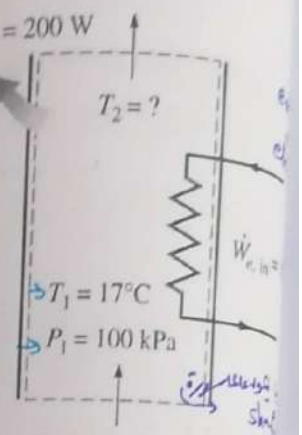
Heat losses from a hot fluid flowing through an uninsulated pipe or duct to the cooler environment may be very significant.

Energy balance for the pipe flow shown in the figure is:

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{W}_{e,in} + \dot{m}h_1 = \dot{Q}_{out} + \dot{m}h_2$$

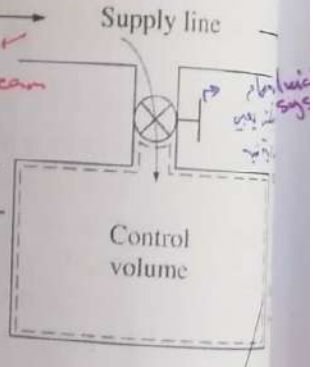
$$\dot{W}_{e,in} - \dot{Q}_{out} = \dot{m}c_p(T_2 - T_1)$$



ENERGY ANALYSIS OF UNSTEADY-FLOW PROCESSES

- Many processes of interest, however, involve *changes* within the control volume with time.
- Such processes are called ***unsteady-flow,*** or ***transient-flow,*** processes.
- Most unsteady-flow processes can be represented reasonably well by the *uniform-flow process*.
- **Uniform-flow process:** The fluid flow at any inlet or exit is uniform and steady, and thus the fluid properties do not change with time or position over the cross section of an inlet or exit.
- If they do, they are averaged and treated as constants for the entire process.

Charging of a rigid tank from a supply line is an unsteady-flow process since it involves changes within the control volume.



The shape and size of a control volume may change during an unsteady-flow process.



ask & recieve
CamScanner الممسوحة ضوئيا بـ

Mass balance

$$\Delta m_{\text{system}} = m_{\text{final}} - m_{\text{initial}}$$

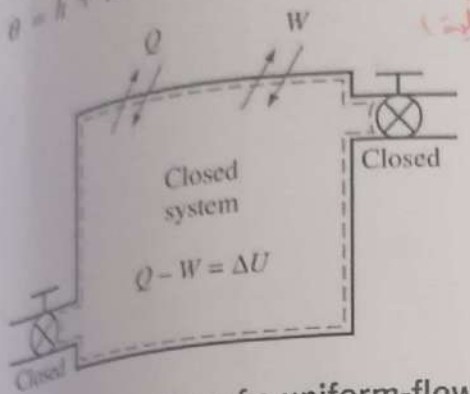
i = inlet, e = exit, 1 = initial state, and 2 = final state

Energy balance

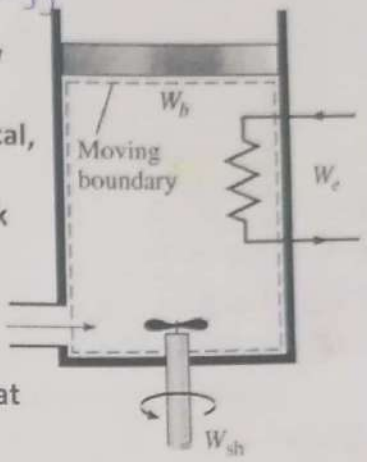
$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{\text{system}}}_{\text{Change in internal, kinetic, potential, etc., energies}}$$

$$\left(Q_{\text{in}} + W_{\text{in}} + \sum_{\text{in}} m\theta\right) - \left(Q_{\text{out}} + W_{\text{out}} + \sum_{\text{out}} m\theta\right) = (m_2 e_2 - m_1 e_1)_{\text{system}}$$

$$\theta = h + \text{ke} + \text{pe} \qquad e = u + \text{ke} + \text{pe}$$



The energy equation of a uniform-flow system reduces to that of a closed system when all the inlets and exits are closed.



A uniform-flow system may involve electrical, shaft, and boundary work all at once.

EXAMPLE 5–4 Deceleration of Air in a Diffuser

Air at 10°C and 80 kPa enters the diffuser of a jet engine steadily with a velocity of 200 m/s. The inlet area of the diffuser is 0.4 m². The air leaves the diffuser with a velocity that is very small compared with the inlet velocity. Determine (*a*) the mass flow rate of the air and (*b*) the temperature of the air leaving the diffuser.

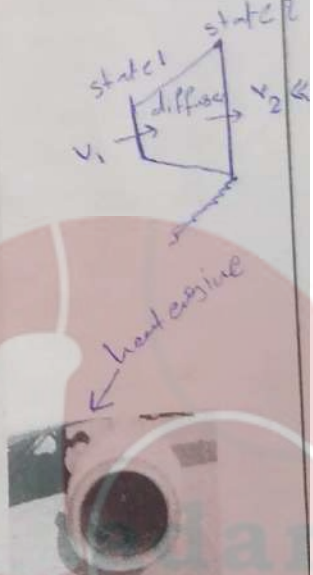
SOLUTION Air enters the diffuser of a jet engine steadily at a specified velocity. The mass flow rate of air and the temperature at the diffuser exit are to be determined.

Assumptions **1** This is a steady-flow process since there is no change with time at any point and thus $\Delta m_{\text{cv}} = 0$ and $\Delta E_{\text{cv}} = 0$. **2** Air is an ideal gas since it is at a high temperature and low pressure relative to its critical-point values. **3** The potential energy change is zero, $\Delta \text{pe} = 0$. **4** Heat transfer is negligible. **5** Kinetic energy at the diffuser exit is negligible. **6** There are no work interactions.

Analysis We take the *diffuser* as the system (Fig. 5–27). This is a *control volume* since mass crosses the system boundary during the process. We observe that there is only one inlet and one exit and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$.

(*a*) To determine the mass flow rate, we need to find the specific volume of the air first. This is determined from the ideal-gas relation at the inlet conditions:

$$v_1 = \frac{RT_1}{P_1} = \frac{(0.287 \text{ kPa·m}^3/\text{kg·K})(283 \text{ K})}{80 \text{ kPa}} = 1.015 \text{ m}^3/\text{kg}$$



CamScanner الممسوحة ضوئيا بـ

Then,

$$\dot{m} = \frac{1}{v_1} V_1 A_1 = \frac{1}{1.015\ \text{m}^3/\text{kg}} (200\ \text{m/s})(0.4\ \text{m}^2) = 78.8\ \text{kg/s}$$

Since the flow is steady, the mass flow rate through the entire diffuser remains constant at this value.

(*b*) Under stated assumptions and observations, the energy balance for this steady-flow system can be expressed in the rate form as

$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{\text{system}}/dt}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} = 0 \quad (\text{0 (steady)})$$

$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

$$\dot{m}\left(h_1 + \frac{V_1^2}{2}\right) = \dot{m}\left(h_2 + \frac{V_2^2}{2}\right) \quad (\text{since } \dot{Q} \cong 0,\ \dot{W} = 0, \text{ and } \Delta pe \cong 0)$$

$$h_2 = h_1 - \frac{V_2^2 - V_1^2}{2}$$

The exit velocity of a diffuser is usually small compared with the inlet velocity ($V_2 << V_1$); thus, the kinetic energy at the exit can be neglected. The enthalpy of air at the diffuser inlet is determined from the air table (Table A–17) to be

$$h_1 = h_{@\,283\,\text{K}} = 283.14\ \text{kJ/kg}$$

Substituting, we get

$$h_2 = 283.14\ \text{kJ/kg} - \frac{0 - (200\ \text{m/s})^2}{2}\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right)$$
$$= 303.14\ \text{kJ/kg}$$

From Table A–17, the temperature corresponding to this enthalpy value is

$$T_2 = 303\ \text{K}$$

EXAMPLE 5–6 Compressing Air by a Compressor

Air at 100 kPa and 280 K is compressed steadily to 600 kPa and 400 K. The mass flow rate of the air is 0.02 kg/s, and a heat loss of 16 kJ/kg occurs during the process. Assuming the changes in kinetic and potential energies are negligible, determine the necessary power input to the compressor.

SOLUTION Air is compressed steadily by a compressor to a specified temperature and pressure. The power input to the compressor is to be determined.

Assumptions **1** This is a steady-flow process since there is no change with time at any point and thus $\Delta m_{\text{CV}} = 0$ and $\Delta E_{\text{CV}} = 0$. **2** Air is an ideal gas since it is at a high temperature and low pressure relative to its critical-point values. **3** The kinetic and potential energy changes are zero, $\Delta ke = \Delta pe = 0$.

Analysis We take the *compressor* as the system (Fig. 5–30). This is a *control volume* since mass crosses the system boundary during the process. We observe that there is only one inlet and one exit and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. Also, heat is lost from the system and work is supplied to the system.

Under stated assumptions and observations, the energy balance for this steady-flow system can be expressed in the rate form as

$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{\text{system}}/dt}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} = 0 \quad (\text{0 (steady)})$$

CamScanner الممسوحة ضوئيا بـ

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{W}_{in} + \dot{m}h_1 = \dot{Q}_{out} + \dot{m}h_2 \quad (\text{since } \Delta ke = \Delta pe \cong 0)$$

$$\dot{W}_{in} = \dot{m}q_{out} + \dot{m}(h_2 - h_1)$$

The enthalpy of an ideal gas depends on temperature only, and the enthalpies of the air at the specified temperatures are determined from the air table (Table A–17) to be

$$h_1 = h_{@\,280\,K} = 280.13\ \text{kJ/kg}$$

$$h_2 = h_{@\,400\,K} = 400.98\ \text{kJ/kg}$$

Substituting, the power input to the compressor is determined to be

$$\dot{W}_{in} = (0.02\ \text{kg/s})(16\ \text{kJ/kg}) + (0.02\ \text{kg/s})(400.98 - 280.13)\ \text{kJ/kg}$$

$$= 2.74\ \text{kW}$$

Discussion Note that the mechanical energy input to the compressor manifests itself as a rise in enthalpy of air and heat loss from the compressor.

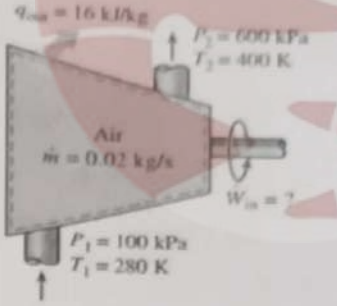


FIGURE 5–30
Schematic for Example 5–6.

EXAMPLE 5–7 Power Generation by a Steam Turbine

The power output of an adiabatic steam turbine is 5 MW, and the inlet and the exit conditions of the steam are as indicated in Fig. 5–31.

(a) Compare the magnitudes of Δh, Δke, and Δpe.
(b) Determine the work done per unit mass of the steam flowing through the turbine.
(c) Calculate the mass flow rate of the steam.

SOLUTION The inlet and exit conditions of a steam turbine and its power output are given. The changes in kinetic energy, potential energy, and enthalpy of steam, as well as the work done per unit mass and the mass flow rate of steam are to be determined.

Assumptions 1 This is a steady-flow process since there is no change with time at any point and thus $\Delta m_{CV} = 0$ and $\Delta E_{CV} = 0$. **2** The system is adiabatic and thus there is no heat transfer.

Analysis We take the *turbine* as the system. This is a *control volume* since mass crosses the system boundary during the process. We observe that there is only one inlet and one exit and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. Also, work is done by the system. The inlet and exit velocities and elevations are given, and thus the kinetic and potential energies are to be considered.

(a) At the inlet, steam is in a superheated vapor state, and its enthalpy is

$$\left.\begin{matrix} P_1 = 2\ \text{MPa} \\ T_1 = 400°\text{C} \end{matrix}\right\} \quad h_1 = 3248.4\ \text{kJ/kg} \quad \text{(Table A–6)}$$

At the turbine exit, we obviously have a saturated liquid–vapor mixture at 15-kPa pressure. The enthalpy at this state is

$$h_2 = h_f + x_2 h_{fg} = [225.94 + (0.9)(2372.3)]\ \text{kJ/kg} = 2361.01\ \text{kJ/kg}$$

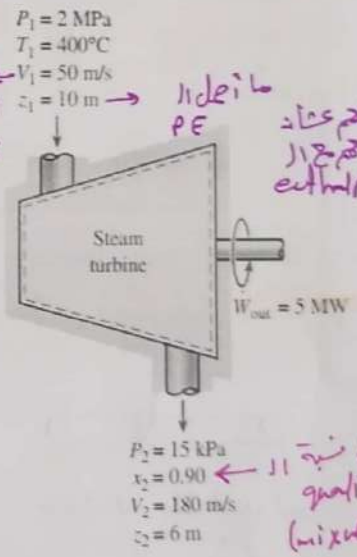


FIGURE 5–31
Schematic for Example 5–7.

Then

$$\Delta h = h_2 - h_1 = (2361.01 - 3248.4)\ \text{kJ/kg} = -887.39\ \text{kJ/kg}$$

$$\Delta ke = \frac{V_2^2 - V_1^2}{2} = \frac{(180\ \text{m/s})^2 - (50\ \text{m/s})^2}{2}\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = 14.95\ \text{kJ/kg}$$

$$\Delta pe = g(z_2 - z_1) = (9.81\ \text{m/s}^2)[(6 - 10)\ \text{m}]\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = -0.04\ \text{kJ/kg}$$

→ negligible

(b) The energy balance for this steady-flow system can be expressed in the rate form as

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt}_{\text{Rate of change in internal, kinetic, potential, etc. energies}} \overset{0\ (\text{steady})}{=} 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}\left(h_1 + \frac{V_1^2}{2} + gz_1\right) = \dot{W}_{out} + \dot{m}\left(h_2 + \frac{V_2^2}{2} + gz_2\right) \quad (\text{since } \dot{Q} = 0)$$

Dividing by the mass flow rate $\dot{m}$ and substituting, the work done by the turbine per unit mass of the steam is determined to be

$$w_{out} = -\left[(h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right] = -(\Delta h + \Delta ke + \Delta pe)$$

$$= -[-887.39 + 14.95 - 0.04]\ \text{kJ/kg} = 872.48\ \text{kJ/kg}$$

← قيمنا كل mass وإنه بدنا إياه per unit mass ::

(c) The required mass flow rate for a 5-MW power output is

$$\dot{m} = \frac{\dot{W}_{out}}{w_{out}} = \frac{5000\ \text{kJ/s}}{872.48\ \text{kJ/kg}} = 5.73\ \text{kg/s}$$

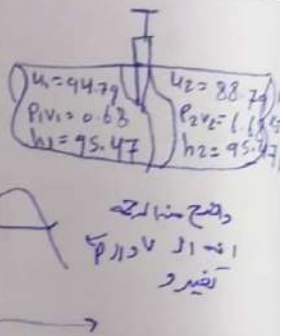
ميكانيكا الحرارة: تحليل الـ conditions كل مرة بالمسألة وبنظبطها

EXAMPLE 5–8 **Expansion of Refrigerant-134a in a Refrigerator**

Refrigerant-134a enters the capillary tube of a refrigerator as saturated liquid at 0.8 MPa and is throttled to a pressure of 0.12 MPa. Determine the quality of the refrigerant at the final state and the temperature drop during this process.

throttling device (أنبوب رفيع)

saturated liquid

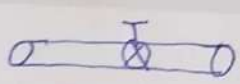


واضح منا الرسمة انه الـ u ثابتة

SOLUTION Refrigerant-134a that enters a capillary tube as saturated liquid is throttled to a specified pressure. The exit quality of the refrigerant and the temperature drop are to be determined.

Assumptions 1 Heat transfer from the tube is negligible. 2 Kinetic energy change of the refrigerant is negligible.

Analysis A capillary tube is a simple flow-restricting device that is commonly used in refrigeration applications to cause a large pressure drop in the refrigerant. Flow through a capillary tube is a throttling process; thus, the enthalpy of the refrigerant remains constant (Fig. 5–34).



adjustable valve

At inlet:	$P_1 = 0.8$ MPa, sat. liquid	$T_1 = T_{\text{sat @ 0.8 MPa}} = 31.31°\text{C}$ $h_1 = h_{f\,@\,0.8\text{ MPa}} = 95.48$ kJ/kg	(Table A–12)
At exit:	$P_2 = 0.12$ MPa, $(h_2 = h_1)$	$h_f = 22.47$ kJ/kg, $h_g = 236.99$ kJ/kg	$T_{sat} = -22.32°\text{C}$

for Ref

Obviously $h_f < h_2 < h_g$; thus, the refrigerant exists as a saturated mixture at the exit state. The quality at this state is

$$x_2 = \frac{h_2 - h_f}{h_{fg}} = \frac{95.48 - 22.47}{236.99 - 22.47} = 0.340$$

→ h_f on 95 c

Since the exit state is a saturated mixture at 0.12 MPa, the exit temperature must be the saturation temperature at this pressure, which is −22.32°C. Then the temperature change for this process becomes

drop in temp → $\Delta T = T_2 - T_1 = (-22.32 - 31.31)°\text{C} = -53.63°\text{C}$

Discussion Note that the temperature of the refrigerant drops by 53.63°C during this throttling process. Also note that 34.0 percent of the refrigerant vaporizes during this throttling process, and the energy needed to vaporize this refrigerant is absorbed from the refrig[illegible]self.

h ثابتة ← u بتقل ← pv بتقل

u بتزيد ← pv بتزيد ← u بتقل

pv زاد بسرعة ← u بتقل بسرعة

throttling!

CamScanner الممسوحة ضوئيا بـ

Cooling of Refrigerant-134a by Water

EXAMPLE 5–10

Refrigerant-134a is to be cooled by water in a condenser. The refrigerant enters the condenser with a mass flow rate of 6 kg/min at 1 MPa and 70°C and leaves at 25°C. The cooling water enters at 300 kPa and 15°C and leaves at 25°C. Neglecting any pressure drops, determine (*a*) the mass flow rate of the cooling water required and (*b*) the heat transfer rate from the refrigerant to water.

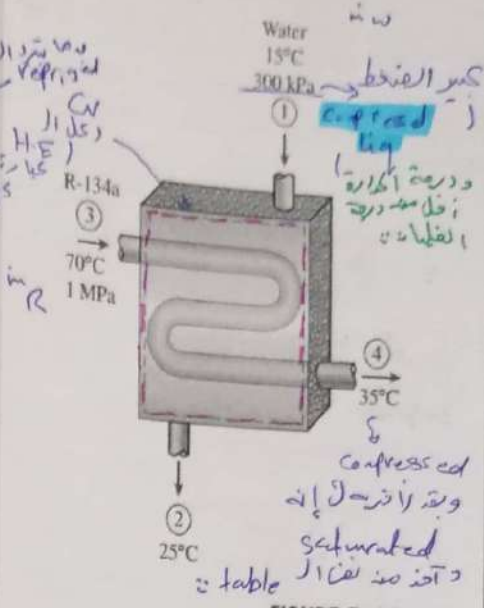


FIGURE 5–40
Schematic for Example 5–10.

SOLUTION Refrigerant-134a is cooled by water in a condenser. The mass flow rate of the cooling water and the rate of heat transfer from the refrigerant to the water are to be determined.

Assumptions 1 This is a steady-flow process since there is no change with time at any point and thus $\Delta m_{cv} = 0$ and $\Delta E_{cv} = 0$. 2 The kinetic and potential energies are negligible, $ke \cong pe \cong 0$. 3 Heat losses from the system are negligible and thus $\dot{Q} \cong 0$. 4 There is no work interaction.

Analysis We take the *entire heat exchanger* as the system (Fig. 5–40). This is a control volume since mass crosses the system boundary during the process. In general, there are several possibilities for selecting the control volume for multiple-stream steady-flow devices, and the proper choice depends on the situation at hand. We observe that there are two fluid streams (and thus two inlets and two exits) but no mixing.

(*a*) Under the stated assumptions and observations, the mass and energy balances for this steady-flow system can be expressed in the rate form as follows:

Mass balance:

$$\dot{m}_{in} = \dot{m}_{out}$$

for each fluid stream since there is no mixing. Thus,

$$\dot{m}_1 = \dot{m}_2 = \dot{m}_w$$

$$\dot{m}_3 = \dot{m}_4 = \dot{m}_R$$

Energy balance:

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} \overset{0 \text{ (steady)}}{} = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}_1 h_1 + \dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_4 h_4 \quad (\text{since } \dot{Q} \cong 0,\ \dot{W} = 0,\ ke \cong pe \cong 0)$$

Combining the mass and energy balances and rearranging give

$$\dot{m}_w(h_1 - h_2) = \dot{m}_R(h_4 - h_3)$$

Now we need to determine the enthalpies at all four states. Water exists as a compressed liquid at both the inlet and the exit since the temperatures at both locations are below the saturation temperature of water at 300 kPa (133.52°C). Approximating the compressed liquid as a saturated liquid at the given temperatures, we have

$$h_1 \cong h_{f@15°C} = 62.982 \text{ kJ/kg} \quad \text{(Table A–4)}$$

$$h_2 \cong h_{f@25°C} = 104.83 \text{ kJ/kg}$$

CamScanner الممسوحة ضوئيا بـ

The refrigerant enters the condenser as a superheated vapor and leaves as a compressed liquid at 35°C. From refrigerant-134a tables,

$$\left.\begin{matrix} P_3 = 1\ \text{MPa} \\ T_3 = 70°\text{C} \end{matrix}\right\} \quad h_3 = 303.87\ \text{kJ/kg} \quad \text{(Table A–13)}$$

for in. Ref → superheated

$$\left.\begin{matrix} P_4 = 1\ \text{MPa} \\ T_4 = 35°\text{C} \end{matrix}\right\} \quad h_4 \cong h_{f\,@\,35°\text{C}} = 100.88\ \text{kJ/kg} \quad \text{(Table A–11)}$$

for out. Ref → compressed)

Substituting, we find

$$\dot{m}_w(62.982 - 104.83)\ \text{kJ/kg} = (6\ \text{kg/min})[(100.88 - 303.87)\ \text{kJ/kg}]$$

$$\dot{m}_w = 29.1\ \text{kg/min}$$

(b) To determine the heat transfer from the refrigerant to the water, we have to choose a control volume whose boundary lies on the path of heat transfer. We can choose the volume occupied by either fluid as our control volume. For no particular reason, we choose the volume occupied by the water. All the assumptions stated earlier apply, except that the heat transfer is no longer zero. Then assuming heat to be transferred to water, the energy balance for this single-stream steady-flow system reduces to

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} \quad (0 \text{ (steady)}) = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\underbrace{\dot{Q}_{w,in}}_{\text{in. water}} + \dot{m}_w h_1 = \underbrace{\dot{m}_w h_2}_{\text{out. for output water}}$$

Rearranging and substituting,

$$\dot{Q}_{w,in} = \dot{m}_w(h_2 - h_1) = (29.1\ \text{kg/min})[(104.83 - 62.982)\ \text{kJ/kg}]$$

$$= 1218\ \text{kJ/min}$$

EXAMPLE 5–12 Charging of a Rigid Tank by Steam

A rigid, insulated tank that is initially evacuated is connected through a valve to a supply line that carries steam at 1 MPa and 300°C. Now the valve is opened, and steam is allowed to flow slowly into the tank until the pressure reaches 1 MPa, at which point the valve is closed. Determine the final temperature of the steam in the tank.

SOLUTION A valve connecting an initially evacuated tank to a steam line is opened, and steam flows in until the pressure inside rises to the line level. The final temperature in the tank is to be determined.

Assumptions **1** This process can be analyzed as a *uniform-flow process* since the properties of the steam entering the control volume remain constant during the entire process. **2** The kinetic and potential energies of the streams are negligible, ke ≅ pe ≅ 0. **3** The tank is stationary and thus its kinetic and potential energy changes are zero; that is, $\Delta KE = \Delta PE = 0$ and $\Delta E_{system} = \Delta U_{system}$. **4** There are no boundary, electrical, or shaft work interactions involved. **5** The tank is well insulated and thus there is no heat transfer.

Analysis We take the *tank* as the system (Fig. 5–50). This is a *control volume* since mass crosses the system boundary during the process. We observe that this is an unsteady-flow process since changes occur within the control volume. The control volume is initially evacuated and thus $m_1 = 0$ and $m_1 u_1 = 0$. Also, there is one inlet and no exits for mass flow.

Noting that microscopic energies of flowing and nonflowing fluids are represented by enthalpy h and internal energy u, respectively, the mass and energy balances for this uniform-flow system can be expres

CamScanner الممسوحة ضوئيا بـ

Inlet

Mass balance:

$$m_{in} - m_{out} = \Delta m_{system} \rightarrow m_i = m_2 - m_1 = m_2$$

($m_1 = 0$ (no exit stream))

Energy balance:

$$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic, potential, etc., energies}}$$

($E_{in} = 0$)

$$m_i h_i = m_2 u_2 \quad (\text{since } W = Q = 0,\ ke \cong pe \cong 0,\ m_1 = 0)$$

Combining the mass and energy balances gives

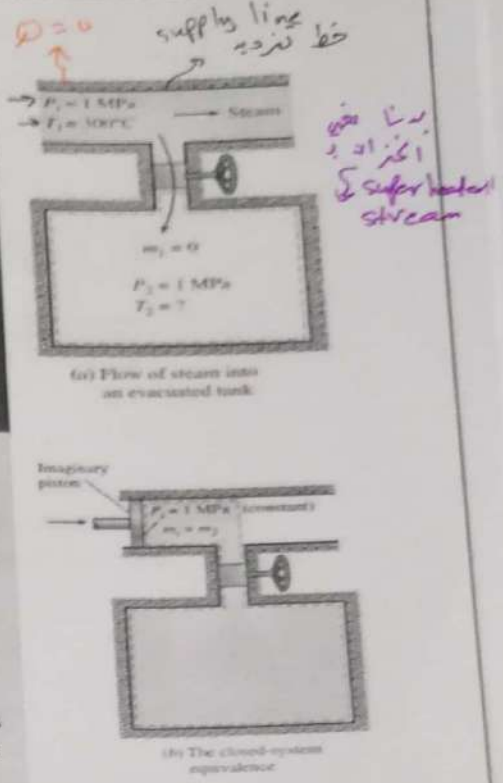
$$u_2 = h_i$$

That is, the final internal energy of the steam in the tank is equal to the enthalpy of the steam entering the tank. The enthalpy of the steam at the inlet state is

$$\left.\begin{matrix} P_i = 1\ \text{MPa} \\ T_i = 300°\text{C} \end{matrix}\right\} \quad h_i = 3051.6\ \text{kJ/kg} \quad \text{(Table A–6)}$$

which is equal to u_2. Since we now know two properties at the final state, it is fixed and the temperature at this state is determined from the same table to be

$$\left.\begin{matrix} P_2 = 1\ \text{MPa} \\ u_2 = 3051.6\ \text{kJ/kg} \end{matrix}\right\} \quad T_2 = 456.1°\text{C}$$



(a) Flow of steam into an evacuated tank

(b) The closed-system equivalence

33

$u_2 = h_i$ فيكون E_2

* اذا كانت ال $u_2 = h_i$ بتكون $m_2 = h_i$

CamScanner الممسوحة ضوئيا بـ



Chapter 6

THE SECOND LAW OF THERMODYNAMICS

Thermodynamics: An Engineering Approach
Yunus A. Cengel, Michael A. Boles, Mehmet Kanoglu
McGraw-Hill

$\frac{P_H}{Q_L} < \frac{T_H}{T_H}$ (1 لأن

Dr. Ahmad M. AbuYaghi
October 2023

ال second law بتحكي عن الطاقة العالية

INTRODUCTION TO THE SECOND LAW

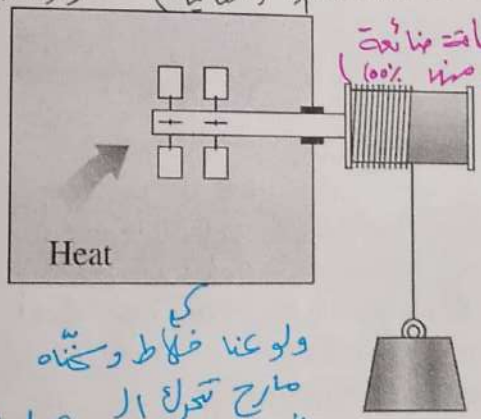
بحدد اتجاه انتقال الطاقة ← بتحكي الطاقة 1/2 والعالية نوعية

ال dilcation (quality)

another process الطاقة spontaneous (تلقائية) من الحرارة العالية للأقل و من الأقل لا يحدث

A cup of hot coffee does not get hotter in a cooler room.





→ Transferring heat to a paddle wheel will not cause it to rotate.

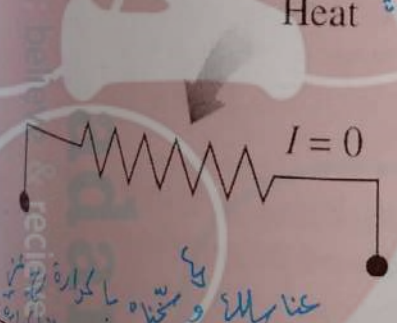
لي بعين ف طاقة ضائعة (100% مستحيل أستفيد منها) → dissipated energy

ولو عنا خلاط وسخناه صار تتحرك ال blades وما تحولت لشغل

طيب كيف صار حيل؟ زي بالسيارة الحرارة سببت انفجار وحركتها

← نتيجة وجود ال cycles

وأكيد ما كل الحرارة تحولت لشغل، في expansion وفي compression، في طاقة ضائعة



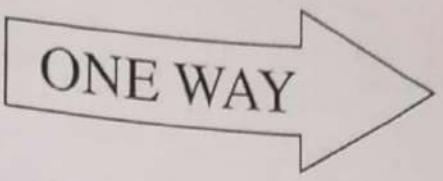
Transferring heat to a wire will not generate electricity.

These processes cannot occur even though they are not in violation of the first law.

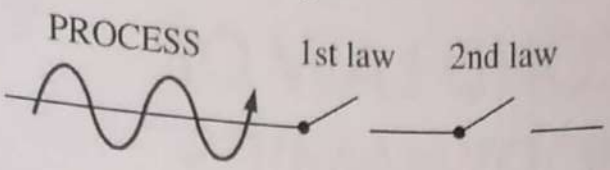
عنا هالاء وسخناه بالحرارة في نفس الوقت بالاتجاه الثاني ما تحول شغل

أي برو سيس بتقدر تطبقه عليه ال second law

CamScanner الممسوحة ضوئيا بـ



Processes occur in a certain direction, and not in the reverse direction.

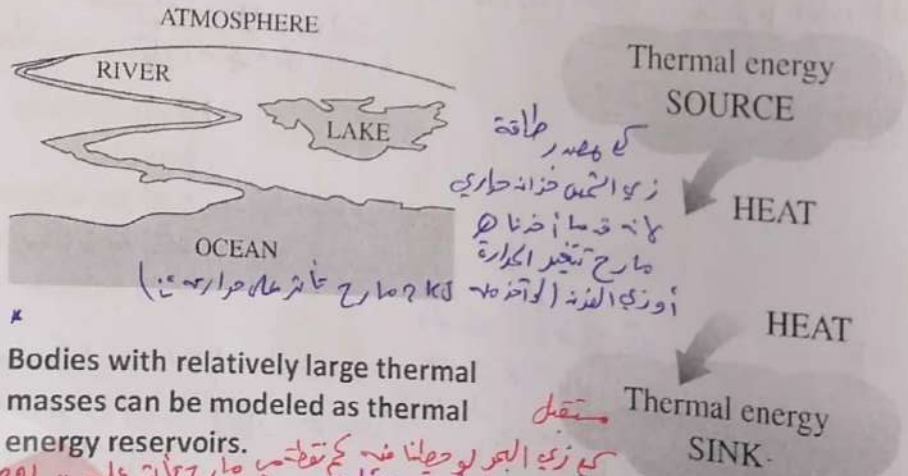


A process must satisfy both the first and second laws of thermodynamics to proceed.

MAJOR USES OF THE SECOND LAW

1) The second law may be used to identify the direction of processes.
2) The second law also asserts that energy has *quality* as well as quanti
The first law is concerned with the quantity of energy and the transformations of energy from one form to another with no regard to
quality. The second law provides the necessary means to determine t
quality as well as the degree of degradation of energy during a proces
3) The second law of thermodynamics is also used in determining the *theoretical limits* for the performance of commonly used engineering systems, such as heat engines and refrigerators, as well as predicting *degree of completion* of chemical reactions.

THERMAL ENERGY RESERVOIRS



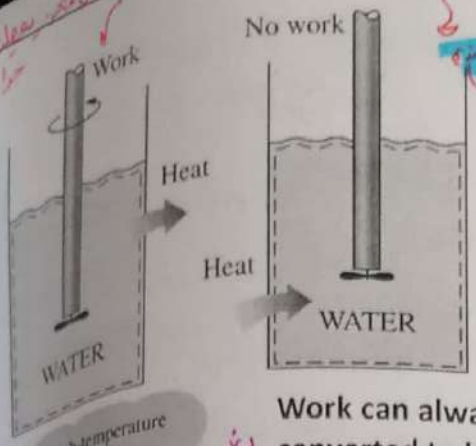
A source supp
energy in the
form of heat,
a sink absorbs

Bodies with relatively large thermal masses can be modeled as thermal energy reservoirs.

- A hypothetical body with a relatively large *thermal energy capacity* (mass specific heat) that can supply or absorb finite amounts of heat without undergoing any change in temperature is called a thermal energy reservoir, or just a reservoir.
- In practice, large bodies of water such as oceans, lakes, and rivers as wel as the atmospheric air can be modeled accurately as thermal energy reservoirs because of their large thermal energy storage capabilities or thermal masses.

CamScanner الممسوحة ضوئيا بـ

HEAT ENGINES

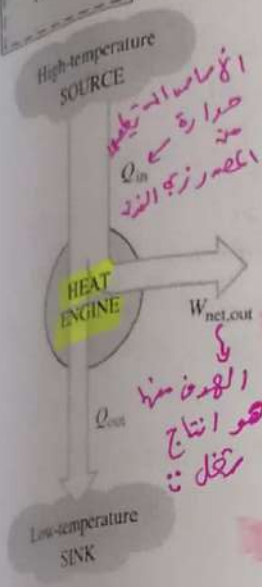


The devices that convert heat to work.

1) They receive heat from a high-temperature source (solar energy, oil furnace, nuclear reactor, etc.).
2) They convert part of this heat to work (usually in the form of a rotating shaft.)
3) They reject the remaining waste heat to a low-temperature sink (the atmosphere, rivers, etc.).
4) They operate on a cycle.

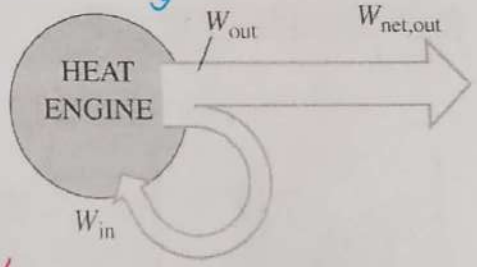
Heat engines and other cyclic devices usually involve a fluid to and from which heat is transferred while undergoing a cycle. This fluid is called the **working fluid**.

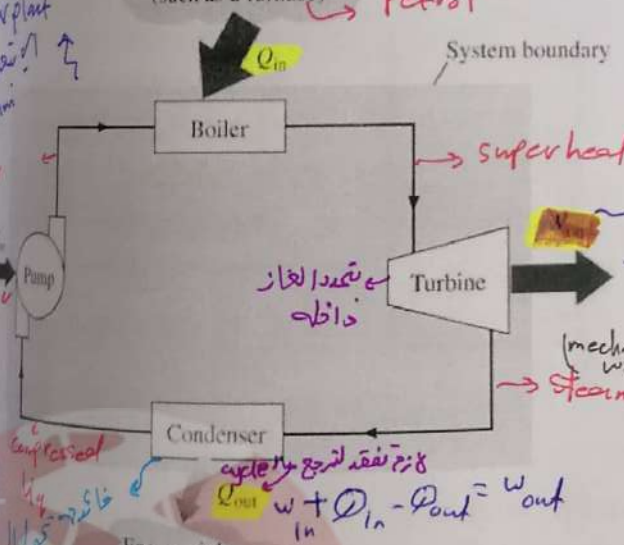
Work can always be converted to heat directly and completely, but the reverse is not true.



Part of the heat received by a heat engine is converted to work, while the rest is rejected to a sink.

A steam power plant





A portion of the work output of a heat engine is consumed internally to maintain continuous operation.

$$W_{net,out} = W_{out} - W_{in} \quad \text{(kJ)}$$

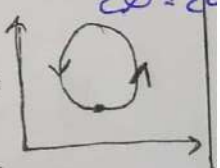
$$W_{net,out} = Q_{in} - Q_{out} \quad \text{(kJ)}$$

Q_{in} = amount of heat supplied to steam in boiler from a high-temperature source (furnace)

Q_{out} = amount of heat rejected from steam in condenser to a low-temperature sink (the atmosphere, a river, etc.)

W_{out} = amount of work delivered by steam as it expands in turbine

W_{in} = amount of work required to compress water to boiler pressure



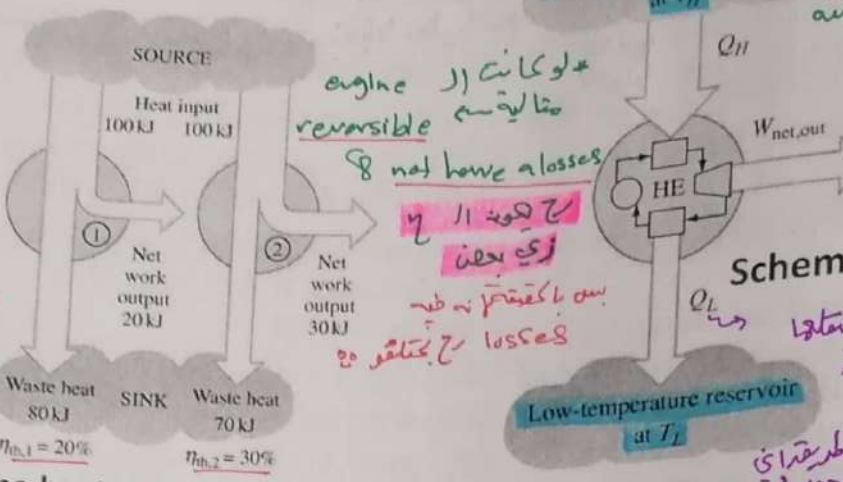
efficiency for cycle

$$\eta = \frac{W_{net,out}}{Q_{in}}$$

(thermal efficiency)

CamScanner الممسوحة ضوئيا بـ

Thermal efficiency



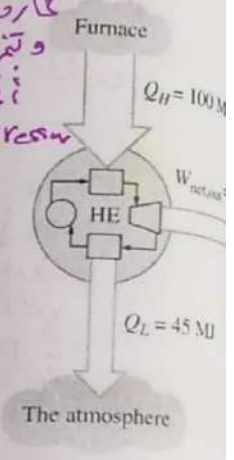
Some heat engines perform better than others (convert more of the heat they receive to work).

$$\text{Thermal efficiency} = \frac{\text{Net work output}}{\text{Total heat input}}$$

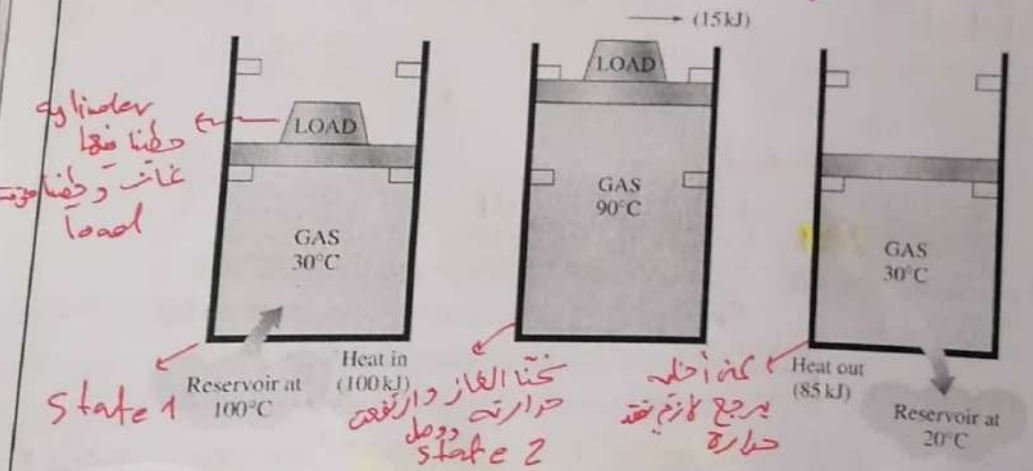
$$\eta_{th} = \frac{W_{net,out}}{Q_{in}} \qquad \eta_{th} = 1 - \frac{Q_{out}}{Q_{in}}$$

$$W_{net,out} = Q_{in} - Q_{out}$$

Even the most efficient heat engines reject almost one-half of the energy they receive as waste heat.



Can we save Q_{out}?



A heat-engine cycle cannot be completed without rejecting some heat to a low-temperature sink.

- Every heat engine must *waste* some energy by transferring it to a low-temperature reservoir in order to complete the cycle, even under idealized conditions.

- In a steam power pl... the condenser is the device where large quantities of waste ... is rejected to rivers, lakes, or the atmosphere.
- Can we not just take condenser out of the plant and save all the waste energy?
- The answer is, unfortunately, a firm ... for the simple reason that without a heat rejection process in the condenser, the cycle cannot be completed

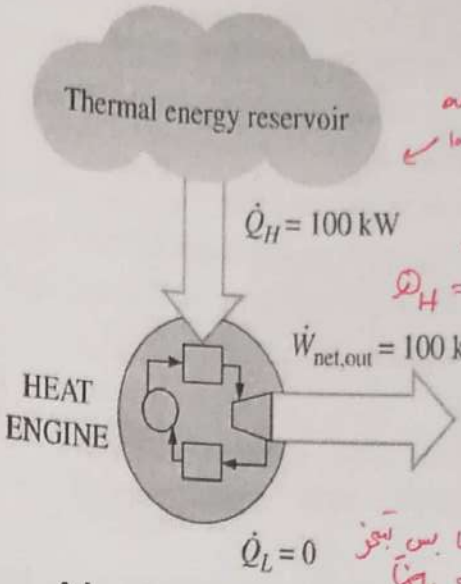
CamScanner الممسوحة ضوئيا بـ

The Second Law of Thermodynamics: Kelvin–Planck Statement

It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work.

- *No heat engine can have a thermal efficiency of 100 percent, or as for a power plant to operate, the working fluid must exchange heat with the environment as well as the furnace.*
- **The impossibility of having a 100% efficient heat engine is not due to friction or other dissipative effects.**

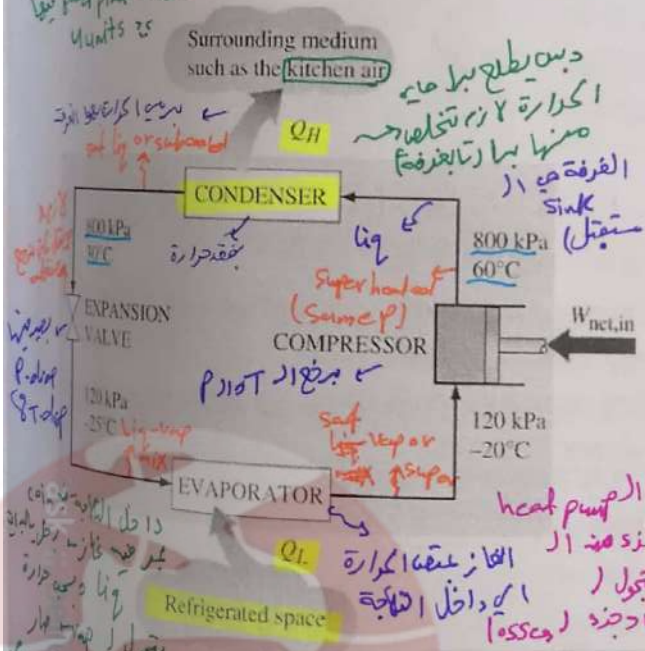
It is a limitation that applies to both the idealized and the actual heat engines.



A heat engine that violates the Kelvin–Planck statement of the second law.

REFRIGERATORS AND HEAT PUMPS

1) The transfer of heat from a low-temperature medium to a high-temperature one requires special devices called **refrigerators**.
2) Refrigerators, like heat engines, are cyclic devices.
3) The working fluid used in the refrigeration cycle is called a **refrigerant**.
4) The most frequently used refrigeration cycle is the *vapor-compression refrigeration cycle*.



Basic components of a refrigeration system and typical operating conditions.

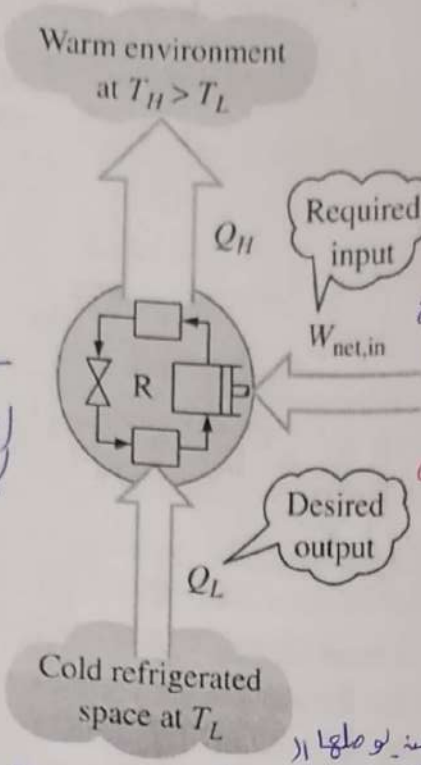
In a household refrigerator, the freezer compartment where heat is absorbed by the refrigerant serves as the evaporator, and the coils usually behind the refrigerator where heat is dissipated to the kitchen air serve as the condenser.

CamScanner الممسوحة ضوئيا بـ

Coefficient of Performance

The *efficiency* of a refrigerator is expressed in terms of the coefficient of performance (COP).

The objective of a refrigerator is to remove heat (Q_L) from the refrigerated space.



$$COP_R = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_L}{W_{net,in}}$$

$$W_{net,in} = Q_H - Q_L \quad \text{(kJ)}$$

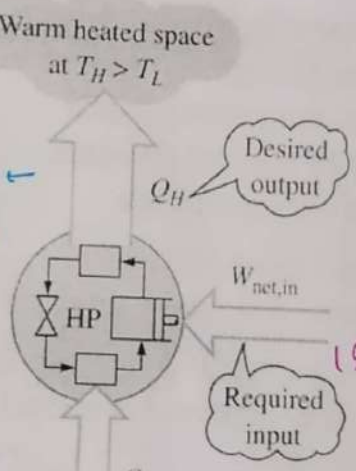
$$COP_R = \frac{Q_L}{Q_H - Q_L} = \frac{1}{Q_H/Q_L - 1}$$

The objective of a refrigerator is to remove Q_L from the cooled space.

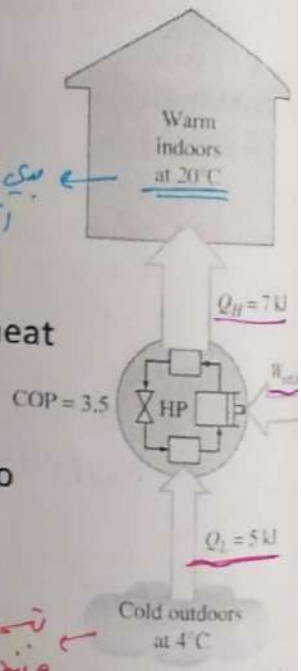
Can the value of COP_R be greater than unity? Yes

Heat Pumps

The objective of a heat pump is to supply heat Q_H into the warmer space.



The work supplied to a heat pump is used to extract energy from the cold outdoors and carry it into the warm indoors.



$$COP_{HP} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_H}{W_{net,in}}$$

$$COP_{HP} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - Q_L/Q_H}$$

$$COP_{HP} = COP_R + 1$$

for fixed values of Q_L and Q_H

Can the value of COP_{HP} be lower than unity?

What does $COP_{HP}=1$ represent?

CamScanner الممسوحة ضوئيا بـ

Heat Pumps

- Most heat pumps in operation today have a seasonally averaged COP of 2 to 3
- Most existing heat pumps use the cold outside air as the heat source in winter (*air-source* HP).
- In cold climates their efficiency drops considerably when temperatures are below the freezing point.
- In such cases, *geothermal* (*ground-source*) HP that use the ground as the heat source can be used.
- Such heat pumps are more expensive to install, but they are also more efficient.
- **Air conditioners** are basically refrigerators whose refrigerated space is a room or a building instead of the food compartment.
- The COP of a refrigerator decreases with decreasing refrigeration temperature.
- Therefore, it is not economical to refrigerate to a lower temperature than needed.

When installed backward, an air conditioner functions as a heat pump.

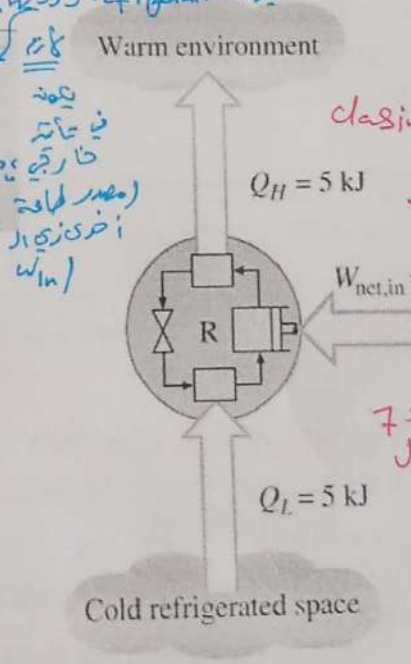
$$EER = 3.412\ COP_R$$

Energy efficiency rating (EER): The amount of heat removed from the cooled space in Btu's for 1 Wh (watthour) of electricity consumed.

The Second Law of Thermodynamics: Clasius Statement

It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower-temperature body to a higher-temperature body.

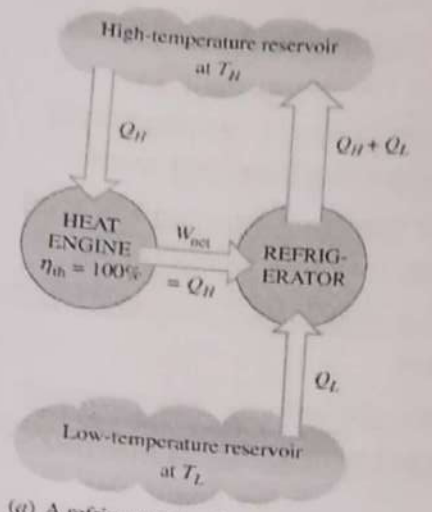
- *It states that a refrigerator cannot operate unless its compressor is driven by an external power source, such as an electric motor.*
- This way, the net effect on the surroundings involves the consumption of some energy in the form of work, in addition to the transfer of heat from a colder body to a warmer one.
- To date, no experiment has been conducted that contradicts the second law, and this should be taken as sufficient proof of its validity.



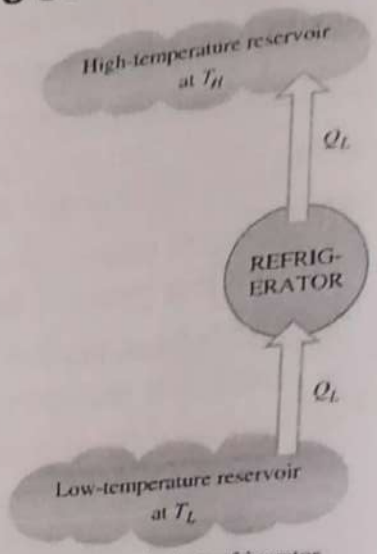
A refrigerator that violates the Clausius statement of the second law.

CamScanner ممسوحة ضوئيا بـ

Equivalence of the Two Statements



(a) A refrigerator that is powered by a 100 percent efficient heat engine



(b) The equivalent refrigerator

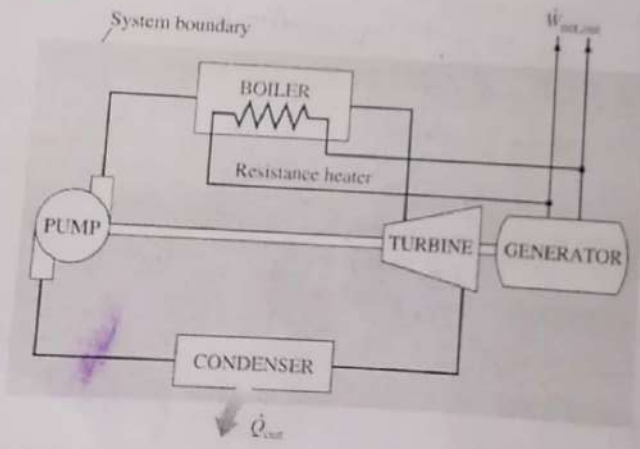
Proof that a violation of the Kelvin–Planck statement leads to the violation of the Clausius statement.

- The Kelvin–Planck and the Clausius statements are equivalent in their consequences, and either statement can be used as the expression of the second law of thermodynamics.
- Any device that violates the Kelvin–Planck statement also violates the Clausius statement, and vice versa.

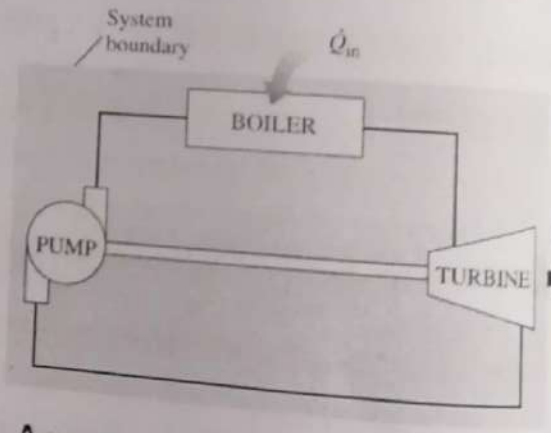
reversible work

PERPETUAL-MOTION MACHINES (PPM)

no entropy



A perpetual-motion machine that violates the first law (PMM1).



A perpetual-motion machine that violates the second law of thermodynamics (PMM2).

- Perpetual-motion machine: Any device that violates the first or the second
- A device that violates the first law (by *creating* energy) is called a PMM1.
- A device that violates the second law is called a PMM2.
- Despite numerous attempts, no perpetual-motion machine is known to have worked. ***If something sounds too good to be true, it probably is.***

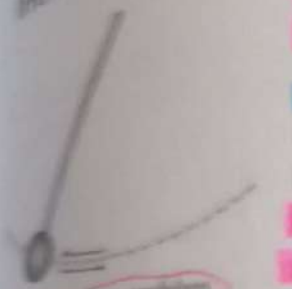
CamScanner الممسوحة ضوئيا بـ

REVERSIBLE AND IRREVERSIBLE PROCESSES

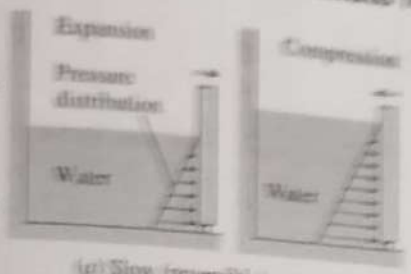
Reversible process: A process that can be reversed without leaving any trace on the surroundings.

Irreversible process: A process that is not reversible (Will leave traces).

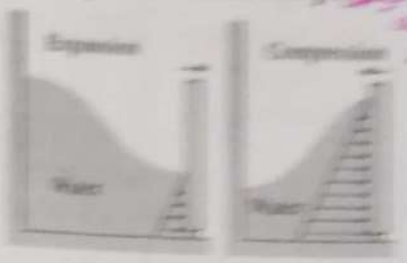
- All the processes occurring in nature are irreversible.
- Why are we interested in reversible processes? (1) they are easy to analyze and (2) they serve as idealized models (theoretical limits) to which actual processes can be compared.
- Some processes are more irreversible than others.
- We try to approximate reversible processes. Why?







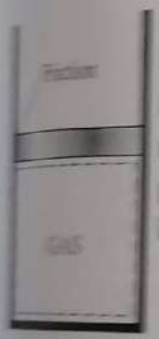
(a) Slow (reversible) process



(b) Fast (irreversible) process

Two familiar reversible processes.

Reversible processes deliver the most and consume the least work.



Friction renders a process irreversible.

- The factors that cause a process to be irreversible are called irreversibilities.
- They include friction, unrestrained expansion, mixing of two fluids, heat transfer across a finite temperature difference, electric resistance, inelastic deformation of solids, and chemical reactions.
- The presence of any of these effects renders a process irreversible.

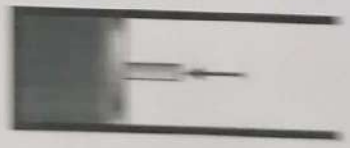


A reversible heat transfer process

Irreversibilities

(a) Heat transfer through a temperature difference is irreversible,

(b) The reverse process is impossible.



(a) Fast compression



(b) Fast expansion



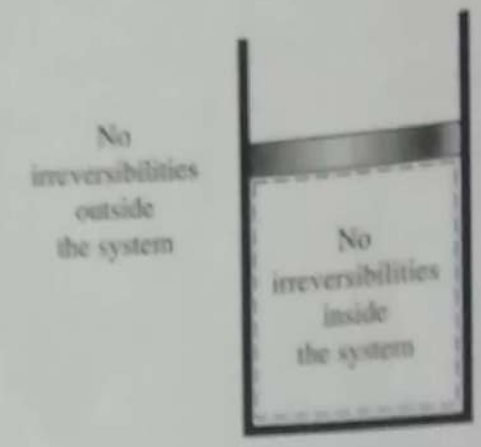
(c) Unrestrained expansion

Irreversible compression and expansion processes.

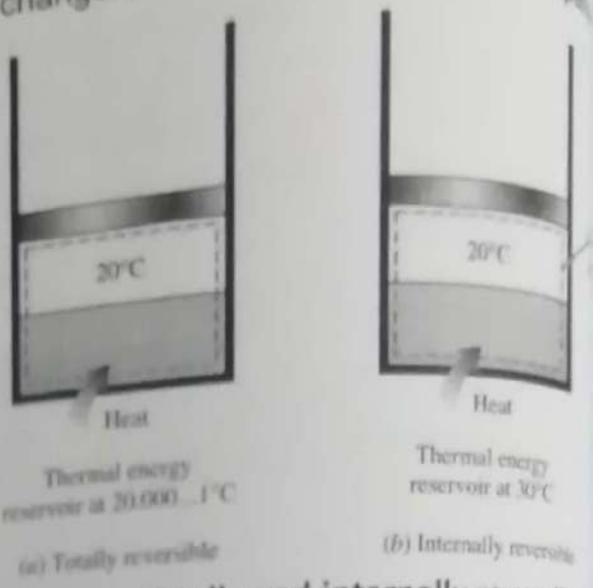
CamScanner الممسوحة ضوئيا بـ

Internally and Externally

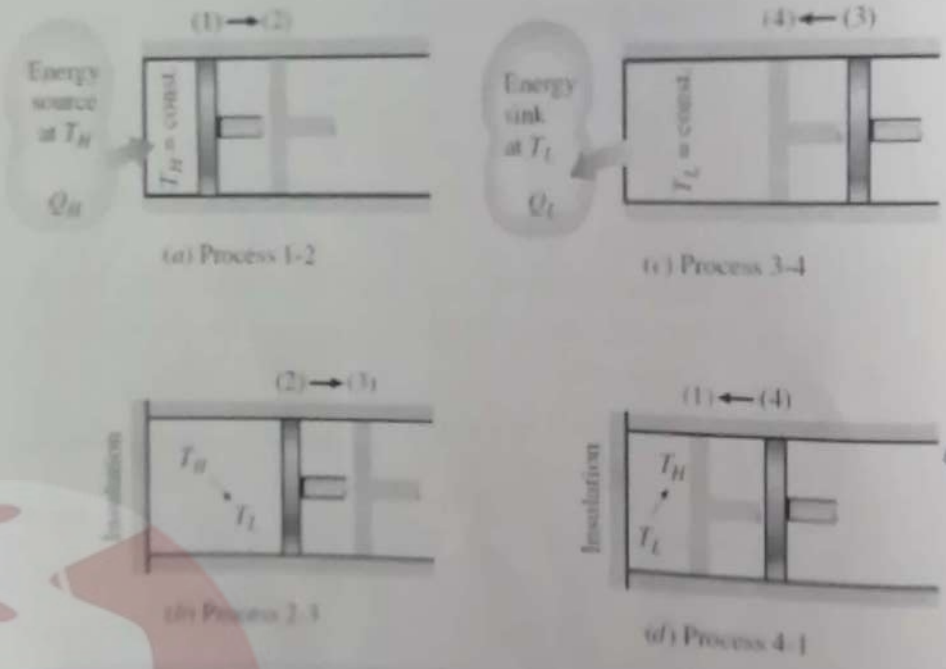
- Internally reversible process: If no irreversibilities occur within the system during the process.
- Externally reversible: If no irreversibilities occur outside the system boundaries during the process.
- Totally reversible process: It involves no irreversibilities within the system or its surroundings.
- A totally reversible process involves no heat transfer through a finite temperature difference, no nonquasi-equilibrium changes, and no friction or other dissipative effects.



A reversible process involves no internal and external irreversibilities.



Totally and internally reversible heat transfer processes.

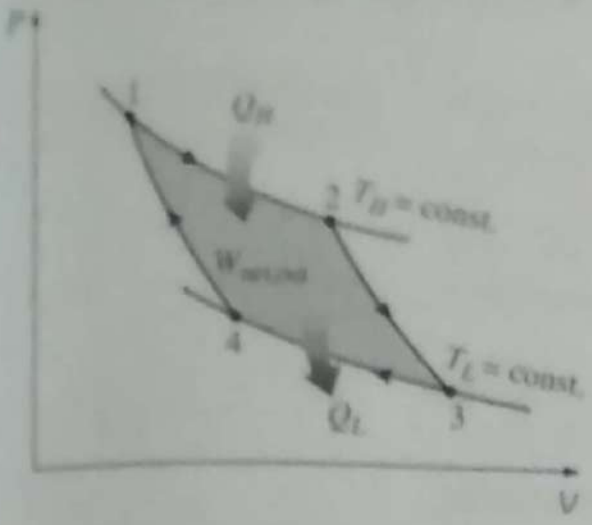


THE CARNOT CYCLE

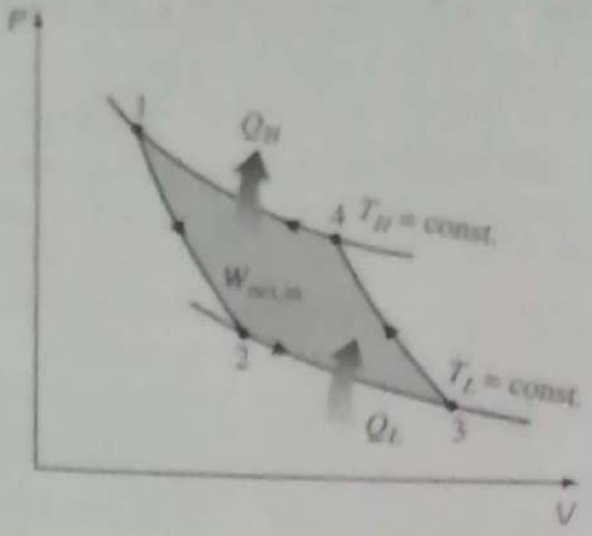
Execution of the Carnot cycle in a closed system

Reversible Isothermal Expansion (process 1-2, T_H = constant)
Reversible Adiabatic Expansion (process 2-3, temperature drops from T_H to
Reversible Isothermal Compression (process 3-4, T_L = constant)
Reversible Adiabatic Compression (process 4-1, temperature rises from T_L t

CamScanner الممسوحة ضوئيا بـ



P-V diagram of the Carnot cycle.



P-V diagram of the reversed Carnot cycle.

The Reversed Carnot Cycle

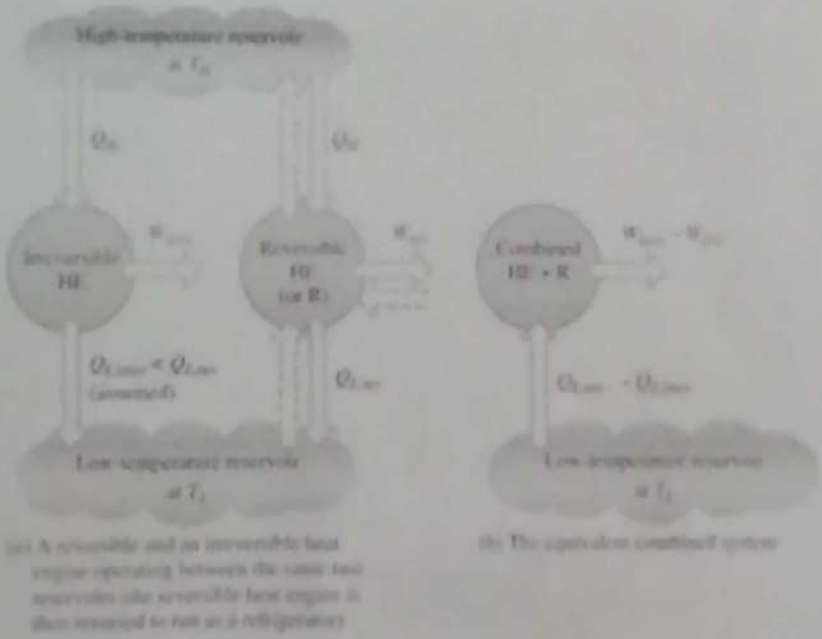
The Carnot heat-engine cycle is a totally reversible cycle.

Therefore, all the processes that comprise it can be *reversed*, in which case it becomes the **Carnot refrigeration cycle**.

THE CARNOT PRINCIPLES



The Carnot principles.



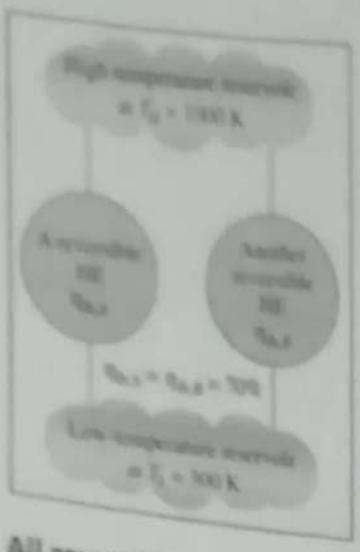
Proof of the first Carnot principle.

The efficiency of an irreversible heat engine is always less than the efficiency of a reversible one operating between the same two reservoirs.

The efficiencies of all reversible heat engines operating between the same two reservoirs are the same.

CamScanner الممسوحة ضوئيا بـ

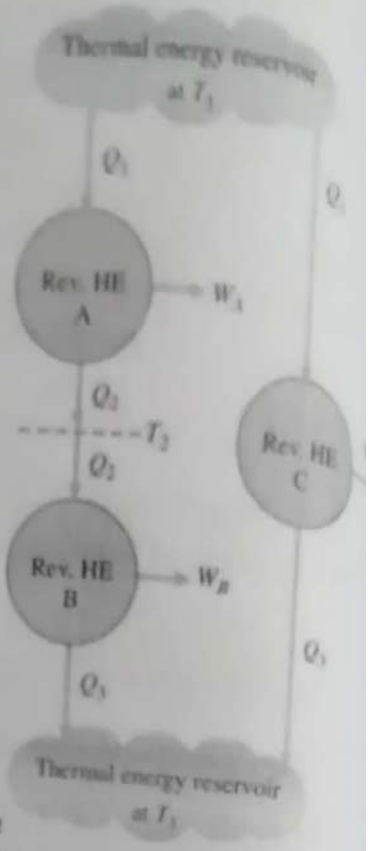
THE THERMODYNAMIC TEMPERATURE SCALE



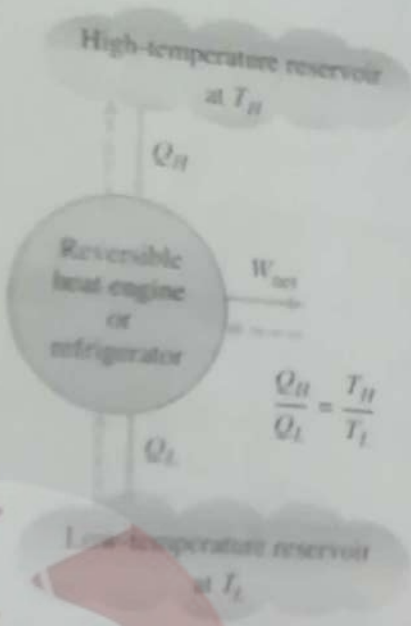
All reversible heat engines operating between the same two reservoirs have the same efficiency.

A temperature scale that is independent of the properties of the substances that are used to measure temperature is called a thermodynamic temperature scale.

Such a temperature scale offers great conveniences in thermodynamic calculations.

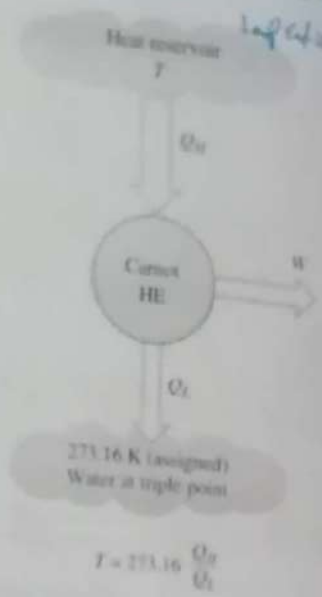


The arrangement of heat engines used to develop the thermodynamic temperature scale.



$$\frac{Q_H}{Q_L} = \frac{T_H}{T_L}$$

For reversible cycles, the heat transfer ratio Q_H/Q_L can be replaced by the absolute temperature ratio T_H/T_L.



A conceptual experimental setup to determine thermodynamic temperatures on the Kelvin scale by measuring heat transfers Q_H and Q_L.

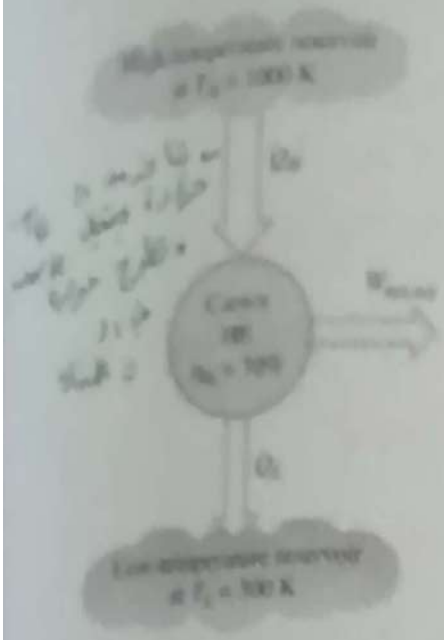
$$\left(\frac{Q_H}{Q_L}\right)_{rev} = \frac{T_H}{T_L}$$

This temperature scale is called the Kelvin scale, and the temperatures on this scale are called absolute temperatures.

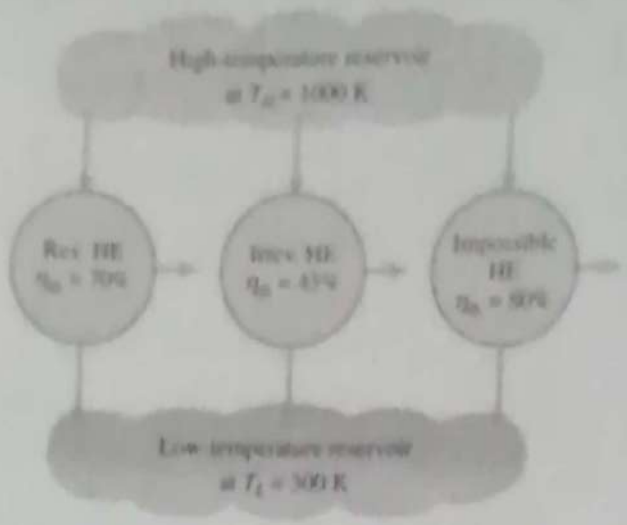
$$T(°C) = T(K) - 273.15$$

CamScanner الممسوحة ضوئيا بـ

THE CARNOT HEAT ENGINE



The Carnot heat engine is the most efficient of all heat engines operating between the same high- and low-temperature reservoirs.



No heat engine can have a higher efficiency than a reversible heat engine operating between the same high- and low-temperature reservoirs.

Any heat engine

$$\eta_{th} = 1 - \frac{Q_L}{Q_H}$$

Carnot heat engine

$$\eta_{th,rev} = 1 - \frac{T_L}{T_H}$$

$$\eta_{th} \begin{cases} < \eta_{th,rev} & \text{irreversible heat engine} \\ = \eta_{th,rev} & \text{reversible heat engine} \\ > \eta_{th,rev} & \text{impossible heat engine} \end{cases}$$

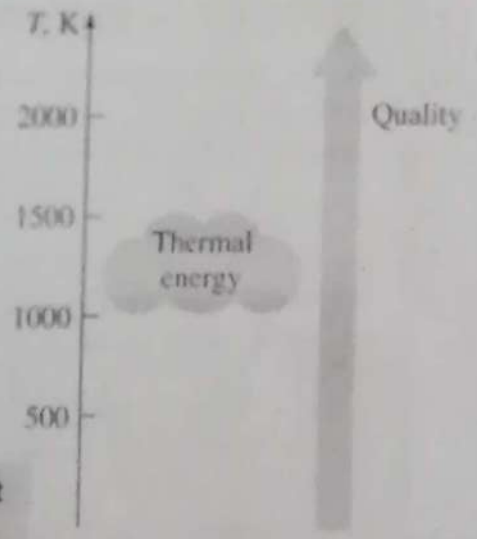
The Quality of Energy



T_H, K	η_{th}, %
925	67.2
800	62.1
700	56.7
500	39.4
350	13.4

$$\eta_{th,rev} = 1 - \frac{T_L}{T_H}$$

Can we use °C unit for temperature here?



The higher the temperature of the thermal energy, the higher its quality.

The fraction of heat that can be converted to work is a function of source temperature.

How do you increase the thermal efficiency of a Carnot heat engine? How about for actual heat engines?

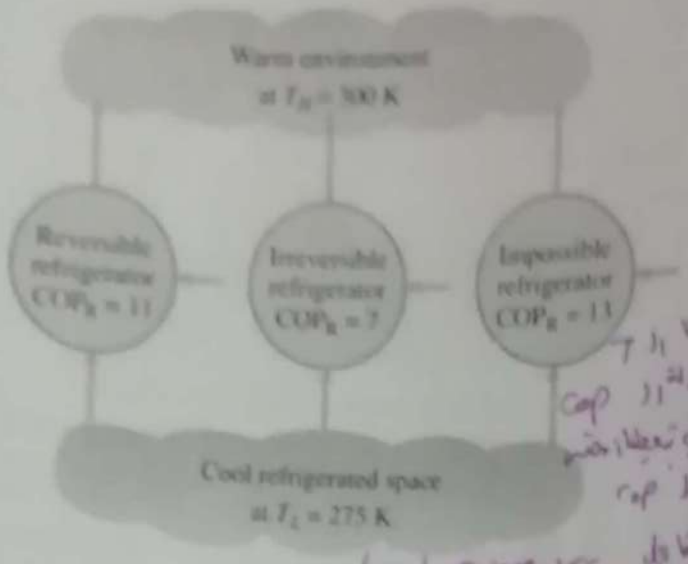
CamScanner الممسوحة ضوئيا بـ

THE CARNOT REFRIGERATOR AND HEAT PUMP

Any refrigerator or heat pump

$$COP_R = \frac{1}{Q_H/Q_L - 1}$$

$$COP_{HP} = \frac{1}{1 - Q_L/Q_H}$$



Carnot refrigerator or heat

$$COP_{HP,rev} = \frac{1}{1 - T_L/T_H}$$

$$COP_{R,rev} = \frac{1}{T_H/T_L - 1}$$

No refrigerator can have a higher COP than a reversible refrigerator operating between the same temperature limits.

How do you increase the COP of a Carnot refrigerator or heat pump? How about for actual ones?

EXAMPLE 6–1 Net Power Production of a Heat Engine

Heat is transferred to a heat engine from a furnace at a rate of 80 MW. If the rate of waste heat rejection to a nearby river is 50 MW, determine the net power output and the thermal efficiency for this heat engine.

SOLUTION The rates of heat transfer to and from a heat engine are given. The net power output and the thermal efficiency are to be determined.

Assumptions Heat losses through the pipes and other components are negligible.

Analysis A schematic of the heat engine is given in Fig. 6–16. The furnace serves as the high-temperature reservoir for this heat engine and the river as the low-temperature reservoir. The given quantities can be expressed as

$$\dot{Q}_H = 80 \text{ MW} \quad \text{and} \quad \dot{Q}_L = 50 \text{ MW}$$

The net power output of this heat engine is

$$\dot{W}_{net,out} = \dot{Q}_H - \dot{Q}_L = (80 - 50) \text{ MW} = 30 \text{ MW}$$

Then the thermal efficiency is easily determined to be

$$\eta_{th} = \frac{\dot{W}_{net,out}}{\dot{Q}_H} = \frac{30 \text{ MW}}{80 \text{ MW}} = 0.375 \text{ (or } 37.5\%)$$

Discussion Note that the heat engine converts 37.5 percent of the heat it receives to work.

الممسوحة ضوئيا بـ CamScanner

EXAMPLE 6–3 Heat Rejection by a Refrigerator

The food compartment of a refrigerator, shown in Fig. 6–23, is maintained at 4°C by removing heat from it at a rate of 360 kJ/min. If the required power input to the refrigerator is 2 kW, determine (a) the coefficient of performance of the refrigerator and (b) the rate of heat rejection to the room that houses the refrigerator.

SOLUTION The power consumption of a refrigerator is given. The COP and the rate of heat rejection are to be determined.

Assumptions Steady operating conditions exist.

Analysis (a) The coefficient of performance of the refrigerator is

$$\text{COP}_R = \frac{Q_L}{W_{\text{net,in}}} = \frac{360 \text{ kJ/min}}{2 \text{ kW}}\left(\frac{1 \text{ kW}}{60 \text{ kJ/min}}\right) = 3$$

That is, 3 kJ of heat is removed from the refrigerated space for each kJ of work supplied.

(b) The rate at which heat is rejected to the room that houses the refrigerator is determined from the conservation of energy relation for cyclic devices,

$$Q_H = Q_L + W_{\text{net,in}} = 360 \text{ kJ/min} + (2 \text{ kW})\left(\frac{60 \text{ kJ/min}}{1 \text{ kW}}\right) = 480 \text{ kJ/min}$$

Discussion Notice that both the energy removed from the refrigerated space as heat and the energy supplied to the refrigerator as electrical work eventually show up in the room air and become part of the internal energy of the air. This demonstrates that energy can change from one form to another, can move from one place to another, but is never destroyed during a process.

EXAMPLE 6–5 Analysis of a Carnot Heat Engine

A Carnot heat engine, shown in Fig. 6–47, receives 500 kJ of heat per cycle from a high-temperature source at 652°C and rejects heat to a low-temperature sink at 30°C. Determine (a) the thermal efficiency of this Carnot engine and (b) the amount of heat rejected to the sink per cycle.

SOLUTION The heat supplied to a Carnot heat engine is given. The thermal efficiency and the heat rejected are to be determined.

Analysis (a) The Carnot heat engine is a reversible heat engine, and so its efficiency can be determined from Eq. 6–18 to be

$$\eta_{th,rev} = 1 - \frac{T_L}{T_H} = 1 - \frac{(30 + 273) \text{ K}}{(652 + 273) \text{ K}} = 0.672$$

That is, this Carnot heat engine converts 67.2 percent of the heat it receives to work.

(b) The amount of heat rejected Q_L by this reversible heat engine is easily determined from Eq. 6–16 to be

$$Q_{L,rev} = \frac{T_L}{T_H} Q_{H,rev} = \frac{(30 + 273) \text{ K}}{(652 + 273) \text{ K}} (500 \text{ kJ}) = 164 \text{ kJ}$$

Discussion Note that this Carnot heat engine rejects to a low-temperature sink 164 kJ of the 500 kJ of heat it receives during each cycle.

CamScanner الممسوحة ضوئيا بـ

EXAMPLE 6–6 **A Carnot Refrigeration Cycle Operating in the Saturation Dome**

A Carnot refrigeration cycle is executed in a closed system in the saturated liquid–vapor mixture region using 0.8 kg of refrigerant-134a as the working fluid (Fig. 6–51). The maximum and the minimum temperatures in the cycle are 20 and −8°C, respectively. It is known that the refrigerant is saturated liquid at the end of the heat rejection process, and the net work input to the cycle is 15 kJ. Determine the fraction of the mass of the refrigerant that vaporizes during the heat addition process and the pressure at the end of the heat rejection process.

SOLUTION A Carnot refrigeration cycle is executed in a closed system. The mass fraction of the refrigerant that vaporizes during the heat addition process and the pressure at the end of the heat rejection process are to be determined.

Assumptions The refrigerator operates on the ideal Carnot cycle.

Analysis Knowing the high and low temperatures, the coefficient of performance of the cycle is

$$\text{COP}_R = \frac{1}{T_H/T_L - 1} = \frac{1}{(20 + 273\text{ K})/(-8 + 273\text{ K}) - 1} = 9.464$$

The amount of cooling is determined from the definition of the coefficient of performance to be

$$Q_L = \text{COP}_R \times W_{net} = (9.464)(15\text{ kJ}) = 142\text{ kJ}$$

The enthalpy of vaporization R-134a at −8°C is $h_{fg} = 204.59$ kJ/kg (Table A-11). Then the amount of refrigerant that vaporizes during heat absorption becomes

$$Q_L = m_{vap} h_{fg@-8°C} \rightarrow m_{vap} = \frac{142\text{ kJ}}{204.59\text{ kJ/kg}} = 0.694\text{ kg}$$

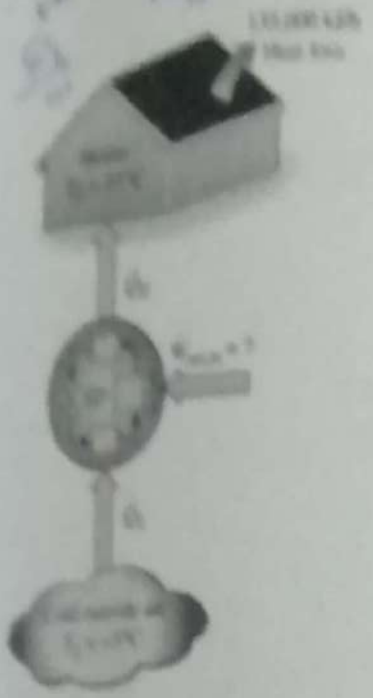
Therefore, the fraction of mass that vaporized during heat addition process to the refrigerant is

$$\text{Mass fraction} = \frac{m_{vap}}{m_{total}} = \frac{0.694\text{ kg}}{0.8\text{ kg}} = 0.868 \text{ or } 86.8\%$$

The pressure at the end of heat rejection process is simply the saturation pressure at heat rejection temperature,

$$P_4 = P_{sat@20°C} = 572.1\text{ kPa}$$

Discussion Carnot cycle is an idealized refrigeration cycle, thus it cannot be achieved in practice. Practical refrigeration cycles are analyzed in Chap. 11.



EXAMPLE 6–7 Heating a House by a Carnot Heat Pump

A heat pump is to be used to heat a house during the winter, as shown in Fig. 6–52. The house is to be maintained at 21°C at all times. The house is estimated to be losing heat at a rate of 135,000 kJ/h when the outside temperature drops to −5°C. Determine the minimum power required to drive this heat pump.

SOLUTION A heat pump maintains a house at a certain temperature. The required minimum power input to the heat pump is to be determined.

Assumptions Steady operating conditions exist.

Analysis The heat pump must supply heat to the house at a rate of Q_H = 135,000 kJ/h = 37.5 kW. The power requirements are minimum when a reversible heat pump is used to do the job. The COP of a reversible heat pump operating between the house and the outside air is

$$\mathrm{COP}_{\mathrm{HP,rev}} = \frac{1}{1 - T_L/T_H} = \frac{1}{1 - (-5 + 273\ \mathrm{K})/(21 + 273\ \mathrm{K})} = 11.3$$

Then, the required power input to this reversible heat pump becomes

$$\dot{W}_{\mathrm{net,in}} = \frac{\dot{Q}_H}{\mathrm{COP}_{\mathrm{HP}}} = \frac{37.5\ \mathrm{kW}}{11.3} = 3.32\ \mathrm{kW}$$

CamScanner الممسوحة ضوئيا بـ

CamScanner الممسوحة ضوئيا بـ

* ال law ده بيقول ان الحرارة موجودة وبتنتقل من شكل لشكل او مكان لمكان

* ال law ده بيقول ان الحرارة اتنقلت اتحولت dissipated energy :: disintegrated

وعبارة lost

← وانتقال الحرارة من الجزيئة كل مرة بتغير فيها ال quality of energy

← ال law ده بيقول ان في حاجة اسمها spontaneous transfer ← وده بيخلي فيها losses و generation

In entropy (زيادة في الـ entropy)

← عشان نقدر نقيس الـ S_u بنحتاج لـ change of entropy وده concept

← لازم ال energy نعرفها انها ability to do work (تعريفها من كتير واسع)

← ال entropy فيها خوف اكتر

Thermodynamics

Chapter 7

Concept & Calculations of ENTROPY

Thermodynamics: An Engineering Approach
Yunus A. Cengel, Michael A. Boles, Mehmet Kanoglu
McGraw-Hill

Dr. Ahmad M. AbuYaghi
October 2023

ENTROPY

Clausius inequality

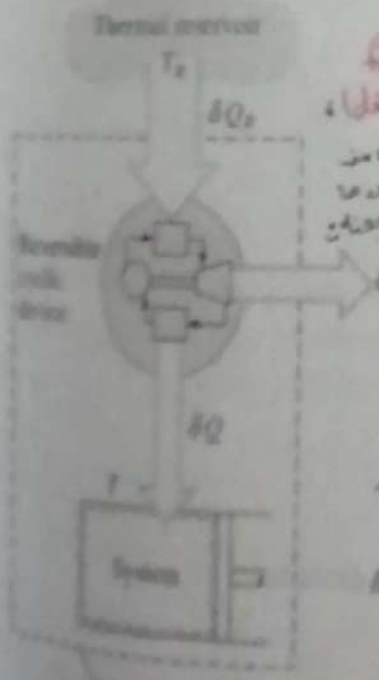
$$\oint \frac{\delta Q}{T} \le 0$$

$$\oint \left(\frac{\delta Q}{T}\right)_{\text{int rev}} = 0$$

$$dS = \left(\frac{\delta Q}{T}\right)_{\text{int rev}} \quad \text{(kJ/K)}$$

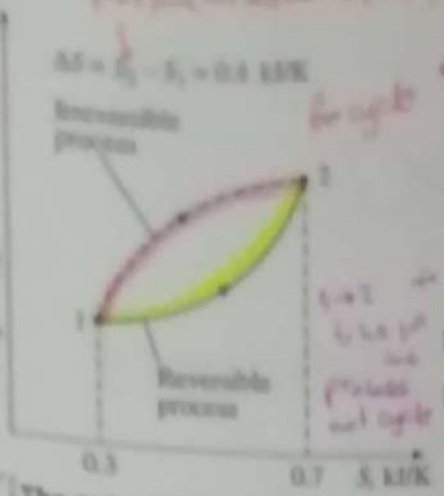
Formal definition of entropy

$$\Delta S = S_2 - S_1 = \int_1^2 \left(\frac{\delta Q}{T}\right)_{\text{int rev}}$$



The system considered in the development of the Clausius inequality.

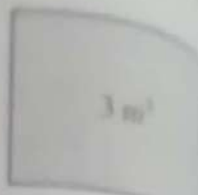
The equality in the Clausius inequality holds for totally or just internally reversible cycles and the inequality for the irreversible ones.



A quantity whose cyclic integral is zero (i.e., a property like volume)

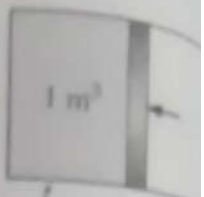
Entropy is an extensive property of a system.





The entropy change between two specified states is the same whether the process is reversible or irreversible.

The net change in volume (a property) during a cycle is always zero.

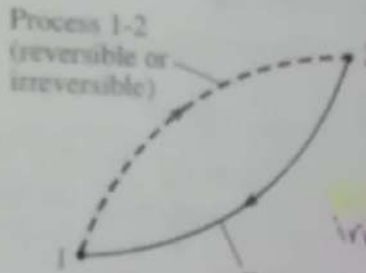


A Special Case: Internally Reversible Isothermal Heat Transfer Processes

$$\Delta S = \int_1^2 \left(\frac{\delta Q}{T}\right)_{\text{int rev}} = \int_1^2 \left(\frac{\delta Q}{T_0}\right)_{\text{int rev}} = \frac{1}{T_0}\int_1^2 (\delta Q)_{\text{int rev}}$$

This equation is particularly useful for determining the entropy changes of thermal energy reservoirs.

THE INCREASE OF ENTROPY PRINCIPLE



A cycle composed of a reversible and an irreversible process.

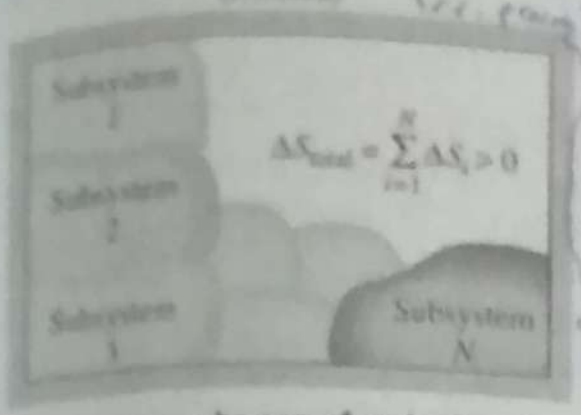
$$dS \geq \frac{\delta Q}{T}$$

The equality holds for an internally reversible process and the inequality for an irreversible process.

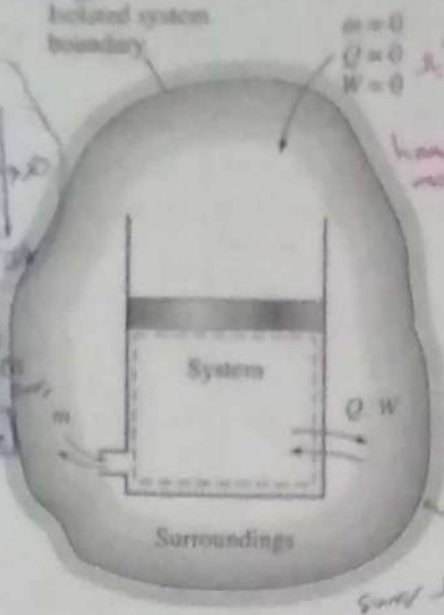
- Some entropy is generated or created during an irreversible process; this generation is due entirely to the presence of irreversibilities.
- The entropy generation S_{gen} is always a positive quantity or zero.

Can the entropy of a system during a process decrease?

الممسوحة ضوئيا بـ CamScanner



The entropy change of an isolated system is the sum of the entropy changes of its components and is never less than zero.



A system and its surroundings form an isolated system.

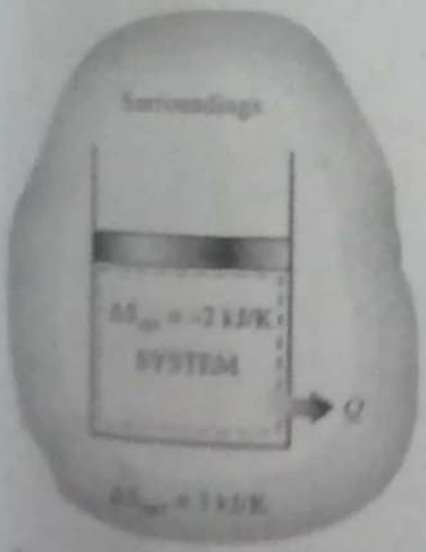
$$\Delta S_{isolated} \geq 0$$

$$S_{gen} = \Delta S_{total} = \Delta S_{sys} + \Delta S_{surr} \geq 0$$

$$S_{gen} \begin{cases} > 0 & \text{Irreversible process} \\ = 0 & \text{Reversible process} \\ < 0 & \text{Impossible process} \end{cases}$$

The increase of entropy principle

Some Remarks about Entropy



The entropy change of a system can be negative, but the entropy generation cannot.

1) Processes can occur in a *certain* direction only, not in *any* direction. A process must proceed in the direction that complies with the increase of entropy principle, that is, $S_{gen} \geq 0$. A process that violates this principle is impossible.

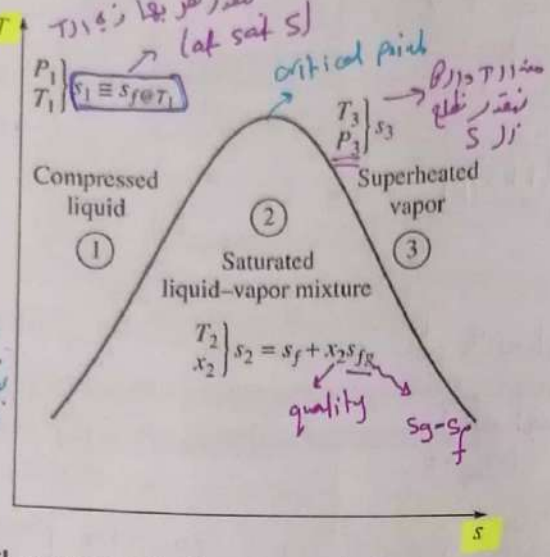
2) Entropy is a *nonconserved property*, and there is *no* such thing as the *conservation of entropy principle*. Entropy is conserved during the idealized reversible processes only and increases during *all* actual processes.

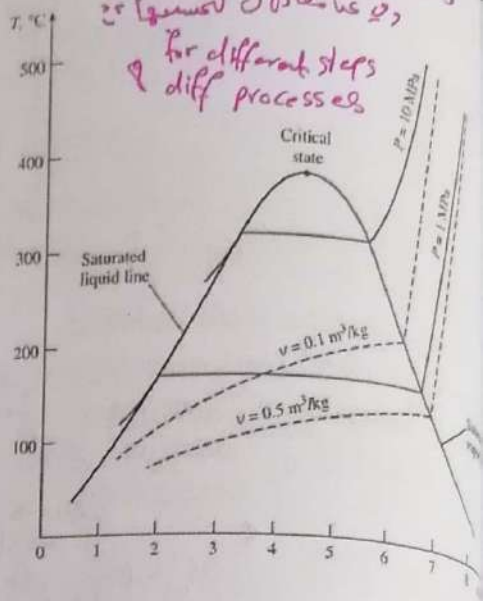
3) The performance of engineering systems is degraded by the presence of irreversibilities, and *entropy generation* is a measure of the magnitudes of the irreversibilities during that process. It is also used to establish criteria for the performance of engineering devices.

ask recieve
الممسوحة ضوئيا بـ CamScanner

ENTROPY CHANGE OF PURE SUBSTANCES

Entropy is a property, and thus the value of entropy of a system is fixed once the state of the system is fixed.





Schematic of the *T-s* diagram for wa

The entropy of a pure substance is determined from the tables (like other properties).

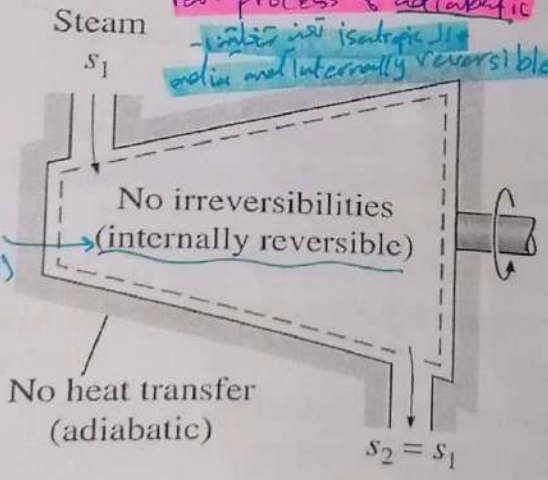
Entropy change:

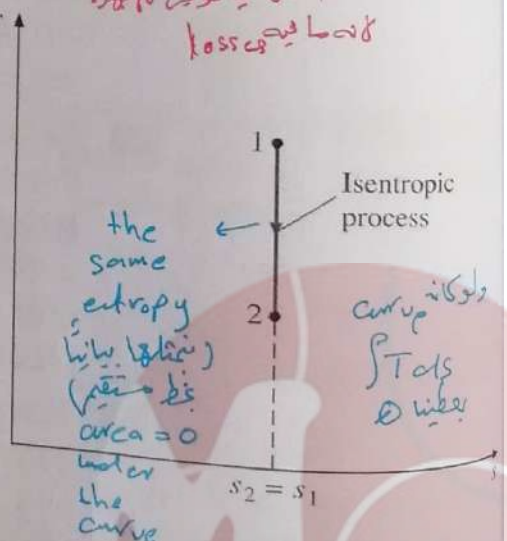
$$\Delta S = m\Delta s = m(s_2 - s_1) \quad \text{(kJ}$$

ISENTROPIC PROCESSES

❑ A process during which the entropy remains constant is called an **isentropic process**.

$$\Delta s = 0 \quad \text{or} \quad s_2 = s_1 \quad \text{(kJ/kg}$$



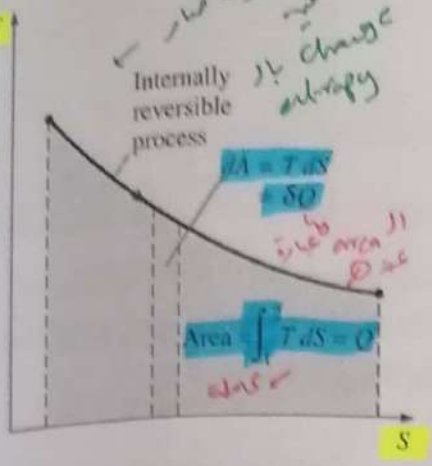


During an internally reversible, adiabatic (isentropic) process, the entropy remains constant.

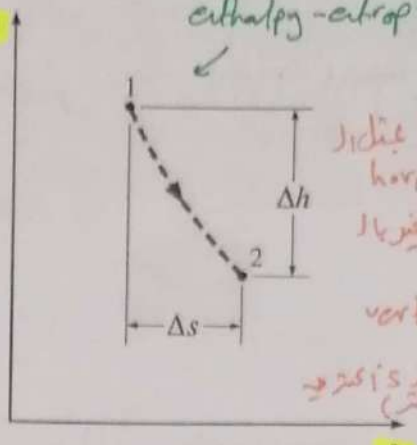
The isentropic process appears as a *vertical* line segment on a *T-s* diagra

CamScanner المسوحة ضوئيا بـ

PROPERTY DIAGRAMS INVOLVING ENTROPY



On a *T-S* diagram, the area under the process curve represents the heat transfer for internally reversible processes.



$$\delta Q_{\text{int rev}} = T\,dS \qquad Q_{\text{int rev}} = \int_1^2 T\,dS$$

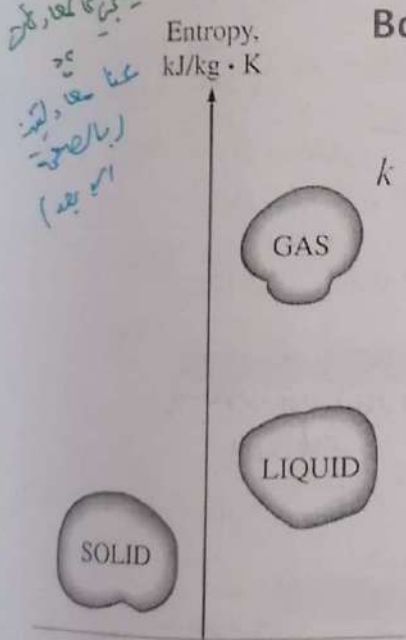
$$\delta q_{\text{int rev}} = T\,ds \qquad q_{\text{int rev}} = \int_1^2 T\,ds$$

$$Q_{\text{int rev}} = T_0\,\Delta S \qquad q_{\text{int rev}} = T_0\,\Delta s$$

For adiabatic steady-flow devices, the vertical distance Δh on an *h-s* diagram is a measure of work and the horizontal distance Δs is a measure of irreversibilities.

Mollier diagram: The *h-s* diagram

WHAT IS ENTROPY?

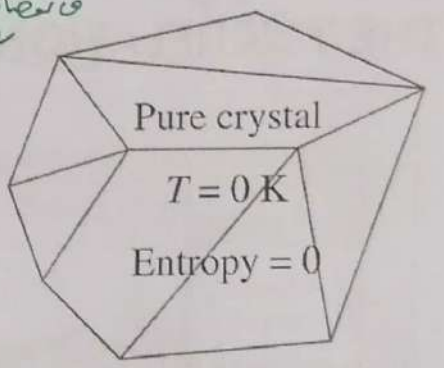


The level of molecular disorder (entropy) of a substance increases as it melts or evaporates.

Boltzmann relation:

$$S = k \ln p$$

$$k = 1.3806 \times 10^{-23}\ \text{J/K}$$

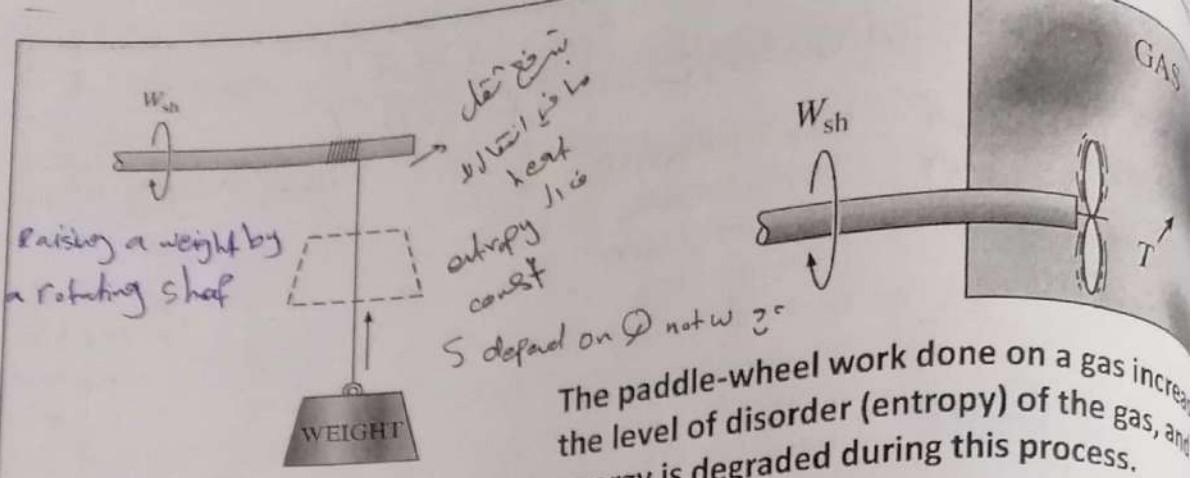


The third law of thermodynamics:
A pure crystalline substance at absolute zero temperature is in perfect order, and its entropy is zero.



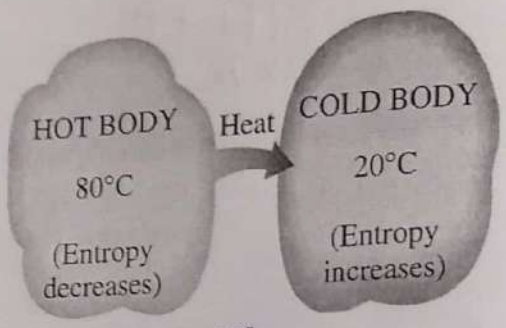
Disorganized energy does not create much useful effect, no matter how large it is.

CamScanner الممسوحة ضوئيا بـ



The paddle-wheel work done on a gas increa the level of disorder (entropy) of the gas, an energy is degraded during this process.

In the absence of friction, raising a weight by a rotating shaft does not create any disorder (entropy), and thus energy is not degraded during this process.



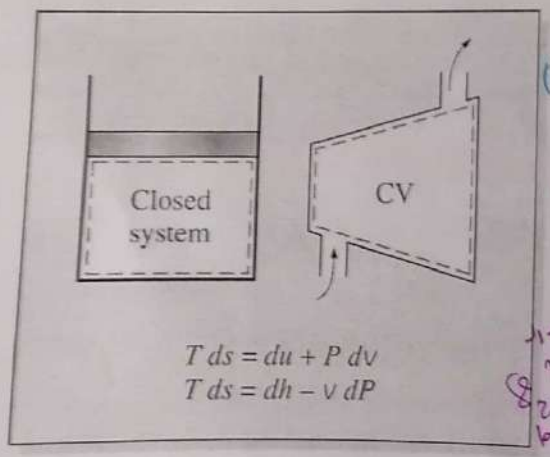
During a heat tran process, the net entropy increases. (The increase in th entropy of the cold body more than of the decrease in the entropy of the hot body.)

$H_{2(g)} + I_{2(g)} = 2\,HI_{(g)}$

$CaCO_{3(s)} \rightleftharpoons CaO_{(s)} + CO_{2(g)}$ → Increase entropy

How entropy change during chemical rxns ?

THE *T ds* RELATIONS



$$\delta Q_{\text{int rev}} - \delta W_{\text{int rev,out}} = dU \quad \text{(1st law)}$$

$$\delta Q_{\text{int rev}} = T\,dS \quad \text{(2nd law)}$$

$$\delta W_{\text{int rev,out}} = P\,dV$$

$$T\,dS = dU + P\,dV \quad \text{(kJ)}$$

$$T\,ds = du + P\,dv \quad \text{(kJ/kg)}$$

First *T ds*, or *Gibbs* equation:

$$h = u + Pv$$

$$dh = du + P\,dv + v\,dP$$

$$T\,ds = du + P\,dv$$

$$T\,ds = dh - v\,dP$$

Second *T ds* equation:

$$ds = \frac{du}{T} + \frac{P\,dv}{T}$$

$$ds = \frac{dh}{T} - \frac{v\,dP}{T}$$

The *T ds* relations are valid for both reversible and irreversible processes and for both closed and open systems.

Differential chang entropy in terms o other properties

الممسوحة ضوئيا بـ CamScanner

ENTROPY CHANGE OF LIQUIDS AND SOLIDS

$$ds = \frac{du}{T} + \frac{P\,dv}{T}$$

Liquids and solids can be approximated as *incompressible substances* since their specific volumes remain nearly constant during a process.

Since $dv \equiv 0$ for liquids and solids

$$ds = \frac{du}{T} = \frac{c\,dT}{T}$$

since $c_p = c_v = c$ and $du = c\,dT$

$$\text{Liquids, solids: } \Delta s = s_2 - s_1 = \int_1^2 c(T)\frac{dT}{T} \cong c_{avg}\ln\frac{T_2}{T_1} \quad (\text{kJ/kg}\cdot\text{K})$$

For and isentropic process of an incompressible substance:

$$\text{Isentropic: } s_2 - s_1 = c_{avg}\ln\frac{T_2}{T_1} = 0 \rightarrow T_2 = T_1$$

THE ENTROPY CHANGE OF IDEAL GASES

From the first *T ds* relation

$$ds = \frac{du}{T} + \frac{P\,dv}{T}$$

$$du = c_v\,dT$$

$$P = RT/v$$

$$ds = c_v\frac{dT}{T} + R\frac{dv}{v}$$

$$s_2 - s_1 = \int_1^2 c_v(T)\frac{dT}{T} + R\ln\frac{v_2}{v_1}$$

From the second *T ds* relation

$$ds = \frac{dh}{T} - \frac{v\,dP}{T}$$

$$dh = c_p\,dT$$

$$v = RT/P$$

$$s_2 - s_1 = \int_1^2 c_p(T)\frac{dT}{T} - R\ln\frac{P_2}{P_1}$$

$$Pv = RT$$
$$du = C_v\,dT$$
$$dh = C_p\,dT$$

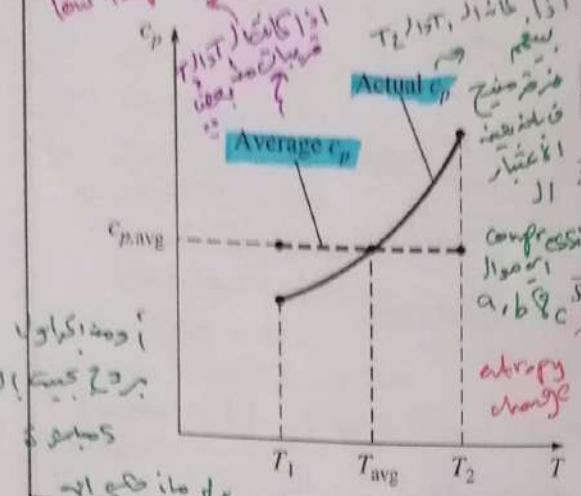
CamScanner الممسوحة ضوئيا بـ

Constant Specific Heats (Approximate Analysis)

$$s_2 - s_1 = \int_1^2 c_v(T)\frac{dT}{T} + R\ln\frac{v_2}{v_1} \longrightarrow s_2 - s_1 = c_{v,avg}\ln\frac{T_2}{T_1} + R\ln\frac{v_2}{v_1}$$

$$s_2 - s_1 = \int_1^2 c_p(T)\frac{dT}{T} - R\ln\frac{P_2}{P_1} \longrightarrow s_2 - s_1 = c_{p,avg}\ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1}$$

(kJ/kg·K)



Entropy change of an ideal gas on a unit–mole basis:

$$\bar{s}_2 - \bar{s}_1 = \bar{c}_{v,avg}\ln\frac{T_2}{T_1} + R_u\ln\frac{v_2}{v_1} \quad (\text{kJ/kmol})$$

$$\bar{s}_2 - \bar{s}_1 = \bar{c}_{p,avg}\ln\frac{T_2}{T_1} - R_u\ln\frac{P_2}{P_1} \quad (\text{kJ/kmol})$$

Under the constant-specific-heat assumption, the specific heat is assumed to be constant at some average value.

Variable Specific Heats (Exact Analysis)

We choose absolute zero as the reference temperature and define a function s° as

$$s^\circ = \int_0^T c_p(T)\frac{dT}{T}$$

$$\int_1^2 c_p(T)\frac{dT}{T} = s_2^\circ - s_1^\circ$$

On a unit–mass basis:

$$s_2 - s_1 = s_2^\circ - s_1^\circ - R\ln\frac{P_2}{P_1} \quad (\text{kJ/kg}\cdot\text{K})$$

On a unit–mole basis:

$$\bar{s}_2 - \bar{s}_1 = \bar{s}_2^\circ - \bar{s}_1^\circ - R_u\ln\frac{P_2}{P_1} \quad (\text{kJ/kmol}\cdot\text{K})$$

T, K	s°, kJ/kg·K
.	.
.	.
.	.
300	1.70203
310	1.73498
320	1.76690
.	.
.	.
.	.

(Table A-17)

The entropy of an ide gas depends on both and P. The function s represents only the temperature-depende part of entropy.

CamScanner الممسوحة ضوئيا بـ

Isentropic Processes of Ideal Gases

Constant Specific Heats (Approximate Analysis)

$$s_2 - s_1 = c_{v,avg} \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1}$$

Setting this eq. equal to zero, we get:

$$\ln \frac{T_2}{T_1} = -\frac{R}{c_v} \ln \frac{v_2}{v_1} \qquad \ln \frac{T_2}{T_1} = \ln \left(\frac{v_1}{v_2}\right)^{R/c_v}$$

$$R = c_p - c_v \quad k = c_p/c_v$$

and thus $R/c_v = k - 1$

$$\left(\frac{T_2}{T_1}\right)_{s=\text{const.}} = \left(\frac{v_1}{v_2}\right)^{k-1}$$

$$\left(\frac{T_2}{T_1}\right)_{s=\text{const.}} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k}$$

$$\left(\frac{P_2}{P_1}\right)_{s=\text{const.}} = \left(\frac{v_1}{v_2}\right)^{k}$$

The isentropic relations of ideal gases are valid for the isentropic processes of ideal gases only.

$$Tv^{k-1} = \text{constant}$$

$$TP^{(1-k)/k} = \text{constant}$$

$$Pv^k = \text{constant}$$

$$P_1 v_1^k = P_2 v_2^k$$

Isentropic Processes of Ideal Gases

Variable Specific Heats (Exact Analysis)

$$0 = s_2^\circ - s_1^\circ - R \ln \frac{P_2}{P_1} \longrightarrow s_2^\circ = s_1^\circ + R \ln \frac{P_2}{P_1}$$

Relative Pressure and Relative Specific Volume

$$\frac{P_2}{P_1} = \exp \frac{s_2^\circ - s_1^\circ}{R}$$

$\exp(s^\circ/R)$ is the relative pressure P_r.

$$\frac{P_2}{P_1} = \frac{\exp(s_2^\circ/R)}{\exp(s_1^\circ/R)}$$

$$\left(\frac{P_2}{P_1}\right)_{s=\text{const.}} = \frac{P_{r2}}{P_{r1}}$$

$$\frac{P_1 v_1}{T_1} = \frac{P_2 v_2}{T_2} \rightarrow \frac{v_2}{v_1} = \frac{T_2}{T_1}\frac{P_1}{P_2} = \frac{T_2}{T_1}\frac{P_{r1}}{P_{r2}} = \frac{T_2/P_{r2}}{T_1/P_{r1}}$$

$$\left(\frac{v_2}{v_1}\right)_{s=\text{const.}} = \frac{v_{r2}}{v_{r1}}$$

T/P_r is the relative specific volume v_r.

The use of P_r data for calculating the final temperature during an isentropic process.

Process: isentropic
Given: P_1, T_1, and P_2
Find: T_2

T	P_r
T_2	$P_{r2} = \frac{P_2}{P_1} P_{r1}$
T_1	P_{r1}

Process: isentropic
Given: v_1, T_1, and v_2
Find: T_2

T	v_r
T_2	$v_{r2} = \frac{v_2}{v_1} v_{r1}$
T_1	v_{r1}

The use of v_r data for calculating the final temperature during an isentropic process

CamScanner المسوحة ضوئيا بـ

REVERSIBLE STEADY-FLOW WORK

$$\delta q_{rev} - \delta w_{rev} = dh + dke + dpe$$

$$\delta q_{rev} = T\,ds \quad \text{(Eq. 7–16)}$$
$$T\,ds = dh - v\,dP \quad \text{(Eq. 7–24)}$$

$$\delta q_{rev} = dh - v\,dP$$

$$-\delta w_{rev} = v\,dP + dke + dpe$$

$$w_{rev} = -\int_1^2 v\,dP - \Delta ke - \Delta pe$$

When kinetic and potential energies are negligible

$$w_{rev} = -\int_1^2 v\,dP$$

$$w_{rev,in} = \int_1^2 v\,dP + \Delta ke + \Delta pe$$

$$w_{rev} = -v(P_2 - P_1) - \Delta ke - \Delta pe$$

For the steady flow of a liquid through a device that involves no work interactions (such as a pipe section), the work term is zero (Bernoulli equation):

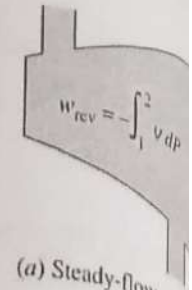
$$v(P_2 - P_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) = 0$$

$$w = -\int_1^2 v\,dP$$

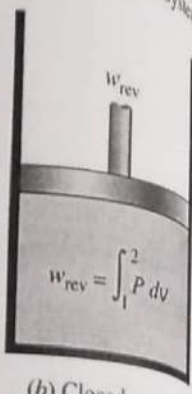
$$W = -\int_1^2 V\,dP$$

$$W = -\int_1^2 V\,dP$$

The larger the specific volume, the greater the work produced (or consumed) by a steady-flow device.



(a) Steady-flow system



(b) Closed system

Reversible work relations for steady flow and closed systems.

Proof that Steady-Flow Devices Deliver the Most and Consume the Least Work when the Process Is Reversible:

Taking heat input and work output positive:

$$\delta q_{act} - \delta w_{act} = dh + dke + dpe \quad \text{Actual}$$

$$\delta q_{rev} - \delta w_{rev} = dh + dke + dpe \quad \text{Reversible}$$

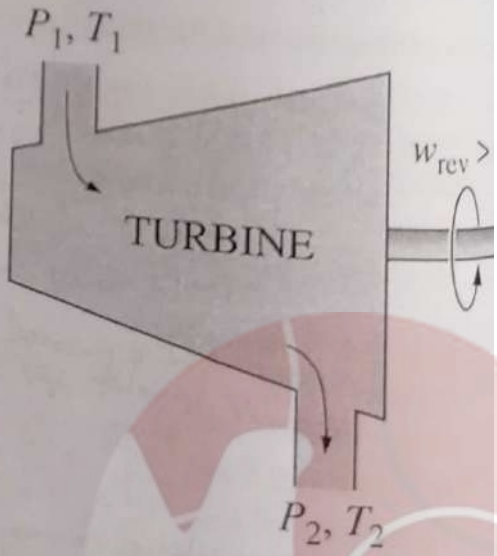
$$\delta q_{act} - \delta w_{act} = \delta q_{rev} - \delta w_{rev}$$
$$\delta w_{rev} - \delta w_{act} = \delta q_{rev} - \delta q_{act}$$

$$\delta q_{rev} = T\,ds \qquad ds \geq \frac{\delta q_{act}}{T}$$

$$\frac{\delta w_{rev} - \delta w_{act}}{T} = ds - \frac{\delta q_{act}}{T} \geq 0$$

$$\partial w_{rev} \geq \partial w_{act}$$

$$w_{rev} \geq w_{act}$$



Work-producing devices such as turbines deliver more work, and work-consuming devices such as pumps and compressors require less work when they operate reversibly.

A reversible turbine delivers m work than an irreversible one i both operate between the same end states.

الممسوحة ضوئيا بـ CamScanner

MINIMIZING THE COMPRESSOR WORK

$$w_{rev,in} = \int_1^2 v\,dP$$

When kinetic and potential energies are negligible

Isentropic (Pv^k = constant):

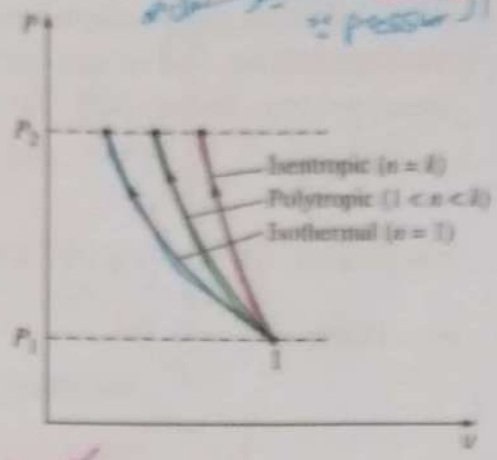
$$w_{comp,in} = \frac{kR(T_2 - T_1)}{k-1} = \frac{kRT_1}{k-1}\left[\left(\frac{P_2}{P_1}\right)^{(k-1)/k} - 1\right]$$

Polytropic (Pv^n = constant):

$$w_{comp,in} = \frac{nR(T_2 - T_1)}{n-1} = \frac{nRT_1}{n-1}\left[\left(\frac{P_2}{P_1}\right)^{(n-1)/n} - 1\right]$$

Isothermal (Pv = constant):

$$w_{comp,in} = RT \ln \frac{P_2}{P_1}$$

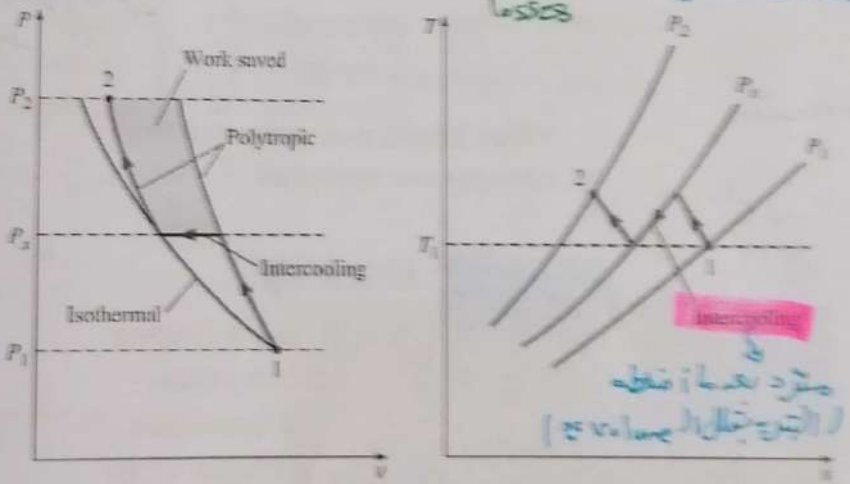


P-v diagrams of isentropic, polytropic, and isothermal compression processes between the same pressure limits.

The adiabatic compression (Pv^k = constant) requires the maximum work, and the isothermal compression (T = constant) requires the minimum. Why?

Multistage Compression with Intercooling

The gas is compressed in stages and cooled between each stage by passing it through a heat exchanger called an *intercooler*.



P-v and *T-s* diagrams for a two-stage steady-flow compression process.

$$W_{comp,in} = W_{comp\ I,in} + W_{comp\ II,in}$$

$$= \frac{nRT_1}{n-1}\left[\left(\frac{P_x}{P_1}\right)^{(n-1)/n} - 1\right] + \frac{nRT_1}{n-1}\left[\left(\frac{P_2}{P_x}\right)^{(n-1)/n} - 1\right]$$

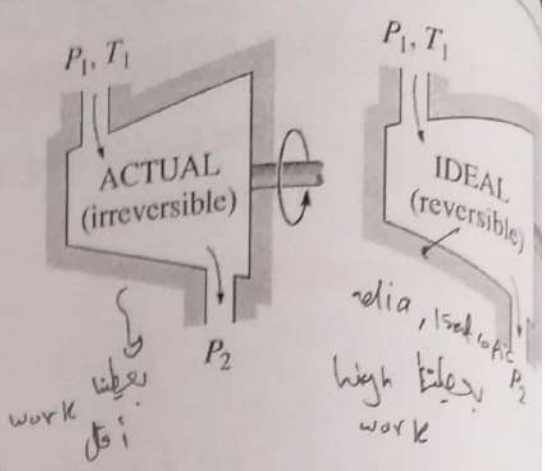
$$P_x = (P_1 P_2)^{1/2} \quad \text{or} \quad \frac{P_x}{P_1} = \frac{P_2}{P_x}$$

To minimize compression work during two-stage compression, the pressure ratio across each stage of the compressor must be the same.

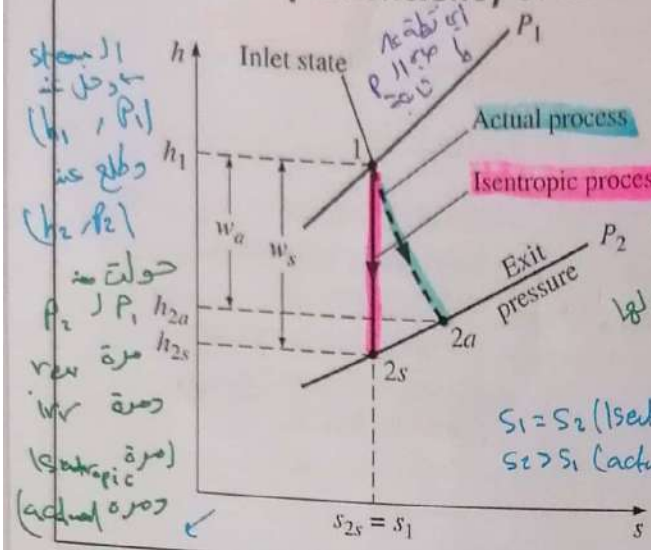
الممسوحة ضوئيا بـ CamScanner

ISENTROPIC EFFICIENCIES OF STEADY-FLOW DEVICES

The isentropic process involves no irreversibilities and serves as the ideal process for adiabatic devices.



Isentropic Efficiency of Turbines



The *h-s* diagram for the actual and isentropic processes of an adiabatic turbine.

$$\eta_T = \frac{\text{Actual turbine work}}{\text{Isentropic turbine work}} = \frac{w_a}{w_s}$$

$$\eta_T \cong \frac{h_1 - h_{2a}}{h_1 - h_{2s}}$$

Isentropic Efficiencies of Compressors and Pumps

$$\eta_C = \frac{\text{Isentropic compressor work}}{\text{Actual compressor work}} = \frac{w_s}{w_a}$$

$$\eta_C \cong \frac{h_{2s} - h_1}{h_{2a} - h_1}$$

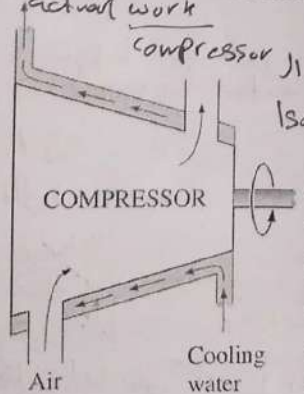
When kinetic and potential energies are negligible

$$\eta_P = \frac{w_s}{w_a} = \frac{v(P_2 - P_1)}{h_{2a} - h_1}$$

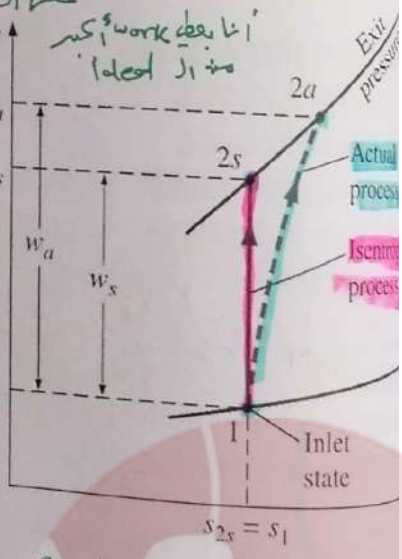
For a pump

$$\eta_C = \frac{w_t}{w_a}$$

Isothermal efficiency



Compressors are sometimes intentionally cooled to minimize the work input.



The *h-s* diagram of the actual and isentropic processes of an adiabatic compressor.

Can you use isentropic efficiency for non-adiabatic compressor?

Can you use isothermal efficiency for adiabatic compressor?

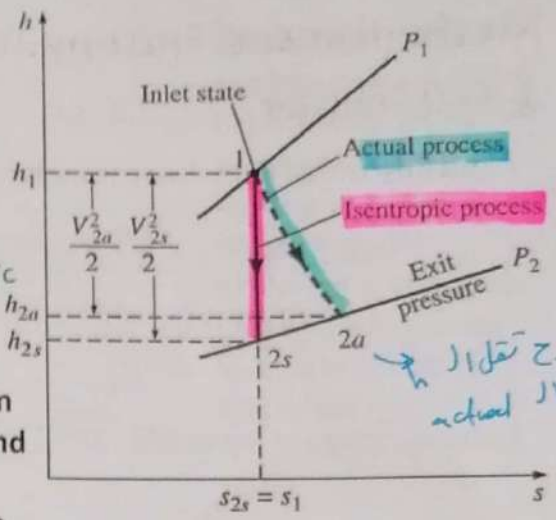
CamScanner الممسوحة ضوئيا بـ

Isentropic Efficiency of Nozzles

$$\eta_N = \frac{\text{Actual KE at nozzle exit}}{\text{Isentropic KE at nozzle exit}} = \frac{V_{2a}^2}{V_{2s}^2}$$

- If the inlet velocity of the fluid is small relative to the exit velocity, the energy balance is:

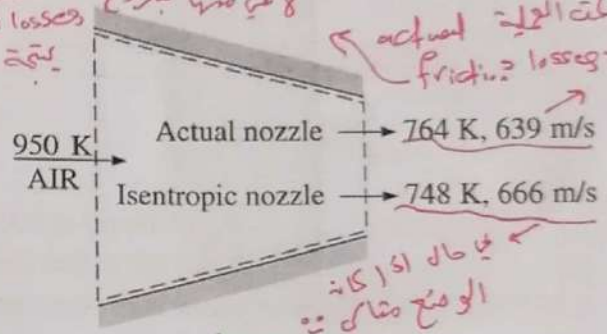
$$h_1 = h_{2a} + \frac{V_{2a}^2}{2}$$



The *h-s* diagram of the actual and isentropic processes of an adiabatic nozzle.

Then,

$$\eta_N \cong \frac{(h_1 - h_{2a})}{(h_1 - h_{2s})}$$



A substance leaves actual nozzles at a higher temperature (thus a lower velocity) as a result of friction.

ENTROPY BALANCE

$$\begin{pmatrix}\text{Total}\\ \text{entropy}\\ \text{entering}\end{pmatrix} - \begin{pmatrix}\text{Total}\\ \text{entropy}\\ \text{leaving}\end{pmatrix} + \begin{pmatrix}\text{Total}\\ \text{entropy}\\ \text{generated}\end{pmatrix} = \begin{pmatrix}\text{Change in the}\\ \text{total entropy}\\ \text{of the system}\end{pmatrix}$$

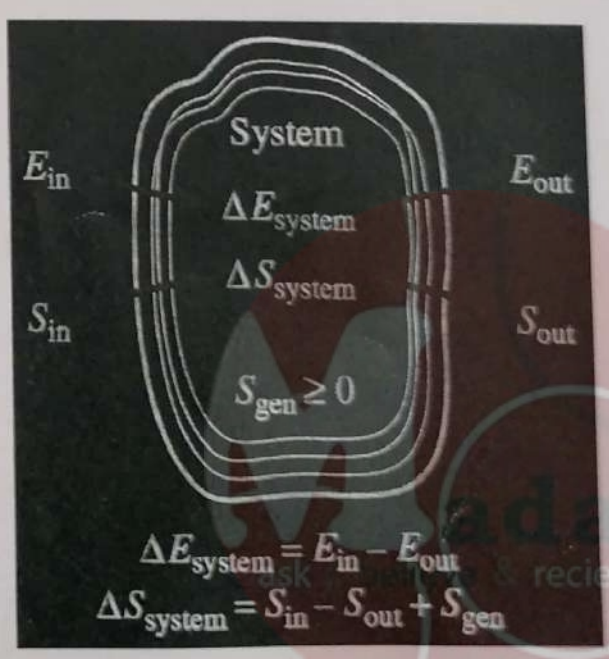
$$S_{in} - S_{out} + S_{gen} = \Delta S_{system}$$

Entropy Change of a System, ΔS_{system}

$$\Delta S_{system} = S_{final} - S_{initial} = S_2 - S_1$$

When the properties of the system are not uniform

$$S_{system} = \int s\,\delta m = \int_V s\rho\,dV$$



Energy and entropy balances for a system.

CamScanner الممسوحة ضوئيا بـ

Mechanisms of Entropy Transfer, S_{in} and S_{out}

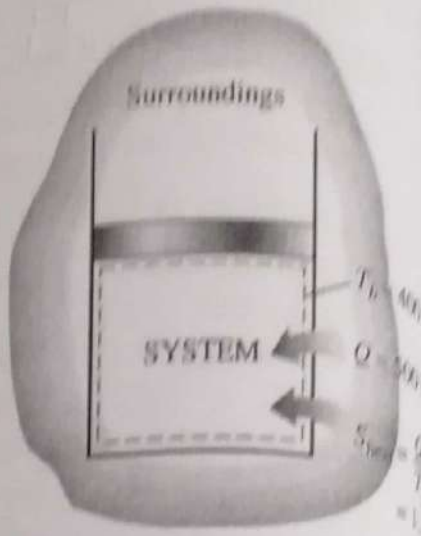
1 Heat Transfer

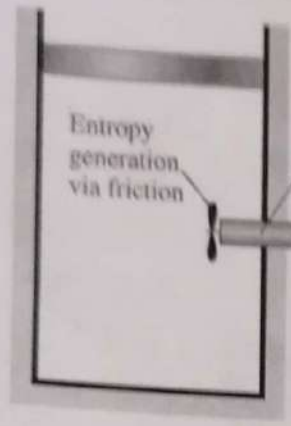
Entropy transfer by heat transfer:

$$S_{heat} = \frac{Q}{T} \qquad (T = \text{constant})$$

$$S_{heat} = \int_1^2 \frac{\delta Q}{T} = \sum \frac{Q_k}{T_k}$$

Entropy transfer by work: $S_{work} = 0$





Heat transfer is always accompanie
entropy transfer in the amount of
where T is the boundary temperat

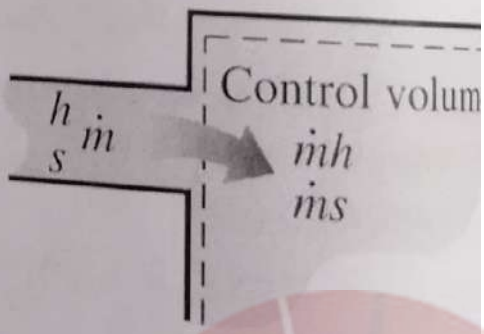
No entropy accompanies work as it crosses the system boundary. But entropy may be generated within the syste work is dissipated into a less useful form of energy.

Mechanisms of Entropy Transfer, S_{in} and S_{out}

2 Mass Flow

Entropy transfer by mass:

$$S_{mass} = ms$$



When the properties of the mass change during the process:

$$\dot{S}_{mass} = \int_{A_c} s\rho V_n \, dA_c$$

$$S_{mass} = \int s \, \delta m = \int_{\Delta t} \dot{S}_{mass} \, dt$$

Mass contains entropy as w
as energy, and thus mass flo
into or out of system is
always accompanied by
energy and entropy transfer

ask & believe & recieve
الممسوحة ضوئيا بـ CamScanner

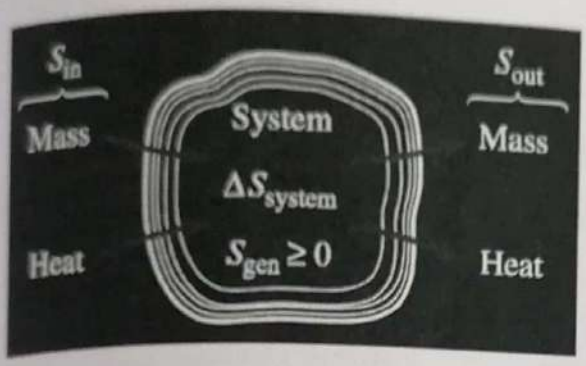
Entropy Generation, S_{gen}

$$\underbrace{S_{in} - S_{out}}_{\text{Net entropy transfer by heat and mass}} + \underbrace{S_{gen}}_{\text{Entropy generation}} = \underbrace{\Delta S_{system}}_{\text{Change in entropy}} \quad (\text{kJ/K})$$

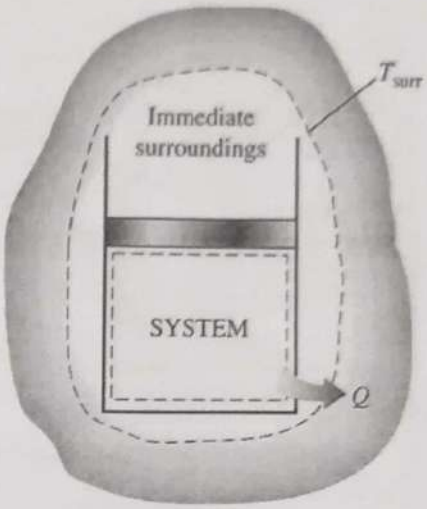
$$\underbrace{\dot{S}_{in} - \dot{S}_{out}}_{\text{Rate of net entropy transfer by heat and mass}} + \underbrace{\dot{S}_{gen}}_{\text{Rate of entropy generation}} = \underbrace{dS_{system}/dt}_{\text{Rate of change in entropy}} \quad (\text{kW/K})$$

$$(s_{in} - s_{out}) + s_{gen} = \Delta s_{system} \quad (\text{kJ/kg} \cdot \text{K})$$

Entropy generation outside system boundaries can be accounted for by writing an entropy balance on an extended system that includes the system and its immediate surroundings.



Mechanisms of entropy transfer for a general system.



Closed Systems

Closed system: $$\sum \frac{Q_k}{T_k} + S_{gen} = \Delta S_{system} = S_2 - S_1 \quad (\text{kJ/K})$$

The entropy change of a closed system during a process is equal to the sum of the net entropy transferred through the system boundary by heat transfer and the entropy generated within the system boundaries.

Adiabatic closed system: $$S_{gen} = \Delta S_{adiabatic\ system}$$

System + Surroundings: $$S_{gen} = \sum \Delta S = \Delta S_{system} + \Delta S_{surroundings}$$

$$\Delta S_{system} = m(s_2 - s_1)$$

$$\Delta S_{surr} = Q_{surr}/T_{surr}$$

ask & believe & recieve
CamScanner الممسوحة ضوئيا بـ

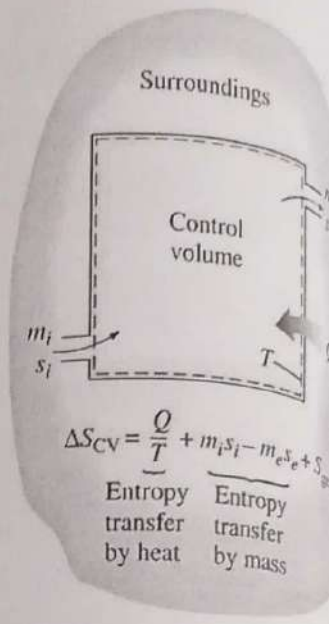
$$\sum \frac{Q_k}{T_k} + \sum m_i s_i - \sum m_e s_e + S_{gen} = (S_2 - S_1)_{CV} \quad \text{(kJ/K)}$$

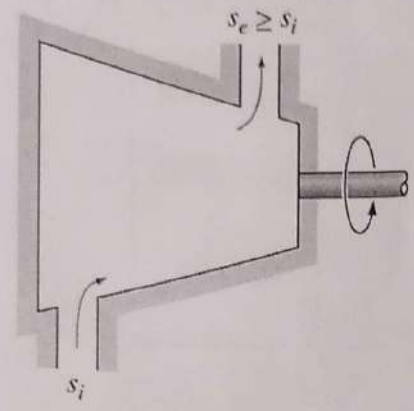
$$\sum \frac{\dot{Q}_k}{T_k} + \sum \dot{m}_i s_i - \sum \dot{m}_e s_e + \dot{S}_{gen} = dS_{CV}/dt \quad \text{(kW/K)}$$

Steady-flow: $\dot{S}_{gen} = \sum \dot{m}_e s_e - \sum \dot{m}_i s_i - \sum \frac{\dot{Q}_k}{T_k}$

Steady-flow, single-stream: $\dot{S}_{gen} = \dot{m}(s_e - s_i) - \sum \frac{\dot{Q}_k}{T_k}$

Steady-flow, single-stream, adiabatic: $\dot{S}_{gen} = \dot{m}(s_e - s_i)$





The entropy of a substance always increases (or remains constant in the case of a reversible process) as it flows through a single-stream, adiabatic, steady-flow device.

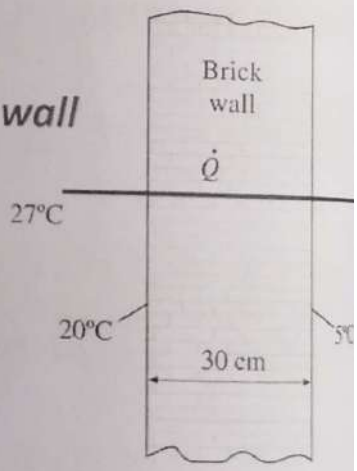
The entropy of a control volume changes as a result of mass flow as well as heat transfer.

EXAMPLES

Entropy balance for heat transfer through a wall

$$\underbrace{\dot{S}_{in} - \dot{S}_{out}}_{\substack{\text{Rate of net entropy}\\ \text{transfer by heat}\\ \text{and mass}}} + \underbrace{\dot{S}_{gen}}_{\substack{\text{Rate of entropy}\\ \text{generation}}} = \underbrace{\overbrace{dS_{system}/dt}^{0\ \text{(steady)}}}_{\substack{\text{Rate of change}\\ \text{in entropy}}}$$

$$\left(\frac{\dot{Q}}{T}\right)_{in} - \left(\frac{\dot{Q}}{T}\right)_{out} + \dot{S}_{gen} = 0$$

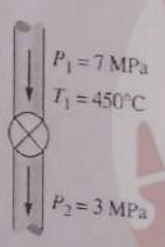


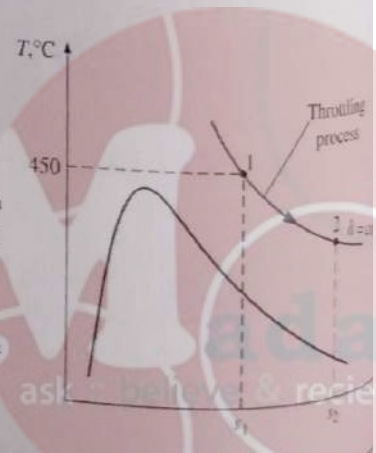
Entropy balance for a throttling process

$$\underbrace{\dot{S}_{in} - \dot{S}_{out}}_{\substack{\text{Rate of net entropy}\\ \text{transfer by heat}\\ \text{and mass}}} + \underbrace{\dot{S}_{gen}}_{\substack{\text{Rate of entropy}\\ \text{generation}}} = \underbrace{\overbrace{dS_{system}/dt}^{0\ \text{(steady)}}}_{\substack{\text{Rate of change}\\ \text{in entropy}}}$$

$$\dot{m}s_1 - \dot{m}s_2 + \dot{S}_{gen} = 0$$

$$\dot{S}_{gen} = \dot{m}(s_2 - s_1)$$



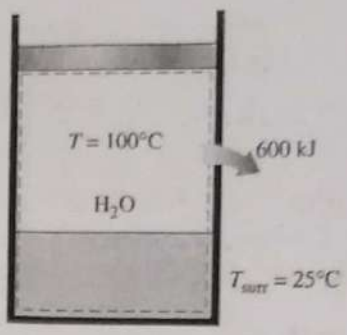


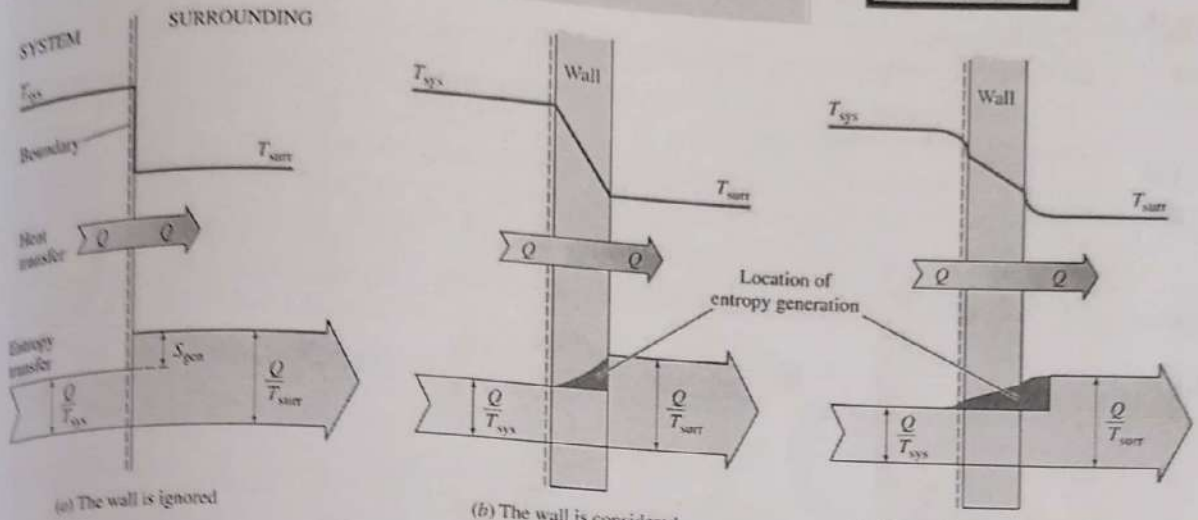
CamScanner الممسوحة ضوئيا بـ

Entropy generation associated with a heat transfer process

$$\underbrace{S_{in} - S_{out}}_{\text{Net entropy transfer by heat and mass}} + \underbrace{S_{gen}}_{\text{Entropy generation}} = \underbrace{\Delta S_{system}}_{\text{Change in entropy}}$$

$$-\frac{Q_{out}}{T_b} + S_{gen} = \Delta S_{sysem}$$





(a) The wall is ignored

(b) The wall is considered

(c) The wall as well as the variations of temperature in the system and the surroundings are considered

Graphical representation of entropy generation during a heat transfer process through a finite temperature difference.

33

EXAMPLE 7–1 Entropy Change during an Isothermal Process

تبخير حرارة ثابتة ← T const

A piston–cylinder device contains a liquid–vapor mixture of water at 300 K. During a constant-pressure process, 750 kJ of heat is transferred to the water. As a result, part of the liquid in the cylinder vaporizes. Determine the entropy change of the water during this process.

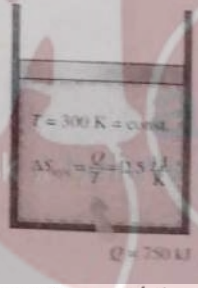
SOLUTION Heat is transferred to a liquid–vapor mixture of water in a piston–cylinder device at constant pressure. The entropy change of water is to be determined.

Assumptions No irreversibilities occur within the system boundaries during the process.

Analysis We take the *entire water* (liquid + vapor) in the cylinder as the system (Fig. 7–4). This is a *closed system* since no mass crosses the system boundary during the process. We note that the temperature of the system remains constant at 300 K during this process since the temperature of a pure substance remains constant at the saturation value during a phase-change process at constant pressure.

The system undergoes an internally reversible, isothermal process, and thus its entropy change can be determined directly from Eq. 7–6 to be

$$\Delta S_{sys,isothermal} = \frac{Q}{T_{sys}} = \frac{750\ \text{kJ}}{300\ \text{K}} = 2.5\ \text{kJ/K}$$



ask & recieve
الممسوحة ضوئيا بـ CamScanner

EXAMPLE 7–2 Entropy Generation during Heat Transfer Processes

A heat source at 800 K loses 2000 kJ of heat to a sink at (*a*) 500 K and (*b*) 750 K. Determine which heat transfer process is more irreversible.

SOLUTION Heat is transferred from a heat source to two heat sinks at different temperatures. The heat transfer process that is more irreversible is to be determined.

Analysis A sketch of the reservoirs is shown in Fig. 7–9. Both cases involve heat transfer through a finite temperature difference, and therefore both are irreversible. The magnitude of the irreversibility associated with each process can be determined by calculating the total entropy change for each case. The total entropy change for a heat transfer process involving two reservoirs (a source and a sink) is the sum of the entropy changes of each reservoir since the two reservoirs form an adiabatic system.

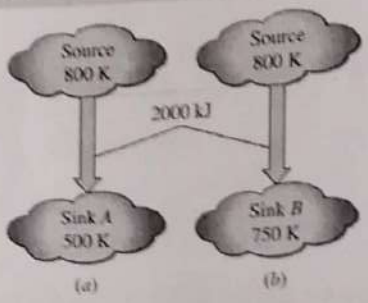


FIGURE 7–9
Schematic for Example 7–2.

The entropy change for each reservoir can be determined from Eq. 7–6 since each reservoir undergoes an internally reversible, isothermal process.

(*a*) For the heat transfer process to a sink at 500 K:

$$\Delta S_{source} = \frac{Q_{source}}{T_{source}} = \frac{-2000\ \text{kJ}}{800\ \text{K}} = -2.5\ \text{kJ/K}$$

$$\Delta S_{sink} = \frac{Q_{sink}}{T_{sink}} = \frac{2000\ \text{kJ}}{500\ \text{K}} = +4.0\ \text{kJ/K}$$

and

$$S_{gen} = \Delta S_{total} = \Delta S_{source} + \Delta S_{sink} = (-2.5 + 4.0)\ \text{kJ/K} = \boxed{1.5\ \text{kJ/K}}$$

Therefore, 1.5 kJ/K of entropy is generated during this process. Noting that both reservoirs have undergone internally reversible processes, the entire entropy generation took place in the partition.

(*b*) Repeating the calculations in part (*a*) for a sink temperature of 750 K, we obtain

$$\Delta S_{source} = -2.5\ \text{kJ/k}$$

$$\Delta S_{sink} = +2.7\ \text{kJ/K}$$

and

$$S_{gen} = \Delta S_{total} = (-2.5 + 2.7)\ \text{kJ/K} = \boxed{0.2\ \text{kJ/K}}$$

The total entropy change for the process in part (*b*) is smaller, and therefore it is less irreversible. This is expected since the process in (*b*) involves a smaller temperature difference and thus a smaller irreversibility.

CamScanner الممسوحة ضوئيا بـ

مثال لنطبق هذا بجدول

EXAMPLE 7–3 Entropy Change of a Substance in a Tank

A rigid tank contains 5 kg of refrigerant-134a initially at 20°C and 140 kPa. The refrigerant is now cooled while being stirred until its pressure drops to 100 kPa. Determine the entropy change of the refrigerant during this process.

SOLUTION The refrigerant in a rigid tank is cooled while being stirred. The entropy change of the refrigerant is to be determined.

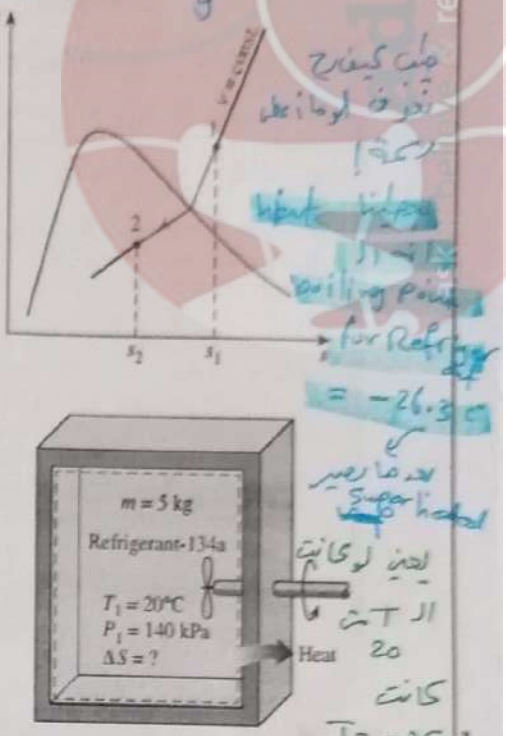
Assumptions The volume of the tank is constant and thus $v_2 = v_1$.

Analysis We take the refrigerant in the tank as the system (Fig. 7–12). This is a *closed system* since no mass crosses the system boundary during the process. We note that the change in entropy of a substance during a process is simply the difference between the entropy values at the final and initial states. The initial state of the refrigerant is completely specified.

Recognizing that the specific volume remains constant during this process, the properties of the refrigerant at both states are

State 1: $P_1 = 140$ kPa, $T_1 = 20°C$ → $s_1 = 1.0625$ kJ/kg·K, $v_1 = 0.16544$ m³/kg

State 2: $P_2 = 100$ kPa, $(v_2 = v_1)$ → $v_f = 0.0007258$ m³/kg, $v_g = 0.19255$ m³/kg



The refrigerant is a saturated liquid–vapor mixture at the final state since $v_f < v_2 < v_g$ at 100 kPa pressure. Therefore, we need to determine the quality first:

$$x_2 = \frac{v_2 - v_f}{v_{fg}} = \frac{0.16544 - 0.0007258}{0.19255 - 0.0007258} = 0.859$$

Thus,

$$s_2 = s_f + x_2 s_{fg} = 0.07182 + (0.859)(0.88008) = 0.8278 \text{ kJ/kg·K}$$

Then, the entropy change of the refrigerant during this process is

$$\Delta S = m(s_2 - s_1) = (5 \text{ kg})(0.8278 - 1.0625) \text{ kJ/kg·K}$$

$$= -1.173 \text{ kJ/K}$$

Discussion The negative sign indicates that the entropy of the system is decreasing during this process. This is not a violation of the second law, however, since it is the *entropy generation* S_{gen} that cannot be negative.

EXAMPLE 7–5 Isentropic Expansion of Steam in a Turbine

Steam enters an adiabatic turbine at 5 MPa and 450°C and leaves at a pressure of 1.4 MPa. Determine the work output of the turbine per unit mass of steam if the process is reversible.

SOLUTION Steam is expanded in an adiabatic turbine to a specified pressure in a reversible manner. The work output of the turbine is to be determined.

Assumptions 1 This is a steady-flow process since there is no change with time at any point and thus $\Delta m_{CV} = 0$, $\Delta E_{CV} = 0$, and $\Delta S_{CV} = 0$. 2 The process is reversible. 3 Kinetic and potential energies are negligible. 4 The turbine is adiabatic and thus there is no heat transfer.

Analysis We take the turbine as the system (Fig. 7–15). This is a control volume since mass crosses the system boundary during the process. We note that there is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$.

The power output of the turbine is determined from the rate form of the energy balance.

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} \xrightarrow{\text{(0 (steady))}} = 0$$



$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}h_1 = \dot{W}_{out} + \dot{m}h_2 \quad (\text{since } \dot{Q} = 0,\ \text{ke} \cong \text{pe} \cong 0)$$

$$\dot{W}_{out} = \dot{m}(h_1 - h_2)$$

The inlet state is completely specified since two properties are given. But only one property (pressure) is given at the final state, and we need one more property to fix it. The second property comes from the observation that the process is reversible and adiabatic, and thus isentropic. Therefore, $s_2 = s_1$, and

State 1: $P_1 = 5$ MPa, $T_1 = 450°C$ → $h_1 = 3317.2$ kJ/kg, $s_1 = 6.8210$ kJ/kg·K

State 2: $P_2 = 1.4$ MPa, $s_2 = s_1$ → $h_2 = 2967.4$ kJ/kg

Then, the work output of the turbine per unit mass of the steam becomes

$$w_{out} = h_1 - h_2 = 3317.2 - 2967.4 = \boxed{349.8 \text{ kJ/kg}}$$

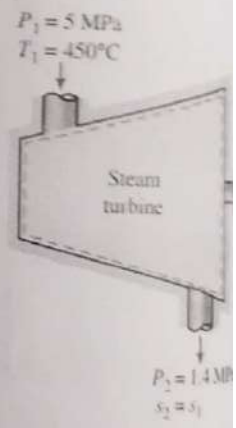


FIGURE
Schematic and T-s diagr
Exam

CamScanner الممسوحة ضوئيا بـ

EXAMPLE 7–6 **The *T-S* Diagram of the Carnot Cycle**

Show the Carnot cycle on a *T-S* diagram and indicate the areas that represent the heat supplied Q_H, heat rejected Q_L, and the net work output $W_{net,out}$ on this diagram.

SOLUTION The Carnot cycle is to be shown on a *T-S* diagram, and the areas that represent Q_H, Q_L, and $W_{net,out}$ are to be indicated.

Analysis Recall that the Carnot cycle is made up of two reversible isothermal (T = constant) processes and two isentropic (s = constant) processes. These four processes form a rectangle on a *T-S* diagram, as shown in Fig. 7–19.

On a *T-S* diagram, the area under the process curve represents the heat transfer for that process. Thus the area $A12B$ represents Q_H, the area $A43B$ represents Q_L, and the difference between these two (the area in color) represents the net work since

$$W_{net,out} = Q_H - Q_L$$

Therefore, the area enclosed by the path of a cycle (area 1234) on a *T-S* diagram represents the net work. Recall that the area enclosed by the path of a cycle also represents the net work on a *P-V* diagram.

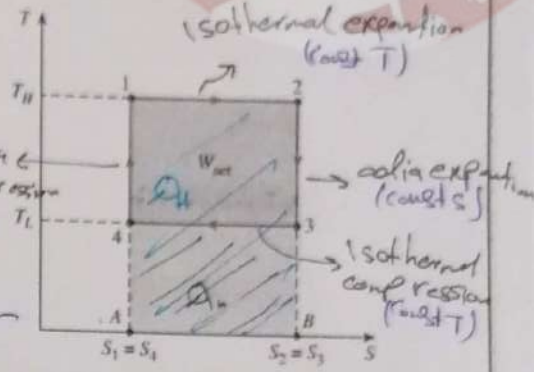


FIGURE 7–19
The *T-S* diagram of a Carnot cycle (Example 7–6).

EXAMPLE 7–7 **Effect of Density of a Liquid on Entropy**

Liquid methane is commonly used in various cryogenic applications. The critical temperature of methane is 191 K (or −82°C), and thus methane must be maintained below 191 K to keep it in liquid phase. The properties of liquid methane at various temperatures and pressures are given in Table 7–1. Determine the entropy change of liquid methane as it undergoes a process from 110 K and 1 MPa to 120 K and 5 MPa (*a*) using tabulated properties and (*b*) approximating liquid methane as an incompressible substance. What is the error involved in the latter case?

SOLUTION Liquid methane undergoes a process between two specified states. The entropy change of methane is to be determined by using actual data and by assuming methane to be incompressible.

Analysis (*a*) We consider a unit mass of liquid methane (Fig. 7–28). The properties of the methane at the initial and final states are

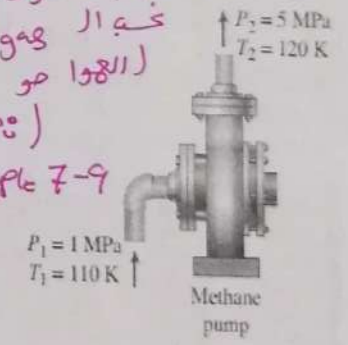


FIGURE 7–28
Schematic for Example 7–7.

TABLE 7–1

Properties of liquid methane

Temp., T, K	Pressure, P, MPa	Density, ρ, kg/m³	Enthalpy, h, kJ/kg	Entropy, s, kJ/kg·K	Specific heat, c_p, kJ/kg·K
110	0.5	425.3	208.3	4.878	3.476
	1.0	425.8	209.0	4.875	3.471
	2.0	426.6	210.5	4.867	3.460
	5.0	429.1	215.0	4.844	3.432
120	0.5	410.4	243.4	5.185	3.551
	1.0	411.0	244.1	5.180	3.543
	2.0	412.0	245.4	5.171	3.528
	5.0	415.2	249.6	5.145	3.486

CamScanner الممسوحة ضوئيا بـ

State 1: $P_1 = 1\ \text{MPa}$, $T_1 = 110\ \text{K}$ $\Rightarrow$ $s_1 = 4.875\ \text{kJ/kg·K}$, $c_{p1} = 3.471\ \text{kJ/kg·K}$

State 2: $P_2 = 5\ \text{MPa}$, $T_2 = 120\ \text{K}$ $\Rightarrow$ $s_2 = 5.145\ \text{kJ/kg·K}$, $c_{p2} = 3.486\ \text{kJ/kg·K}$

Therefore,

$$\Delta s = s_2 - s_1 = 5.145 - 4.875 = 0.270\ \text{kJ/kg·K}$$

(*b*) Approximating liquid methane as an incompressible substance, its entropy change is determined to be

$$\Delta s = c_{avg} \ln \frac{T_2}{T_1} = (3.4785\ \text{kJ/kg·K}) \ln \frac{120\ \text{K}}{110\ \text{K}} = 0.303\ \text{kJ/kg·K}$$

since

$$c_{avg} = \frac{c_{p1} + c_{p2}}{2} = \frac{3.471 + 3.486}{2} = 3.4785\ \text{kJ/kg·K}$$

Therefore, the error involved in approximating liquid methane as an incompressible substance is

$$\text{Error} = \frac{|\Delta s_{actual} - \Delta s_{ideal}|}{\Delta s_{actual}} = \frac{|0.270 - 0.303|}{0.270} = 0.122\ (\text{or } 12.2\%)$$

EXAMPLE 7–9 Entropy Change of an Ideal Gas

Air is compressed from an initial state of 100 kPa and 17°C to a final state of 600 kPa and 57°C. Determine the entropy change of air during this compression process by using (*a*) property values from the air table and (*b*) average specific heats.

SOLUTION Air is compressed between two specified states. The entropy change of air is to be determined by using tabulated property values and also by using average specific heats.

Assumptions Air is an ideal gas since it is at a high temperature and low pressure relative to its critical-point values. Therefore, entropy change relations developed under the ideal-gas assumption are applicable.

Analysis A sketch of the system and the *T-s* diagram for the process are given in Fig. 7–33. We note that both the initial and the final states of air are completely specified.

(*a*) The properties of air are given in the air table (Table A–17). Reading s° values at given temperatures and substituting, we find

$$s_2 - s_1 = s_2^\circ - s_1^\circ - R \ln \frac{P_2}{P_1}$$

$$= [1.79783 - 1.66802)\ \text{kJ/kg·K}] - (0.287\ \text{kJ/kg·K}) \ln \frac{600\ \text{kPa}}{100\ \text{kPa}}$$

$$= -0.3844\ \text{kJ/kg·K}$$

(*b*) The entropy change of air during this process can also be determined approximately from Eq. 7–34 by using a c_p value at the average temperature of 37°C (Table A–2*b*) and treating it as a constant:

$$s_2 - s_1 = c_{p,avg} \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$$

$$= (1.006\ \text{kJ/kg·K}) \ln \frac{330\ \text{K}}{290\ \text{K}} - (0.287\ \text{kJ/kg·K}) \ln \frac{600\ \text{kPa}}{100\ \text{kPa}}$$

$$= -0.3842\ \text{kJ/kg·K}$$

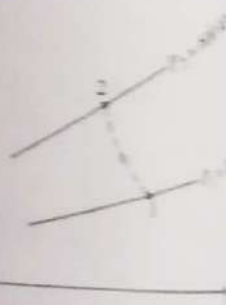


FIGURE
Schematic and *T-s* diagram for Example

EXAMPLE 7–10 **Isentropic Compression of Air in a Car Engine**

Air is compressed in a car engine from 22°C and 95 kPa in a reversible and adiabatic manner. If the compression ratio V_1/V_2 of this engine is 8, determine the final temperature of the air.

SOLUTION Air is compressed in a car engine isentropically. For a given compression ratio, the final air temperature is to be determined.

Assumptions At specified conditions, air can be treated as an ideal gas. Therefore, the isentropic relations for ideal gases are applicable.

Analysis A sketch of the system and the T-s diagram for the process are given in Fig. 7–37.

This process is easily recognized as being isentropic since it is both reversible and adiabatic. The final temperature for this isentropic process can be determined from Eq. 7–50 with the help of relative specific volume data (Table A–17), as illustrated in Fig. 7–38.

For closed systems: $$\frac{V_2}{V_1} = \frac{v_2}{v_1}$$

At $T_1 = 295$ K: $$v_{r1} = 647.9$$

From Eq. 7–50: $$v_{r2} = v_{r1}\left(\frac{V_2}{V_1}\right) = (647.9)\left(\frac{1}{8}\right) = 80.99 \rightarrow T_2 = 662.7 \text{ K}$$

Therefore, the temperature of air will increase by 367.7°C during this process.

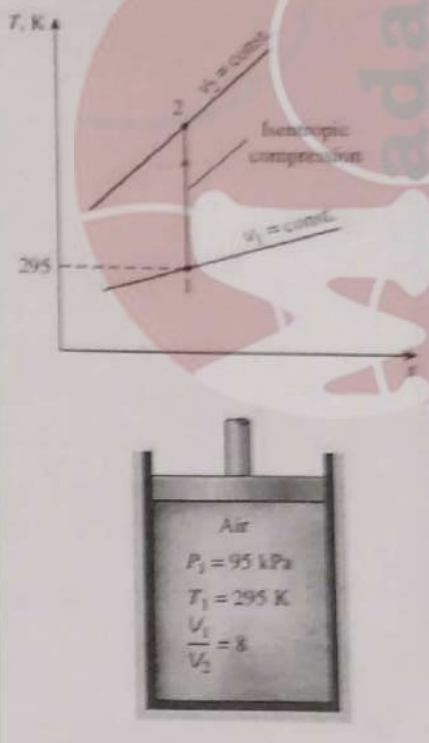


FIGURE 7–37
Schematic and T-s diagram for Example 7–10.

ALTERNATIVE SOLUTION The final temperature could also be determined from Eq. 7–42 by assuming constant specific heats for air:

$$\left(\frac{T_2}{T_1}\right)_{s=\text{const.}} = \left(\frac{V_1}{V_2}\right)^{k-1}$$

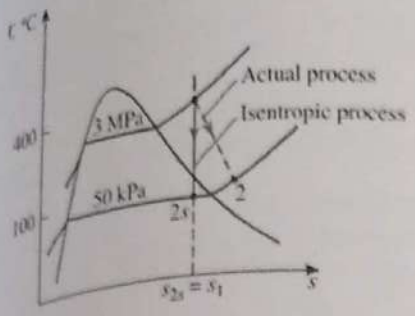
The specific heat ratio k also varies with temperature, and we need to use the value of k corresponding to the average temperature. However, the final temperature is not given, and so we cannot determine the average temperature in advance. For such cases, calculations can be started with a k value at the initial or the anticipated average temperature. This value could be refined later, if necessary, and the calculations can be repeated. We know that the temperature of the air will rise considerably during this adiabatic compression process, so we *guess* the average temperature to be about 450 K. The k value at this anticipated average temperature is determined from Table A–2*b* to be 1.391. Then, the final temperature of air becomes

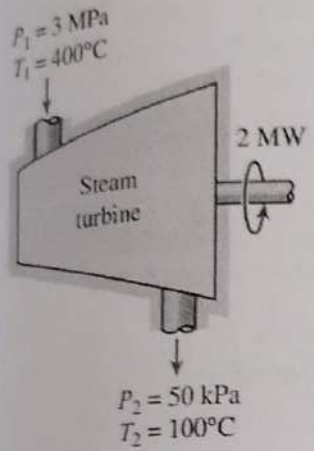
$$T_2 = (295 \text{ K})(8)^{1.391-1} = 665.2 \text{ K}$$

CamScanner الممسوحة ضوئيا بـ

EXAMPLE 7–14 **Isentropic Efficiency of a Steam Turbine**

Steam enters an adiabatic turbine steadily at 3 MPa and 400°C and leaves at 50 kPa and 100°C. If the power output of the turbine is 2 MW, determine (*a*) the isentropic efficiency of the turbine and (*b*) the mass flow rate of the steam flowing through the turbine.





SOLUTION Steam flows steadily in a turbine between inlet and exit states. For a specified power output, the isentropic efficiency and the mass flow rate are to be determined.

Assumptions 1 Steady operating conditions exist. 2 The changes in kinetic and potential energies are negligible.

Analysis A sketch of the system and the *T*-*s* diagram of the process are given in Fig. 7–49.

(*a*) The enthalpies at various states are

$$\textit{State 1:}\quad \left.\begin{matrix} P_1 = 3\ \text{MPA} \\ T_1 = 400°\text{C} \end{matrix}\right\} \begin{matrix} h_1 = 3231.7\ \text{kJ/kg} \\ s_1 = 6.9235\ \text{kJ/kg·K} \end{matrix} \quad \text{(Table A–6)}$$

$$\textit{State 2a:}\quad \left.\begin{matrix} P_{2a} = 50\ \text{kPa} \\ T_{2a} = 100°\text{C} \end{matrix}\right\} h_{2a} = 2682.4\ \text{kJ/kg} \quad \text{(Table A–6)}$$

The exit enthalpy of the steam for the isentropic process h_{2s} is determined from the requirement that the entropy of the steam remain constant ($s_{2s} = s_1$):

$$\textit{State 2s:}\quad \begin{matrix} P_{2s} = 50\ \text{kPa} \\ (s_{2s} = s_1) \end{matrix} \longrightarrow \begin{matrix} s_f = 1.0912\ \text{kJ/kg·K} \\ s_g = 7.5931\ \text{kJ/kg·K} \end{matrix} \quad \text{(Table A–5)}$$

Obviously, at the end of the isentropic process steam exists as a saturated mixture since $s_f < s_{2s} < s_g$. Thus, we need to find the quality at state 2s first:

$$x_{2s} = \frac{s_{2s} - s_f}{s_{fg}} = \frac{6.9235 - 1.0912}{6.5019} = 0.897$$

and

$$h_{2s} = h_f + x_{2s}h_{fg} = 340.54 + 0.897(2304.7) = 2407.9\ \text{kJ/kg}$$

By substituting these enthalpy values into Eq. 7–61, the isentropic efficiency of this turbine is determined to be

$$\eta_T \cong \frac{h_1 - h_{2a}}{h_1 - h_{2s}} = \frac{3231.7 - 2682.4}{3231.7 - 2407.9} = 0.667\ (\text{or } 66.7\%)$$

(*b*) The mass flow rate of steam through this turbine is determined from the energy balance for steady-flow systems:

$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

$$\dot{m}h_1 = \dot{W}_{a,\text{out}} + \dot{m}h_{2a}$$

$$\dot{W}_{a,\text{out}} = \dot{m}(h_1 - h_{2a})$$

$$\left(1000\ \text{kJ/s}\right) = \dot{m}(3231.7 - 2682.4)\ \text{kJ/kg}$$

CamScanner الممسوحة ضوئيا بـ

EXAMPLE 7–12 Compressing a Substance in the Liquid versus Gas Phases

Determine the compressor work input required to compress steam isentropically from 100 kPa to 1 MPa, assuming that the steam exists as (*a*) saturated liquid and (*b*) saturated vapor at the inlet state.

SOLUTION Steam is to be compressed from a given pressure to a specified pressure isentropically. The work input is to be determined for the cases of steam being a saturated liquid and saturated vapor at the inlet.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible. **3** The process is given to be isentropic.

Analysis We take first the turbine and then the pump as the *system*. Both are *control volumes* since mass crosses the boundary. Sketches of the pump and the turbine together with the *T-s* diagram are given in Fig. 7–42.

(*a*) In this case, steam is a saturated liquid initially, and its specific volume is

$$v_1 = v_{f@\ 100\ kPa} = 0.001043\ m^3/kg \quad \text{(Table A–5)}$$

which remains essentially constant during the process. Thus,

$$w_{rev,in} = \int_1^2 v\,dP \cong v_1(P_2 - P_1)$$
$$= (0.001043\ m^3/kg)[(1000 - 100)\ kPa]\left(\frac{1\ kJ}{1\ kPa \cdot m^3}\right)$$
$$= 0.94\ kJ/kg$$

(*b*) This time, steam is a saturated vapor initially and remains a vapor during the entire compression process. Since the specific volume of a gas changes considerably during a compression process, we need to know how v varies

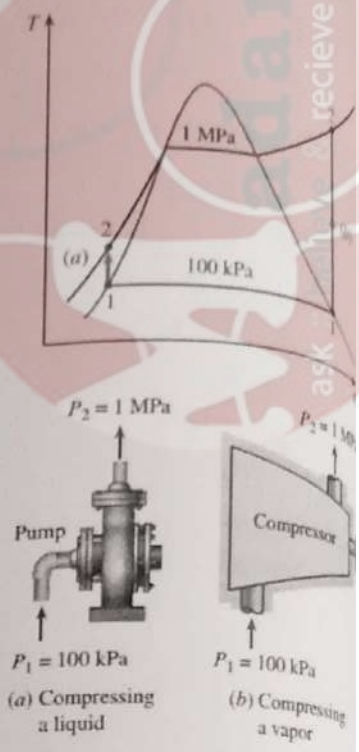


FIGURE 7–
Schematic and *T-s* diagram
Example 7–

with P to perform the integration in Eq. 7–53. This relation, in general, is not readily available. But for an isentropic process, it is easily obtained from the second $T\,ds$ relation by setting $ds = 0$:

$$\left.\begin{aligned} T\,ds &= dh - v\,dP \quad \text{(Eq. 7-24)} \\ ds &= 0 \quad \text{(isentropic process)} \end{aligned}\right\} \quad v\,dP = dh$$

Thus,

$$w_{rev,in} = \int_1^2 v\,dP = \int_1^2 dh = h_2 - h_1$$

This result could also be obtained from the energy balance relation for an isentropic steady-flow process. Next we determine the enthalpies:

$$\textit{State 1:} \quad \left.\begin{aligned} P_1 &= 100\ kPa \\ \text{(sat. vapor)} \end{aligned}\right\} \quad \begin{aligned} h_1 &= 2675.0\ kJ/kg \\ s_1 &= 7.3589\ kJ/kg \cdot K \end{aligned} \quad \text{(Table A–5)}$$

$$\textit{State 2:} \quad \left.\begin{aligned} P_2 &= 1\ MPa \\ s_2 &= s_1 \end{aligned}\right\} \quad h_2 = 3194.5\ kJ/kg \quad \text{(Table A–6)}$$

Thus,

$$w_{rev,in} = (3194.5 - 2675.0)\ kJ/kg = 519.5\ kJ/kg$$

Discussion Note that compressing steam in the vapor form would require over 500 times more work than compressing it in the liquid form between the same pressure limits.

CamScanner الممسوحة ضوئيا بـ

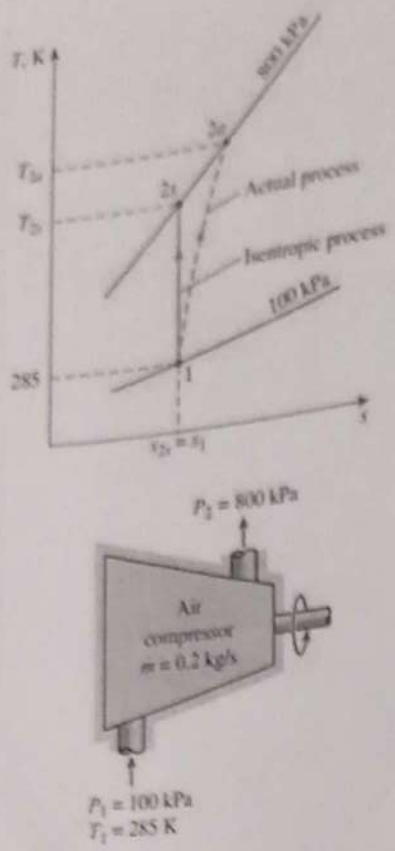


FIGURE 7–52
Schematic and *T-s* diagram for Example 7–15.

EXAMPLE 7–15 Effect of Efficiency on Compressor Power

Air is compressed by an adiabatic compressor from 100 kPa and 285 K to a pressure of 800 kPa at a steady rate of 0.2 kg/s. If the isentropic efficiency of the compressor is 80 percent, determine (*a*) the exit temperature of air and (*b*) the required power input to the compressor.

SOLUTION Air is compressed to a specified pressure at a specified rate by a given isentropic efficiency. The exit temperature and the power input are to be determined.

Assumptions 1 Steady operating conditions exist. 2 Air is an ideal gas. 3 The changes in kinetic and potential energies are negligible.

Analysis A sketch of the system and the *T-s* diagram of the process are given in Fig. 7–52.

(*a*) We know only one property (pressure) at the exit state, and we need to know one more to fix the state and thus determine the exit temperature. The property that can be determined with minimal effort in this case is h_1 since the isentropic efficiency of the compressor is given. At the compressor inlet,

$$T_1 = 285 \text{ K} \rightarrow h_1 = 285.14 \text{ kJ/kg} \quad \text{(Table A–17)}$$
$$(P_{r1} = 1.1584)$$

The enthalpy of the air at the end of the isentropic compression process is determined by using one of the isentropic relations of ideal gases,

$$P_{r2} = P_{r1}\left(\frac{P_2}{P_1}\right) = 1.1584\left(\frac{800 \text{ kPa}}{100 \text{ kPa}}\right) = 9.2672$$

and

$$P_{r2} = 9.2672 \rightarrow h_{2s} = 517.05 \text{ kJ/kg}$$

Substituting the known quantities into the isentropic efficiency relation, we have

$$\eta_C \cong \frac{h_{2s} - h_1}{h_{2a} - h_1} \rightarrow 0.80 = \frac{(517.05 - 285.14) \text{ kJ/kg}}{(h_{2a} - 285.14) \text{ kJ/kg}}$$

Thus,

$$h_{2a} = 575.03 \text{ kJ/kg} \rightarrow T_{2a} = \mathbf{569.5 \text{ K}}$$

(*b*) The required power input to the compressor is determined from the energy balance for steady-flow devices,

$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$
$$\dot{m}h_1 + \dot{W}_{a,\text{in}} = \dot{m}h_{2a}$$
$$\dot{W}_{a,\text{in}} = \dot{m}(h_{2a} - h_1)$$
$$= (0.2 \text{ kg/s})[(575.03 - 285.14) \text{ kJ/kg}]$$
$$= \mathbf{58.0 \text{ kW}}$$

Discussion Notice that in determining the power input to the compressor, we used h_{2a} instead of h_{2s} since h_{2a} is the actual enthalpy of the air as it exits the compressor. The quantity h_{2s} is a hypothetical enthalpy value that the air would have if the process were isentropic.

CamScanner الممسوحة ضوئيا بـ

Introduction and Basic Concepts

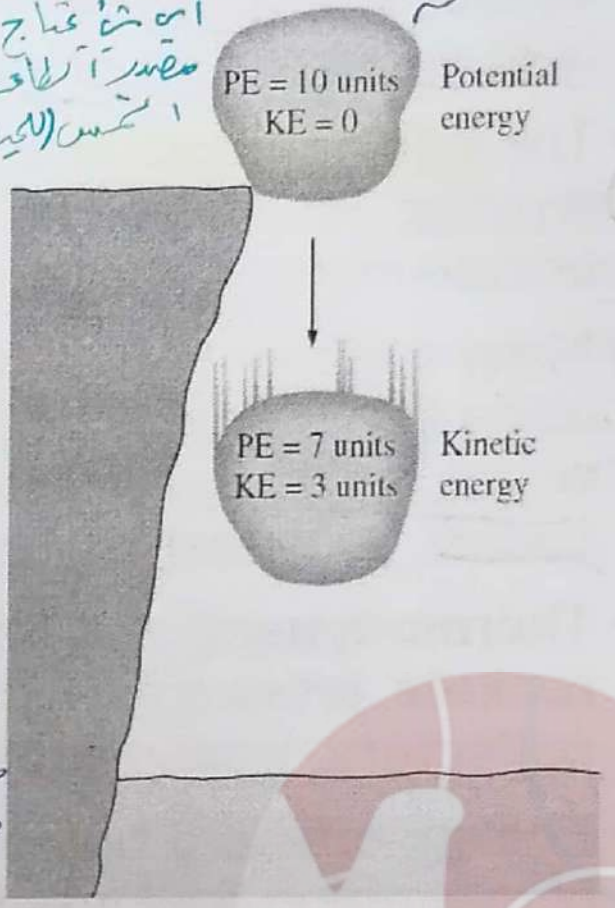
- One of the most fundamental laws of nature is the conservation of energy principle. It simply states that during an interaction, energy can change from one form to another, but the **total amount of energy** remains constant. That is, energy cannot be created or destroyed.
- A rock falling off a cliff, for example, picks up speed as a result of its potential energy being converted to kinetic energy.
- A person who has a greater energy input (food) than energy output (exercise) will gain weight (store energy in the form of fat), and a person who has a smaller energy input than output will lose weight.
- The change in the energy content of a body or any other system is equal to the difference between the energy input and the energy output, and the energy balance is expressed as:

$$E_{in} - E_{out} = \Delta E.$$

CamScanner الممسوحة ضوئيا بـ

THERMODYNAMICS AND ENERGY-1

- **Thermodynamics**: The science of *energy*.
- **Energy**: The ability to cause changes.
- The name *thermodynamics* stems from the Greek words *therme* (heat) and *dynamis* (power).
- **Conservation of energy principle**: During an interaction, *energy can change from one form to another*, but the total amount of energy remains constant.
- Energy cannot be created or destroyed.
- **The first law of thermodynamics**: An expression of the conservation of energy principle.
- The first law asserts that *energy* is a thermodynamic property.



Energy cannot be created or destroyed; it can only change forms (the first law).

الممسوحة ضوئيا بـ CamScanner

THERMODYNAMICS AND ENERGY-2

- **The second law of thermodynamics**: It asserts that energy has *quality* as well as *quantity*, and actual processes occur in the direction of decreasing quality of energy.



Heat flows in the direction of decreasing temperature.

Types of Thermodynamic Studies:

- **Classical thermodynamics**: A macroscopic approach to the study of thermodynamics that does not require a knowledge of the behavior of individual particles.
  - It provides a direct and easy way to the solution of engineering problems (used in this course).
- **Statistical thermodynamics**: A microscopic approach, based on the average behavior of large groups of individual particles (molecules).

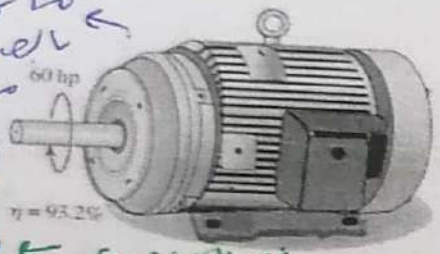
CamScanner الممسوحة ضوئيا بـ

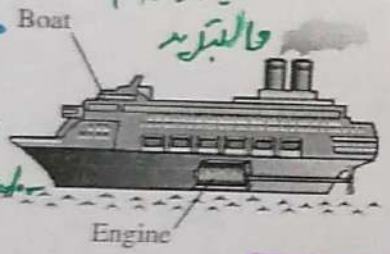
Applications of Thermodynamics

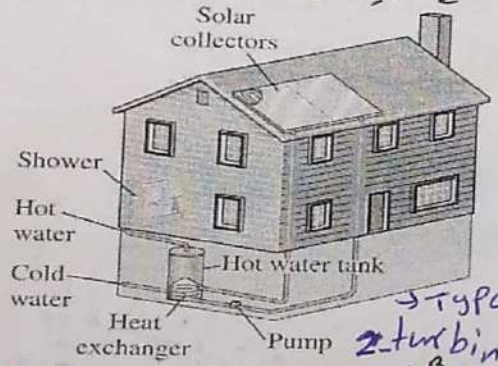
- **Thermodynamics** is encountered in many engineering systems and other aspects of life.
- The **heart** is constantly pumping blood to all parts of the human body, various energy conversions occur in trillions of body cells, and the body heat generated is constantly rejected to the environment.
- The **human comfort** is closely tied to the rate of this metabolic heat rejection (controlling heat transfer rate by adjusting clothing to environmental conditions).
- Many ordinary **household appliances** are designed, in whole or in part, by using the principles of **thermodynamics.** Some examples include electric or gas range, heating and air-conditioning systems, refrigerator, pressure cooker, water heater, computer, etc.
- **Thermodynamics** is basic in design and analysis of **automotive engines, rockets, jet engines, power plants, electrochemical cells, solar collectors, transportation vehicles from ordinary cars to airplanes.**
- **Energy-efficient home** that you may be living in is designed on the basis of minimizing heat loss in winter and heat gain in summer.
- Size, location, and power input of the **fan of your computer** is also selected after an analysis that involves **th**

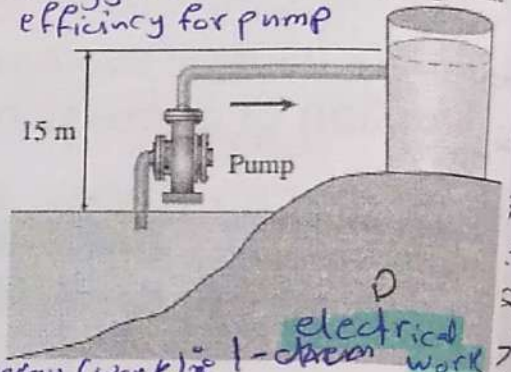
CamScanner الممسوحة ضوئيا بـ

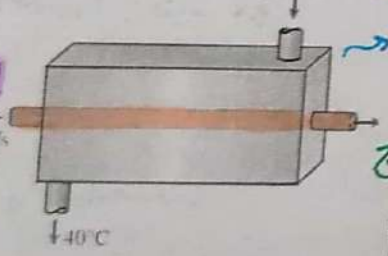
Applications of Thermodynamics



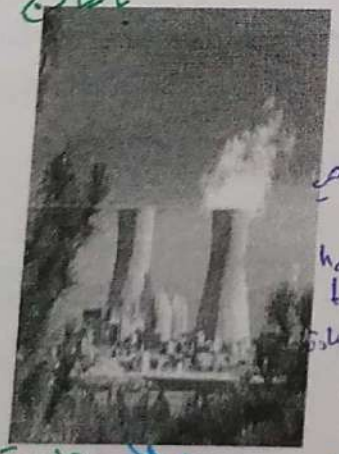


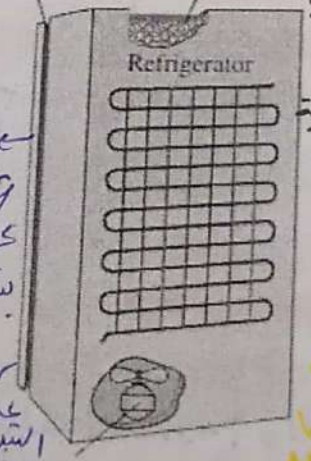


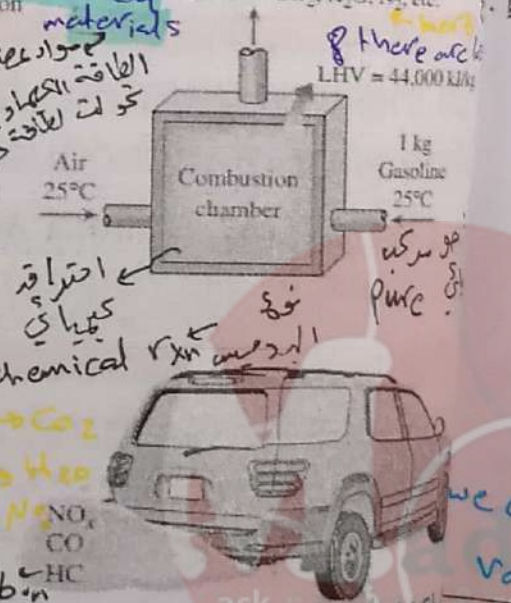












IMPORTANCE OF DIMENSIONS AND UNITS

Two types of units :-

- Any physical quantity can be characterized by **dimensions**.
- The magnitudes assigned to the dimensions are called **units**.
- Some basic dimensions such as **mass *m*, length *L*, time *t*, and temperature *T*** are selected as **primary** or **fundamental dimensions**.
- Others such as **velocity *V*, energy *E*, and volume *V*** are expressed in terms of the primary dimensions and are called **secondary dimensions**, or **derived dimensions**.

primary أي وحدة مشتقة من ال

TABLE 1–1

The seven fundamental (or primary) dimensions and their units in SI

Dimension	Unit
Length	meter (m)
Mass	kilogram (kg)
Time	second (s)
Temperature	kelvin (K)
Electric current	ampere (A)
Amount of light	candela (cd)
Amount of matter	mole (mol)

(kg · m · s)

TABLE 1–2

Standard prefixes in SI units

Multiple	Prefix
10^{12}	tera, T
10^{9}	giga, G
10^{6}	mega, M
10^{3}	kilo, k
10^{2}	hecto, h
10^{1}	deka, da
10^{-1}	deci, d
10^{-2}	centi, c
10^{-3}	milli, m
10^{-6}	micro, μ
10^{-9}	nano, n
10^{-12}	pico, p

ask & believe & recieve
CamScanner الممسوحة ضوئيا بـ

12/10/2023

SYSTEMS AND CONTROL VOLUMES

- **System**: A quantity of matter or a region in space chosen for study.
- **Surroundings**: The mass or region outside the system.
- **Boundary (Control Surface)**: The real or imaginary surface that separates the system from its surroundings.
- The boundary of a system can be *fixed* or *movable*.
- Systems may be considered to be *closed* or *open*.

Types of Systems

I) Closed (Control mass).

II) Open (Control volume).

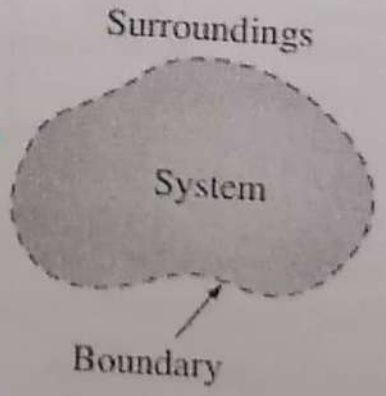


FIGURE 1–18
System, surroundings, and boundary.

Madar ask & believe & recieve
الممسوحة ضوئيا بـ CamScanner

* Closed Systems (Control Mass) *

* اذا ثبتت ال mass بغض النظر volume والعكس كذلك

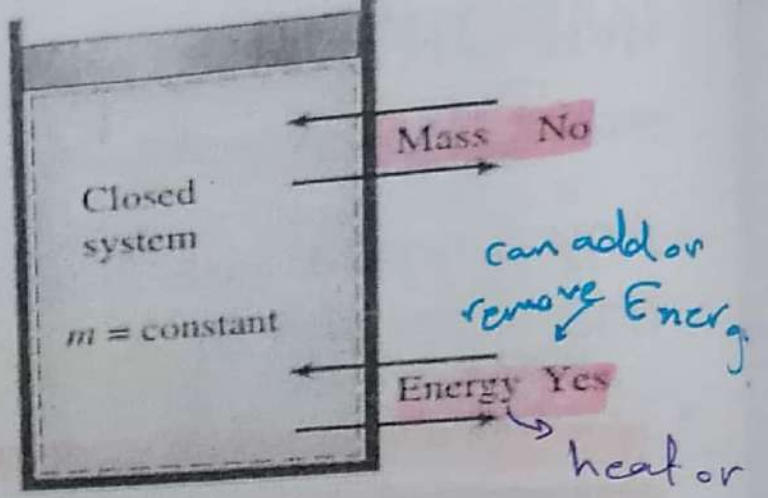


FIGURE 1–19
Mass cannot cross the boundaries of a closed system, but energy can.

- Energy, not Mass, crosses Closed System boundaries.

- **Example Applications:**

1) Piston-cylinder devices.
2) Batch reactor tank.
3) Refrigerator.
4) Air conditioner.
5) Small electric heater.

اذا حللت حرارة أو حللت ضغط بترتفع piston بتحرك

ماشيه ← عبر ثابتة الغاز

كمية الحارة فيه flow ثابتة

If we do mixing we add ing work

← مخانه الكهرباء العاديه في

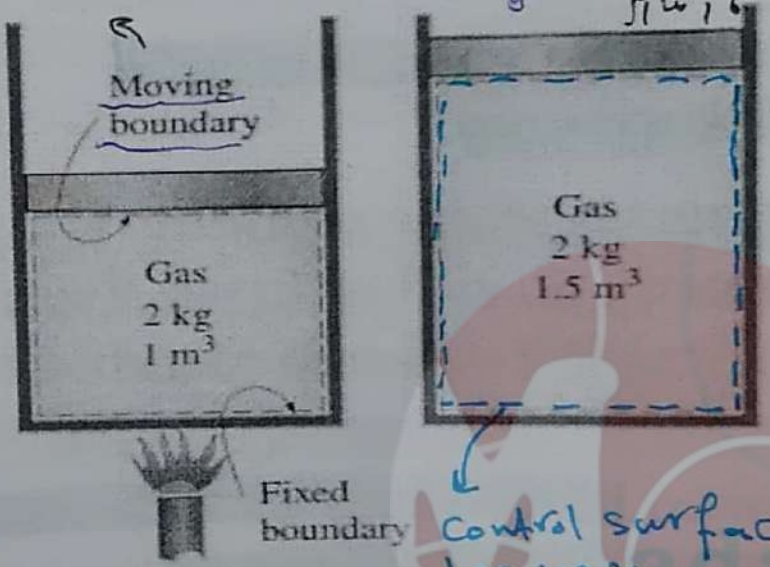


FIGURE 1–20
A closed system with a moving boundary.

لانه ال fixed sys بالتالي ما في ل طاقة ال kinetic و potential و heat و work بتضيف وبتوقف

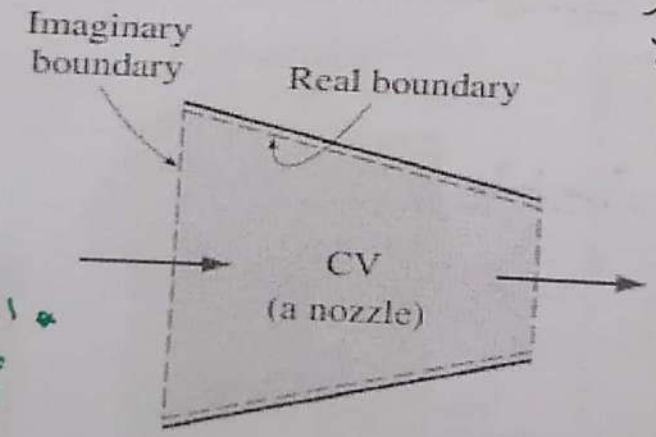
عند ال

CamScanner الممسوحة ضوئيا بـ

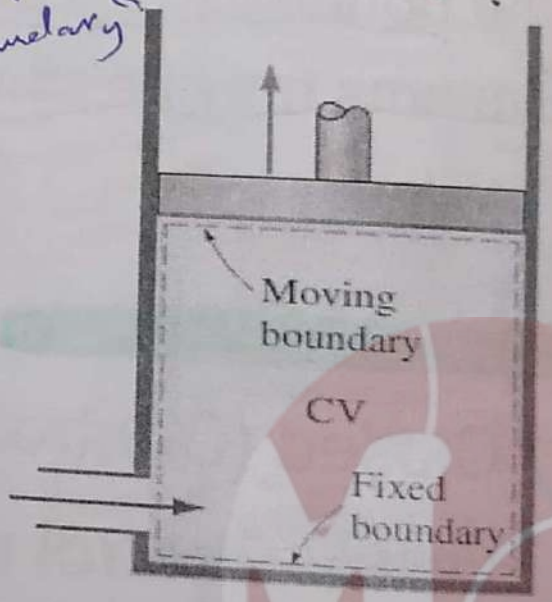
*Open Systems (Control Volume)

- Both Mass and Energy Cross Open System (Control Volume) Boundaries.
- Control surface: The boundaries of a control volume. It can be *real or imaginary.*
- **Example applications:**

1) Fluid flow in pipes, water pumps, air compressors, heat exchangers, etc.
2) Continuous-flow chemical reactors.
3) Automobile motor engines.
4) Power plant turbine systems.



(a) A control volume (CV) with real and imaginary boundaries



(b) A control volume (CV) with fixed and moving boundaries as well as real and imaginary boundaries

الممسوحة ضوئيا بـ CamScanner

PROPERTIES OF A SYSTEM

- **Property**: Any characteristic of a system.
- Some familiar properties are pressure P, temperature T, volume V, and mass m.
- Properties are considered to be either *intensive* or *extensive*.

❑ **Intensive properties**: Those that are *independent of the mass* of a system, such as temperature, pressure, and density.

❑ **Extensive properties**: Those whose values *depend on the size* (or extent) of the system.

- **Specific properties**: Extensive properties *per unit mass.*

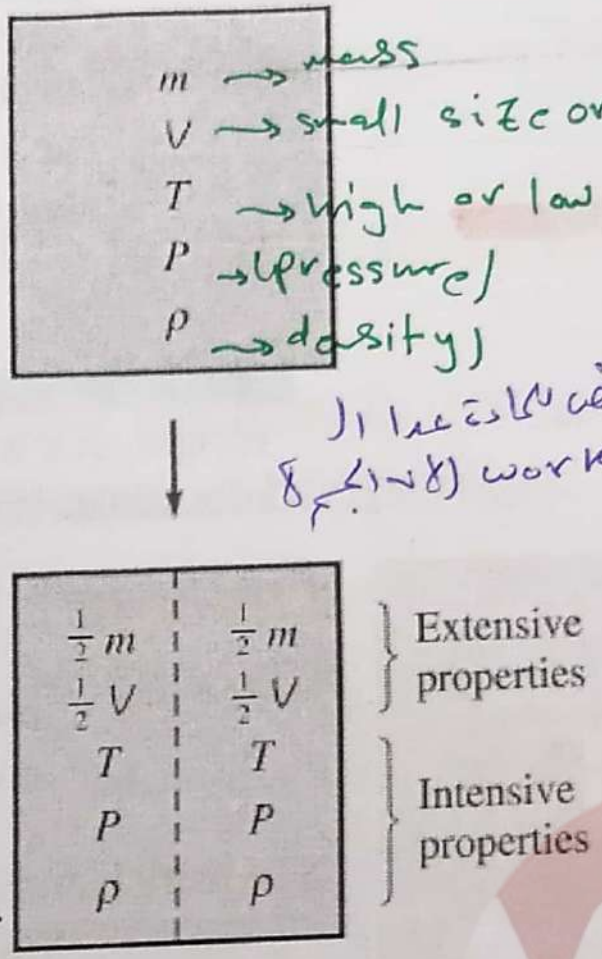


FIGURE 1–23
Criterion to differentiate intensive and extensive properties.

CamScanner الممسوحة ضوئيا بـ

properties *per unit mass.*

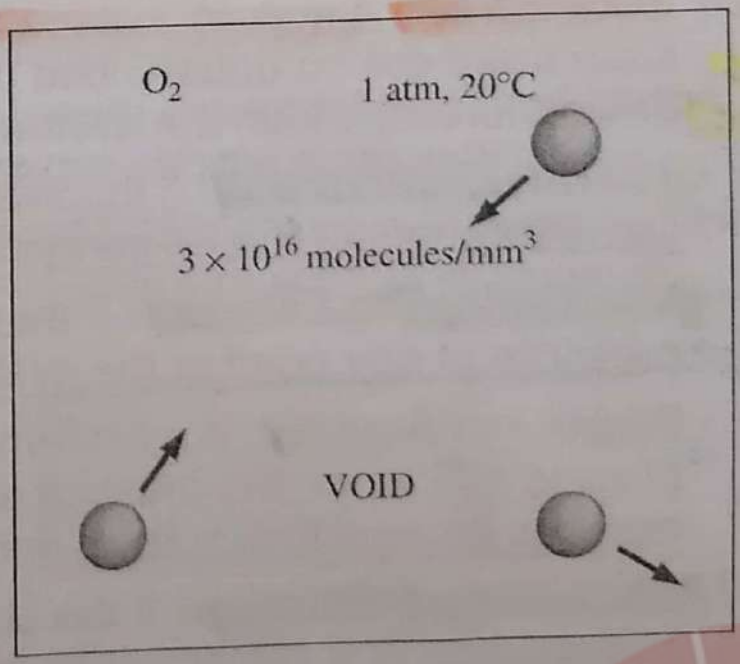
13

* الفرق بين Intensive properties و Extensive properties

* عكس الحجم النوعي specific volume (م³/كجم) المادة تتكون من molecules متفرقة (في الغازات) لكنه احنا بنتعاملها بنعتبره Continuous

Continuum

- Matter is made up of atoms that are widely spaced in the gas phase. Yet it is very convenient to disregard the atomic nature of a substance and view it as a *continuous, homogeneous matter* with no holes, that is, a ***continuum***.
- The continuum idealization allows us to treat properties as point functions and to assume the properties vary continually in space with no jump discontinuities.
- This idealization is valid as long as the size of the system we deal with is large relative to the space between the molecules.
- This is the case in practically all problems.
- In this text we will limit our consideration to substances that can be modeled as a ***continuum.***



Despite the large gaps between molecules, a substance can be treated as a *continuum* because of the very large number of molecules even in an extremely small volume.

14

Nadar ask & believe & recieve
الممسوحة ضوئيا بـ CamScanner

DENSITY AND SPECIFIC GRAVITY

Density

$$\rho = \frac{m}{V} \qquad (\text{kg/m}^3)$$

Specific volume

$$v = \frac{V}{m} = \frac{1}{\rho}$$

$V = 12\ \text{m}^3$
$m = 3\ \text{kg}$

$\rho = 0.25\ \text{kg/m}^3$

$v = \frac{1}{\rho} = 4\ \text{m}^3/\text{kg}$

Specific gravity: The ratio of the density of a substance to the density of some standard substance at a specified temperature (usually water at 4°C).

$$\text{SG} = \frac{\rho}{\rho_{H_2O}}$$

It is a ratio between ρ of any substance with ρ of water (dimentionless)

Specific weight: The weight of a unit volume of a substance.

$$\gamma_s = \rho g \qquad (\text{N/m}^3)$$

weight = mass * acc of gravity
$w = m * g$

→ Density is mass per unit volume;
→ specific volume is volume per unit mass.

TABLE 1–3

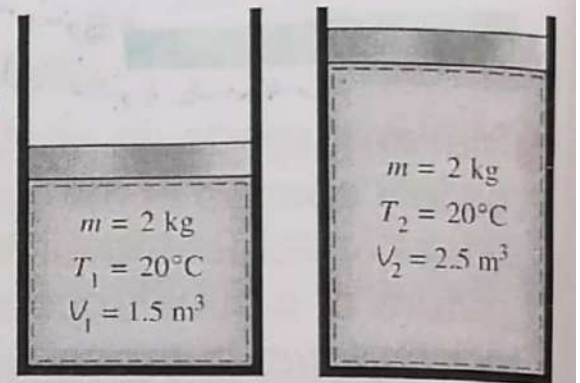
Specific gravities of some substances at 0°C

Substance	SG
Water	1.0
Blood	1.05
Seawater	1.025
Gasoline	0.7
Ethyl alcohol	0.79
Mercury	13.6
Wood	0.3–0.9
Gold	19.2
Bones	1.7–2.0
Ice	0.92
Air (at 1 atm)	0.0013

CamScanner الممسوحة ضوئيا بـ

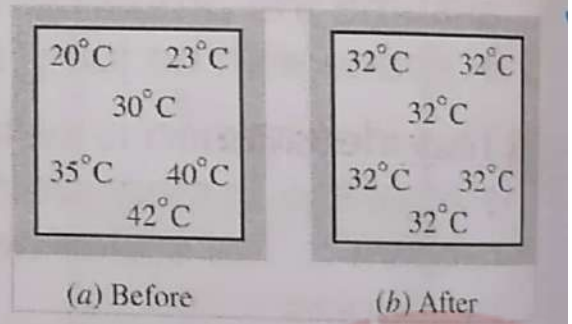
STATE AND EQUILIBRIUM

- Thermodynamics deals with ***equilibrium* states.**
- **Equilibrium:** A state of balance. In an equilibrium state there are no unbalanced potentials (or driving forces) within the system.
- **Thermal equilibrium:** If the temperature is the same throughout the entire system.
- **Mechanical equilibrium:** If there is no change in pressure at any point of the system with time.
- **Phase equilibrium:** If a system involves two phases and when the mass of each phase reaches an equilibrium level and stays there.
- **Chemical equilibrium:** If the chemical composition of a system does not change with time, that is, no chemical reactions occur.



(*a*) State 1 (*b*) State 2

A system at two different states



(*a*) Before (*b*) After

A closed system reaching thermal equilibrium.

❑ A system is said to be "in **thermodynamic equilibrium**" if it maintains:

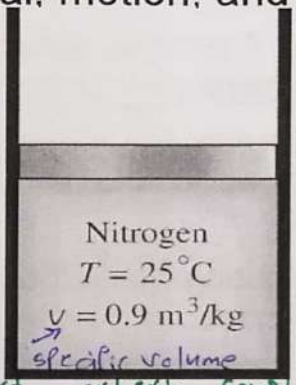
(1) thermal (uniform temp.), (2) mechanical (uniform pressure), (3) phase (mass of two phases, e.g., ice and liquid water, in equilibrium), and (4) chemical equilibrium (uniform composition).

الممسوحة ضوئيا بـ CamScanner

The State Postulate

- The state of a system is described by its properties.
- But, by experience not all properties must be known before the state is specified.
- The number of properties required to fix the state of a system is given by the **state postulate**:
  - *The state of a simple compressible system is completely specified by two independent, intensive properties.*
- **Simple compressible system:** If a system involves no electrical, magnetic, gravitational, motion, and surface tension effects.

The state of nitrogen is fixed by two independent, intensive properties.



equation of state : ideal gas law

$PV = nRT$

$P\hat{V} = RT$, $[v_m] = m^3/kmol$

molar volume (intensive) $[\hat{V}] = m^3/kg = \frac{v}{mass}$

PROCESSES AND CYCLES-1

Process: Any change that a system undergoes from one equilibrium state to another.

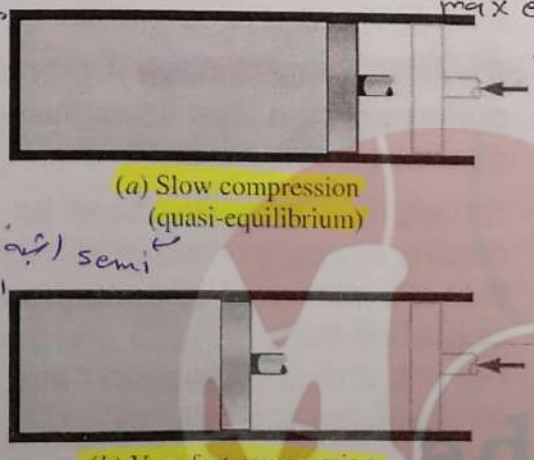
Path: The series of states through which a system passes during a process.

To describe a process completely, one should specify **the initial and final states**, as well as **the path** it follows, and the interactions with the surroundings.

Quasi-equilibrium process: When a process proceeds in such a manner that the system remains **infinitesimally close to an equilibrium** state at all times.

Characteristics:

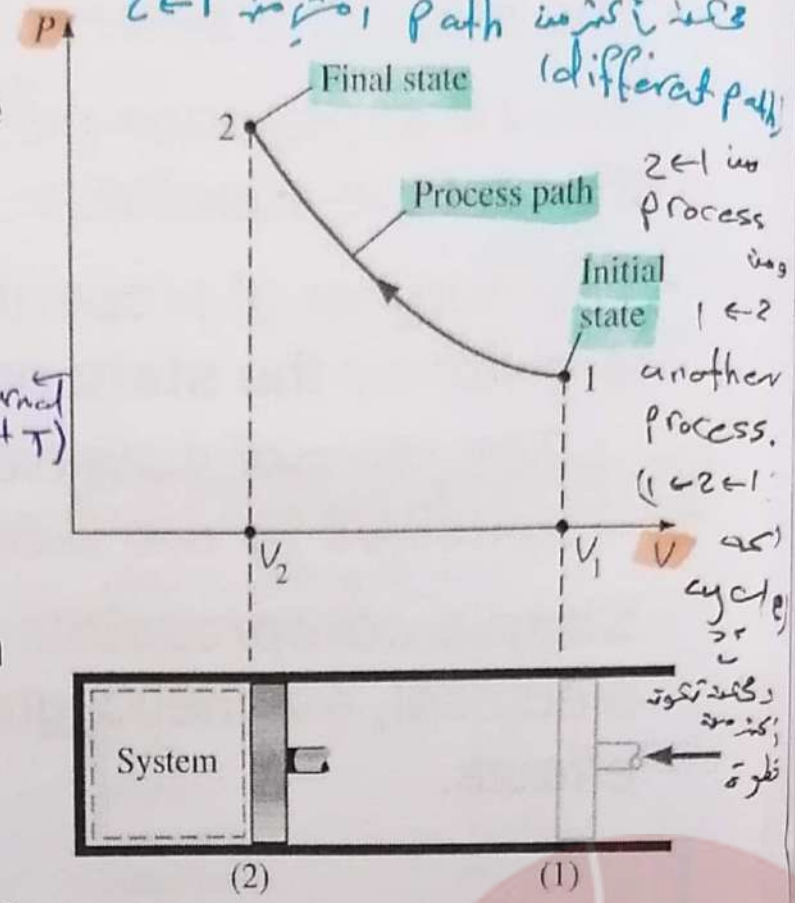
1) During a quasi-equilibrium (slow) process, the system remains practically at equilibrium at all times.
2) They are Easier to analyze (equations of state can apply).
3) Work-producing devices deliver the most work.
4) Work-consuming devices consume the least amount of work.



CamScanner الممسوحة ضوئيا بـ

PROCESSES AND CYCLES-2

- Process diagrams plotted by employing thermodynamic properties as coordinates are very useful in visualizing the processes.
- Some common properties that are used as coordinates are temperature T, pressure P, and volume V (or specific volume v).
- The prefix ***iso***- is often used to designate a process for which a particular property remains constant.
- **Isothermal process**: A process during which the temperature T remains constant.
- **Isobaric process**: A process during which the pressure P remains constant.
- **Isochoric (or isometric) process**: A process during which the specific volume v remains constant.
- **Cycle**: A process during which the initial and final states are identical.



The *P-V* diagram of a compression process.

The Steady-Flow Process

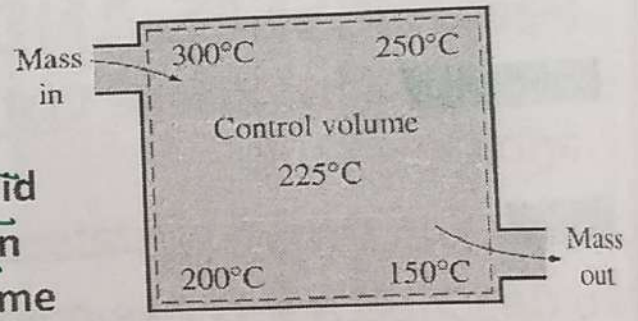
change with space → uniform

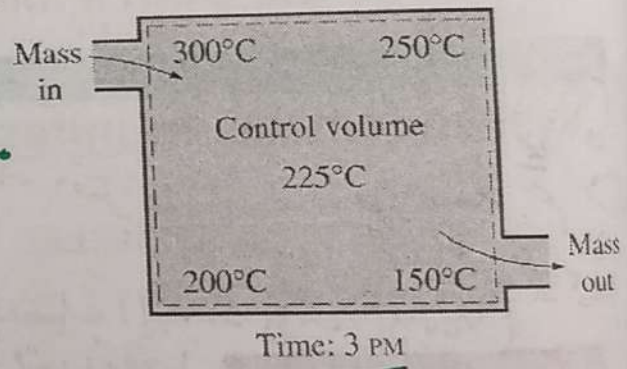
- The term *steady* implies *no change with time*. The opposite of steady is *unsteady*, or *transient*.
- A large number of engineering devices operate for long periods of time under the same conditions, and they are classified as *steady-flow devices*.
- **Steady-flow process**: A process during which a fluid flows through a control volume steadily.
- Steady-flow conditions can be closely approximated by devices that are intended for continuous operation such as turbines, pumps, boilers, condensers, and heat exchangers or power plants or refrigeration systems.

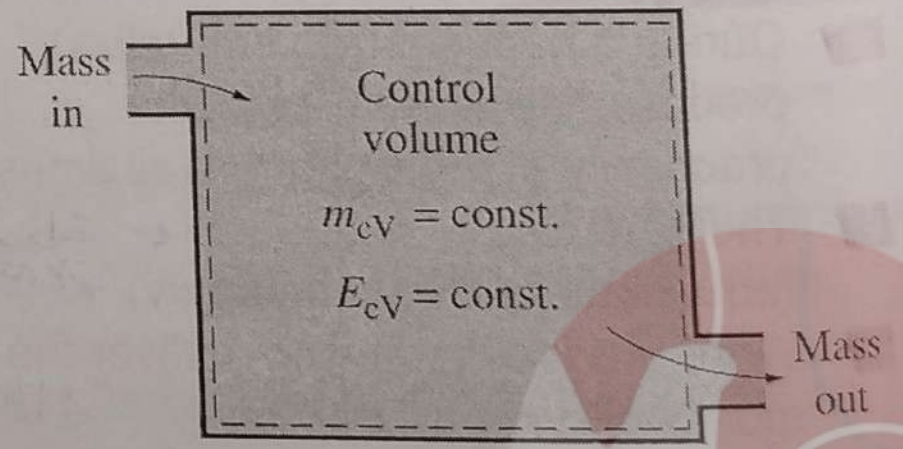
معظم اة اجهزة والمصانع تشتغل Steady state عند

During a steady-flow process, fluid properties within the control volume may change with position but not with time.

ما تتغير مع الزمن







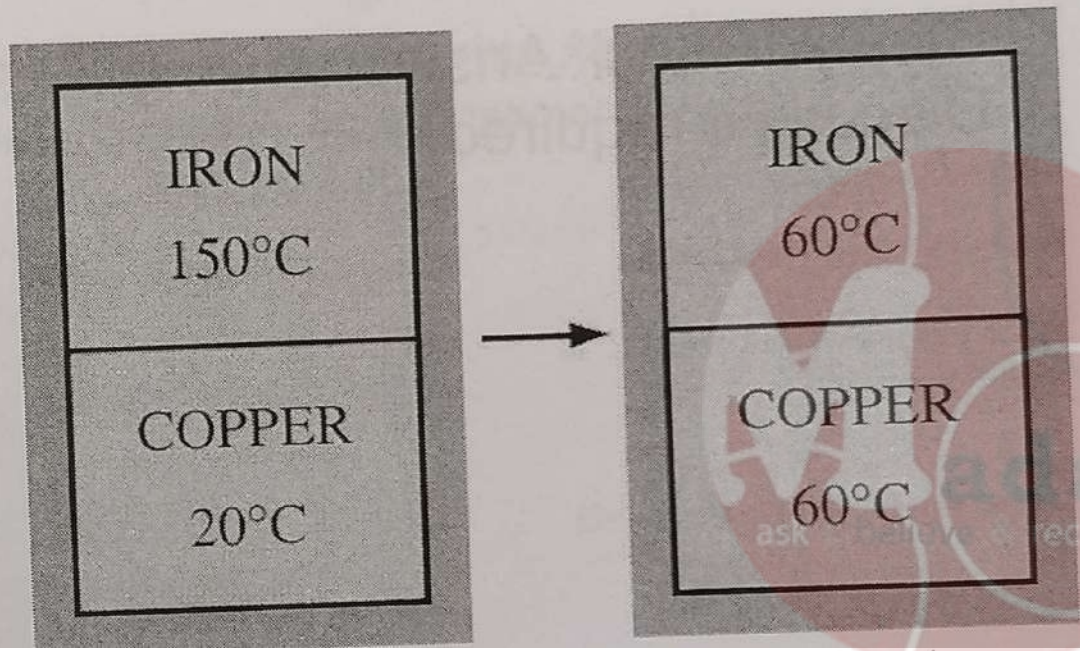
Under steady-flow conditions, the mass and energy contents of a control volume remain constant.

الممسوحة ضوئيا بـ CamScanner

TEMPERATURE AND THE ZEROTH LAW OF THERMODYNAMICS

thermal equilibrium نفس قانون ال

- **The zeroth law of thermodynamics**: If two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other.
- By replacing the third body with a thermometer, the zeroth law can be restated as *two bodies are in thermal equilibrium if both have the same temperature reading even if they are not in contact.*



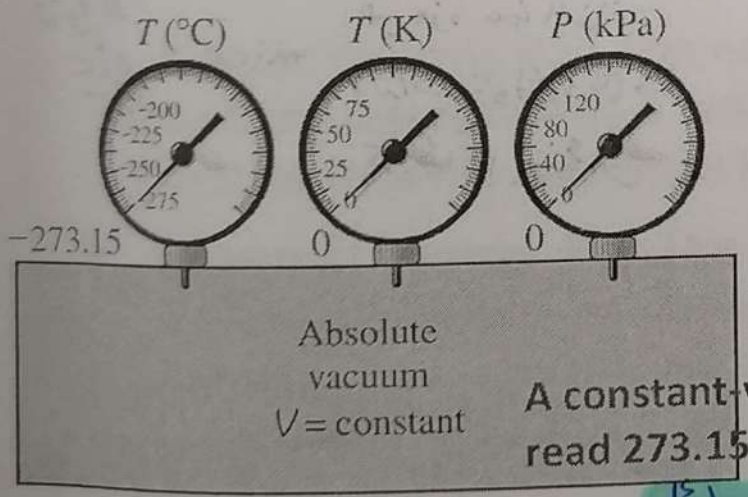
Two bodies reaching thermal equilibrium after being brought into contact in an isolated enclosure.

الممسوحة ضوئيا بـ CamScanner

absolute temp scale less relative temp scale

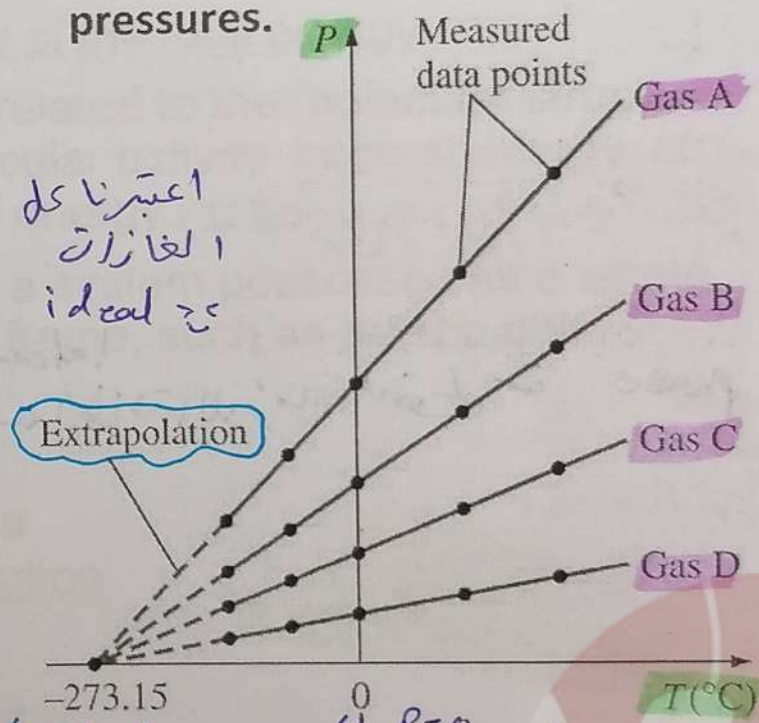
Temperature Scales

- All temperature scales are based on some easily reproducible states such as the freezing and boiling points of water: the *ice point* and the *steam point.*
- **Thermodynamic temperature scale**: A temperature scale that is independent of the properties of any substance.
- **Kelvin scale** (SI)
- A temperature scale nearly identical to the Kelvin scale is the **ideal-gas temperature scale**. The temperatures on this scale are measured using a constant-volume gas thermometer.



A constant-volume gas thermometer would read 273.15°C at absolute zero pressure.

P versus T plots of the experimental data obtained from a constant-volume gas thermometer using four different gases at different (but low) pressures.



CamScanner الممسوحة ضوئيا بـ

Forms of Energy

- Energy can exist in numerous forms such as thermal, mechanical, kinetic, potential, electric, magnetic, chemical, and nuclear, and their sum constitutes the total energy, E of a system.
- Thermodynamics deals with the *change* of the total energy.
- **Microscopic forms of energy**: Those related to the molecular structure of a system and the degree of the molecular activity. Internal energy, U: The sum of all the microscopic forms of energy.
- **Macroscopic forms of energy**: Those a system possesses as a whole with respect to some outside reference frame, such as *kinetic and potential energies*.

- **Kinetic energy, KE**: The energy that a system possesses as a result of its motion relative to some reference frame.
- **Potential energy, PE**: The energy that a system possesses as a result of its elevation in a gravitational field.

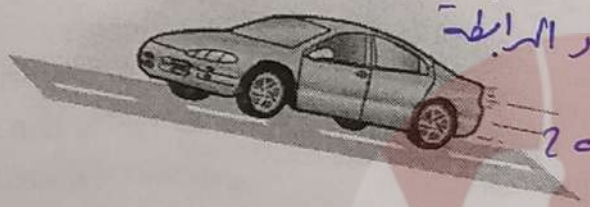


FIGURE 2–4
The macroscopic energy of an object changes with velocity and elevation.

CamScanner الممسوحة ضوئيا بـ

Energy ... numerous forms:

- Thermal
- Mechanical
- Kinetic
- Potential
- Electric
- Magnetic
- Chemical
- Nuclear

Their sum constitutes the total energy, E of a system

The total energy of a system on a unit mass:

$$e = \frac{E}{m} \quad (kJ/kg)$$

Those related to the molecular structure of a system and the degree of the molecular activity.

Internal energy, U

The sum of all the microscopic forms of energy.

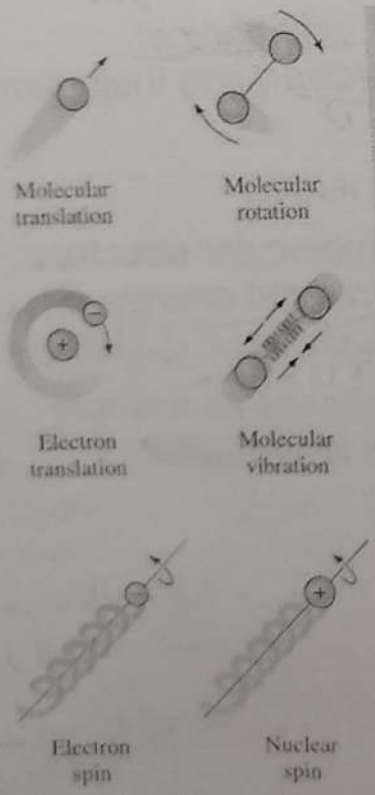
Kinetic energy, KE

The energy that a system possesses as a result of its motion relative to some reference frame.

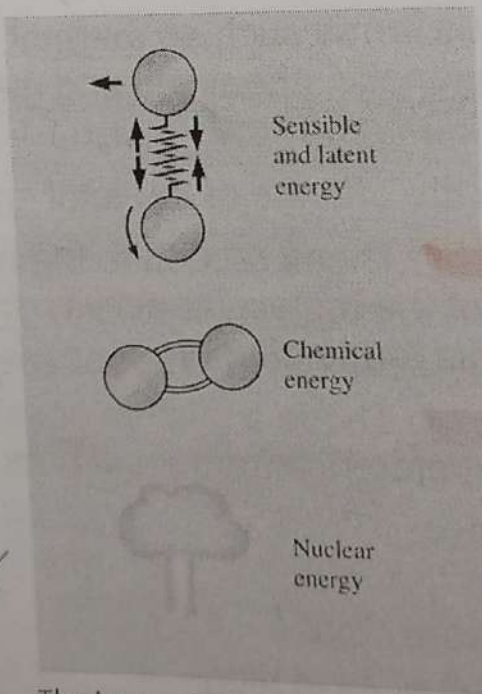
Potential energy, PE

The energy that a system possesses as a result of its elevation in a gravitational field.

Some Physical Insight to Internal Energy



The various forms of microscopic energies that make up ***sensible*** **energy.**



The internal energy of a system is the sum of all forms of the ***microscopic energies***.

Sensible energy: The portion of the internal energy of a system associated with the kinetic energies of the molecules.

Latent energy: The internal energy associated with the phase of a system.

Chemical energy: The internal energy associated with the atomi bonds in a molecule.

Nuclear energy: The tremendous amount of energy associated wit the strong bonds within the nucleus of the atom itself.

Thermal = Sensible + Latent

Internal = Sensible + Latent + Chemical + Nuclear

CamScanner الممسوحة ضوئيا بـ

* heat & work not properties for the sys (فقط process اثناء نظهر)

Energy of A System

*KE, PE & IE → are properties for the sys

1) The **total energy of a system**, can be *contained* or ***stored*** in a system, and thus can be viewed as the ***static* forms of energy**. like PE, KE, IE

2) The forms of energy ***not stored*** in a system can be viewed as the ***dynamic* forms of energy** or as ***energy interactions***. like heat & work

- ❑ The dynamic forms of energy are recognized at the system boundary as they cross it, and they represent the *energy gained or lost by a system during a process.* (عكزنه sys واثناء نظهرها boundary)
- ❑ The only two forms of energy interactions associated with a **closed system** are **heat transfer** and **work**.

3) The difference between **heat transfer** and **work:**

An energy interaction is heat transfer if its driving force is a temperature difference. Otherwise, it is work.

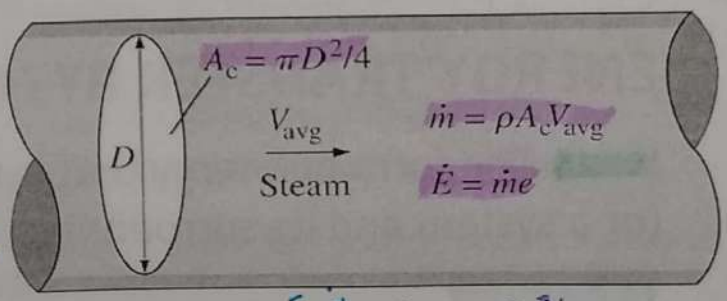
-: work اذا

1-piston rising (piston حركة)
2- rotation like mixers
3- wire passes through current

5

Energy of A System

(not energy balance)



Capital letter : tot energy
small : per unit mass

$$KE = m\frac{V^2}{2} \quad (kJ)$$ **Kinetic energy**

$$ke = \frac{V^2}{2} \quad (kJ/kg)$$ **Kinetic energy per unit mass**

$$PE = mgz \quad (kJ)$$ **Potential energy**

$$pe = gz \quad (kJ/kg)$$ **Potential energy per unit mass**

$$E = U + KE + PE = U + m\frac{V^2}{2} + mgz \quad (kJ)$$ **Total energy of a system**

Mass flow rate ← energy flow rate

$$\dot{m} = \rho\dot{V} = \rho A_c V_{avg} \quad (kg/s)$$

volume flow rate

Energy flow rate

$$\dot{E} = \dot{m}e \quad (kJ/s \text{ or } kW)$$

$A_c = \pi D^2/4$

$V_{avg} = \frac{\dot{V}}{A_c}$

الممسوحة ضوئيا بـ CamScanner

Energy of A System

(not energy balance)

Capital letter : tot energy
small " : per unit mass

$$KE = m\frac{V^2}{2} \quad (kJ)$$ Kinetic energy

$$ke = \frac{V^2}{2} \quad (kJ/kg)$$ Kinetic energy per unit mass

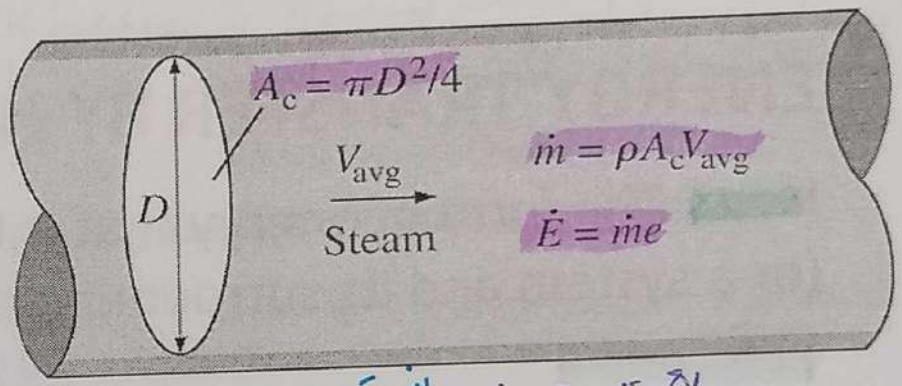
$$PE = mgz \quad (kJ)$$ Potential energy

$$pe = gz \quad (kJ/kg)$$ Potential energy per unit mass

$$E = U + KE + PE = U + m\frac{V^2}{2} + mgz \quad (kJ)$$ Total energy of a system

$$e = u + ke + pe = u + \frac{V^2}{2} + gz \quad (kJ/kg)$$ Energy of a system per unit mass

$$e = \frac{E}{m} \quad (kJ/kg)$$ Total energy per unit mass



Mass flow rate

$$\dot{m} = \rho\dot{V} = \rho A_c V_{avg} \quad (kg/s)$$

Energy flow rate

$$\dot{E} = \dot{m}e \quad (kJ/s \text{ or } kW)$$

ask : believe & recieve

الممسوحة ضوئيا بـ CamScanner

$$e = \frac{E}{m} \qquad (\text{kJ/kg})$$

Mechanical Energy

- **Mechanical energy:** The form of energy ***that can be converted to mechanical work completely*** and directly by an ideal mechanical device such as an ideal turbine.
- **Kinetic and potential energies:** The **familiar forms** of mechanical energy.

$$e_{\text{mech}} = \frac{P}{\rho} + \frac{V^2}{2} + gz$$

Mechanical energy of a flowing fluid per unit mass

$$\dot{E}_{\text{mech}} = \dot{m}e_{\text{mech}} = \dot{m}\left(\frac{P}{\rho} + \frac{V^2}{2} + gz\right)$$

Rate of mechanical energy of a flowing fluid

Mechanical energy change of a fluid during incompressible flow per unit mass

$$\Delta e_{\text{mech}} = \frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \qquad (\text{kJ/kg})$$

= rate of change

Rate of mechanical energy change of a fluid during incompressible flow

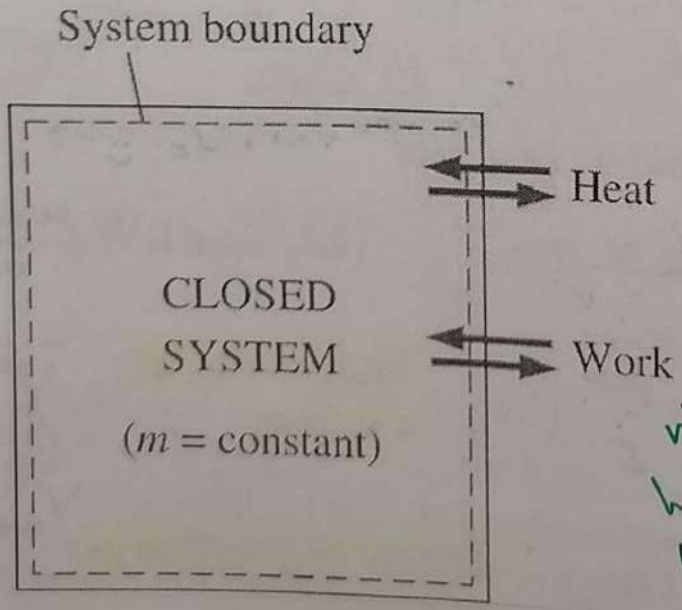
$$\Delta \dot{E}_{\text{mech}} = \dot{m}\Delta e_{\text{mech}} = \dot{m}\left(\frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right) \qquad (\text{kW})$$

(small P ∵) ≠ property of pressure

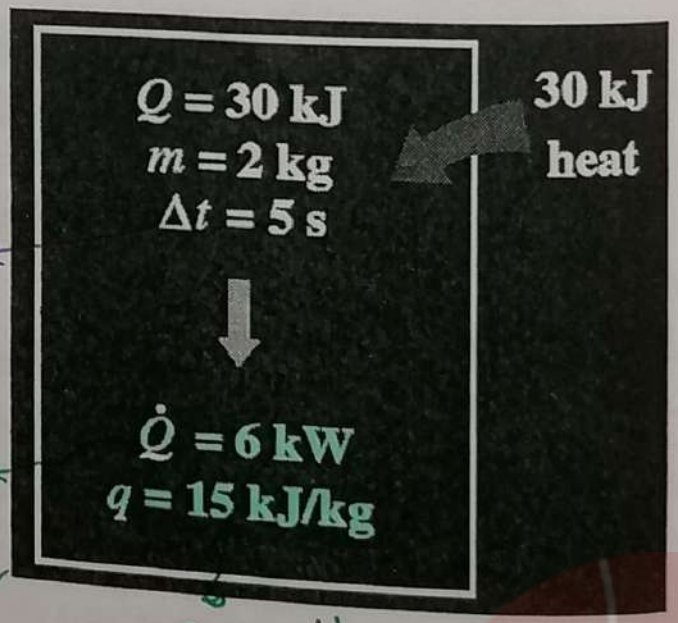
CamScanner الممسوحة ضوئيا بـ

ENERGY TRANSFER BY HEAT

Heat: The form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a *temperature difference.*



Energy can cross the boundaries of a closed system in the form of **heat** and **work.**



Heat transfer is expressed both:

- As time rate (kJ/s or KW), and
- As specific heat transfer, kJ/kg of system mass

heat & work can be express in two ways

ENERGY TRANSFER BY HEAT

$$q = \frac{Q}{m} \quad (\text{kJ/kg})$$

Heat transfer per unit mass

$$Q = \dot{Q}\,\Delta t \quad (\text{kJ})$$

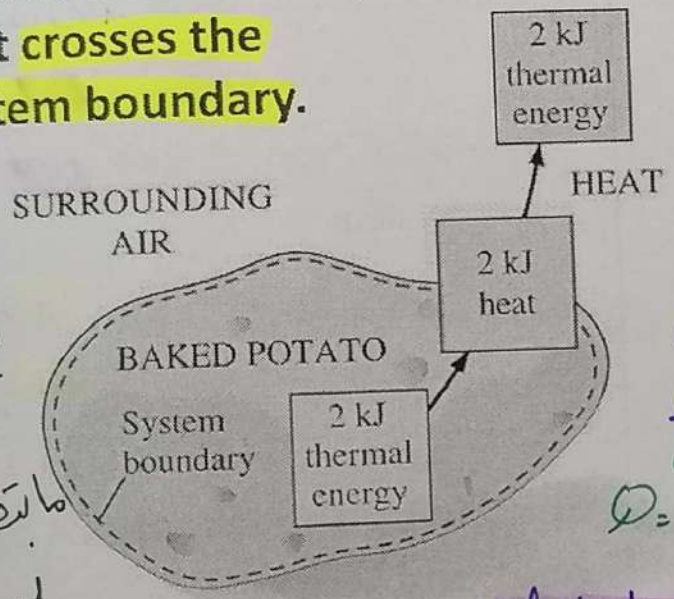
Amount of heat transfer when heat transfer rate is constant

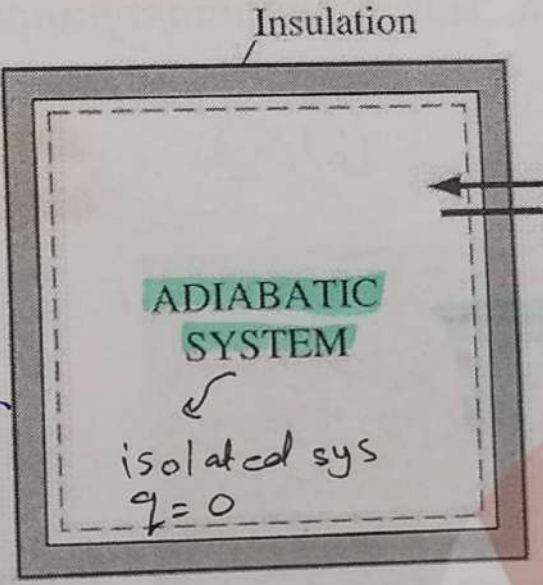
rate of heat transfer or specific heat

$$Q = \int_{t_1}^{t_2} \dot{Q}\,dt \quad (\text{kJ})$$

Amount of heat transfer when heat transfer rate changes with time

Energy is recognized as heat transfer only as it crosses the system boundary.





During an adiabatic process, a system exchanges no heat with its surroundings.

adiabatic = isentropic

CamScanner الممسوحة ضوئيا بـ

Kinetic & thermal energy مرتبطة
اذا كانت الحرارة قليلة في تفاعل

Historical Background on Heat

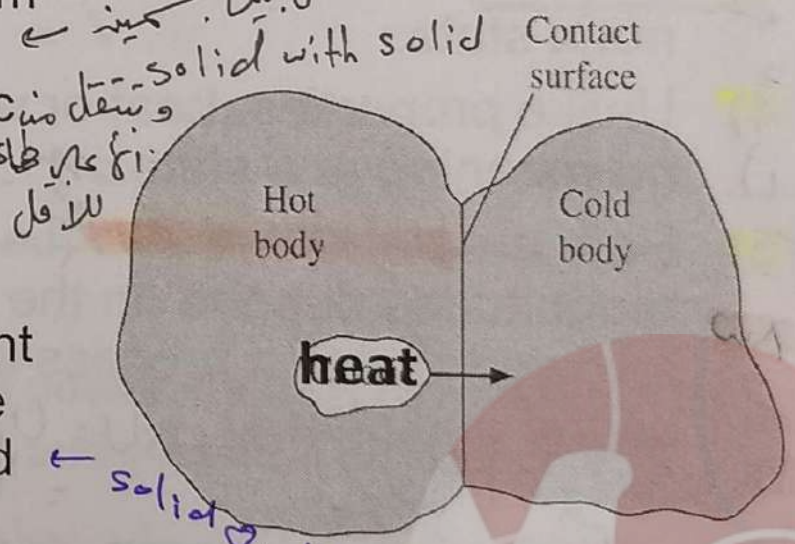
طاقة حركية
- **Kinetic theory**: Treats molecules as tiny balls that are in motion and thus possess kinetic energy.
  ال molecule
- **Heat**: The energy associated with the random motion of atoms and molecules.

كيف تنتقل الحرارة من ال sys لل surrounding والعكس!

Heat transfer mechanisms:

by 3 mechanisms :-

1. **Conduction**: The transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interaction between particles.
   انتقال بين جسمين ← solid with solid وتنتقل من الأعلى طاقة للأقل
2. **Convection**: The transfer of energy between a solid surface and the adjacent fluid that is in motion, and it involves the combined effects of conduction and fluid motion.
   الحمل الحرارة ← solid & liq phase
   فوتونات وانكاءات
3. **Radiation**: The transfer of energy due to the emission of electromagnetic waves (or photons). at high tem



(واحد بكون بارد وواحد بكون ساخن) السطح ساخن وننزل عليه بفلويد أو الفلويد ساخن بخلي السطح ساخن

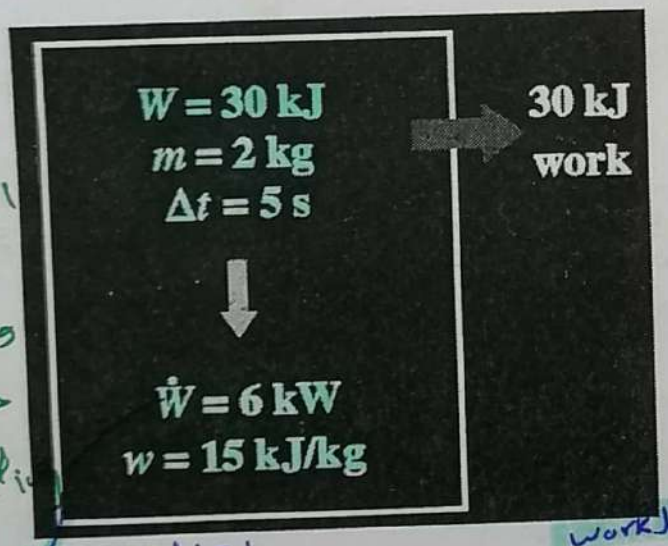
CamScanner الممسوحة ضوئيا بـ

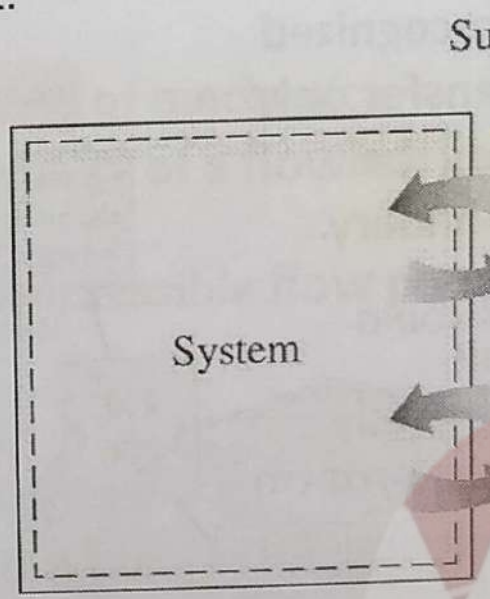
ENERGY TRANSFER BY WORK

- **Work:** The energy transfer associated with a force acting through a distance.
- **A rising piston, a rotating shaft, and an electric wire crossing the system boundaries** are all associated with work interactions
- **Formal sign convention**: *Heat transfer to a system and work done by a system are positive; heat transfer from a system and work done on a system are negative.*
- **Alternative to sign convention** is to use the subscripts ***in*** and ***out*** to indicate direction. This is the primary approach in this text.

$$w = \frac{W}{m} \qquad (\text{kJ/kg})$$

Work done per unit mass





Specifying the directions of heat and work.

Power is the work done per unit time (kW)

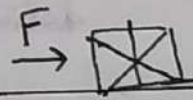
$$\dot{W} = \frac{\delta W}{\delta t}$$

$$\dot{W} = \frac{dW}{dt}$$

$$\dot{W} = F \cdot V$$

$$dW = F\,dL$$

$$W = \int F\,dL$$



heat and work.

rate of work transfer = power

$dW = F\,dL$ (function) — أول تعريف للـ work

$W = \int F\,dL$ (for solid)

Heat and Work مقارنة بينهم

1) Both are recognized at the boundaries of a system as they cross the boundaries. That is, both heat and work are *boundary* phenomena.

2) Systems possess energy, but **not** heat or work.

3) Both are associated with a *process*, not a state.

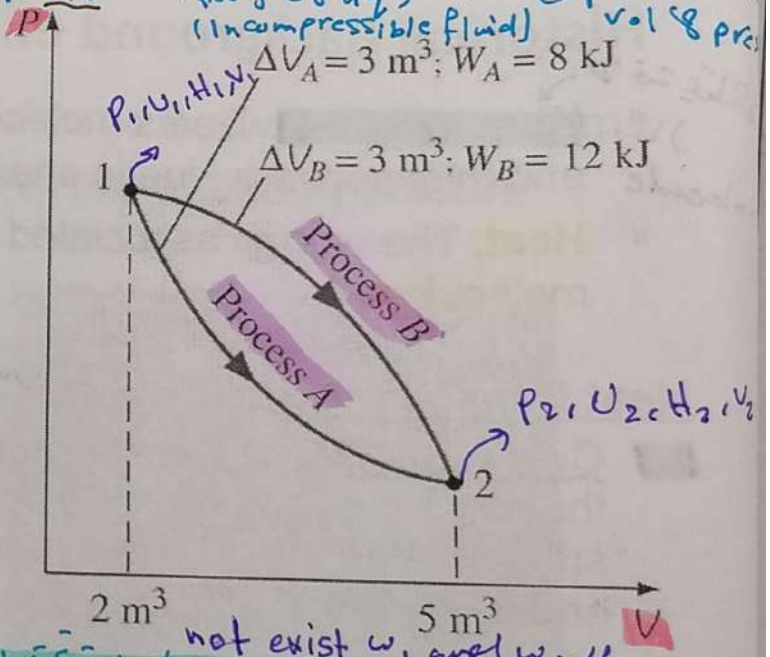
4) Unlike properties, heat or work has no meaning at a state.

5) Both are *path functions* (i.e., their magnitudes depend on the path followed during a process as well as the end states).

$dW = P(A\,dL)$

$W = \int P\,dV$ (for gas & liq) (incompressible fluid)

for gas we express it with vol & pressure



Properties are point functions; but heat and work are path functions (their magnitudes depend on the path followed).

not exist w_1 and w_2 — الـ work مش بالحالة دي

curve يتكون w_{12}

$\Delta U = U_2 - U_1 = \int_{P_1}^{P_2} dP$

w_1 & w_2 q_1 & q_2 ✗

$$\int_1^2 dV = V_2 - V_1 = \Delta V$$

تفاضل كامل

$$\int_1^2 \delta W = W_{12} \quad (not\ \Delta W)$$

inexact يعني تفاضل غير تامة

Properties are point functions; they have exact differentials (d)

Path functions have inexact differentials (δ)

الممسوحة ضوئيا بـ CamScanner

Forms of Work

❑ **Various forms of work are expressed as follows:**

› ***Electrical work:***
$$W_e = VI\Delta t \quad \textbf{(kJ)}$$

› ***Boundary work:*** or (flow work)
$$W_b = \int_1^2 P dV$$

› ***Gravitational work*** **(= ΔPE):**
$$W_g = mg(z_2 - z_1)$$

› ***Acceleration work*** **(= ΔKE):**
$$W_a = \frac{1}{2} m(\vec{V}_2^2 - \vec{V}_1^2)$$

› ***Shaft (stirring) work:***
$$W_{sh} = 2\pi n \tau$$

› ***Spring work:***
$$W_{spring} = \frac{1}{2} k(x_2^2 - x_1^2)$$

CamScanner الممسوحة ضوئيا بـ

قانون أوم: التيار يتناسب طردياً مع فرق الجهد أي يعني ← طاقة كهربائية

$V = IR$ ∴

Electrical Work

Electrical work — كمية الكهرباء

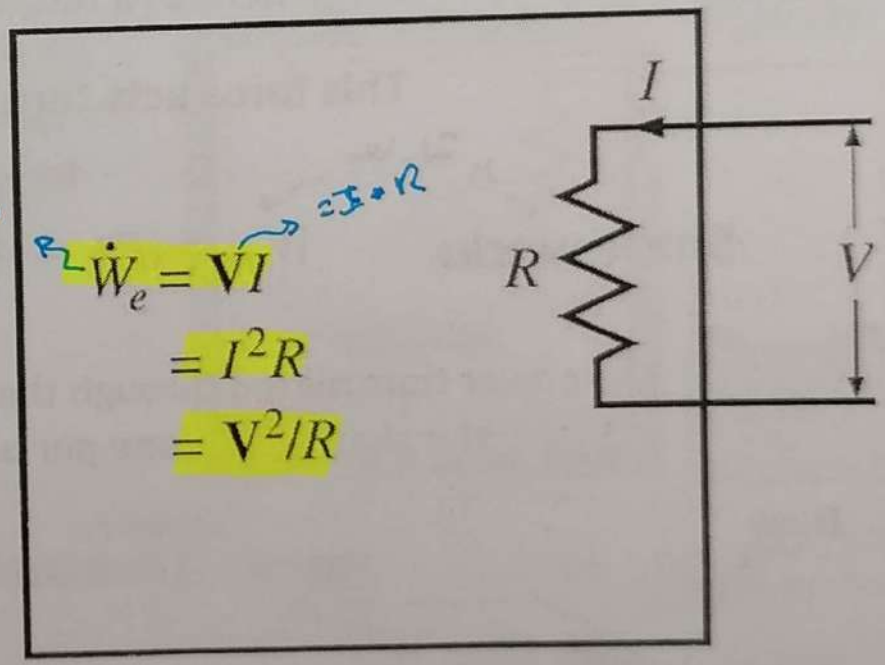
$$W_e = VN$$

V: voltage (volt)

Electrical power

$$\dot{W}_e = VI \quad (W)$$

I: current (A)



$\dot{W}_e = VI = I \cdot R$

$= I^2R$

$= V^2/R$

قسمنا على الزمن

When potential difference and current change with time

$$W_e = \int_1^2 VI\,dt \quad (kJ)$$

dt: In second

When potential difference and current remain constant

$$W_e = VI\,\Delta t \quad (kJ)$$

Electrical power in terms of resistance R, current I, and potential difference V.

→ N = coulombs of electrons move through a potential difference V

$N = I \cdot \Delta t$ ←

1 coulomb = 1 Ampere * 1 second

ohm's law: $V = I * R$

1 Joule = 1 Volt * 1 coulomb

قاس بالكولوم — قانون فاراداي: كمية الكهرباء = التيار * الزمن

$Q = I t$

[Colomb] = A * Sec

Qadar recieve

الممسوحة ضوئيا بـ CamScanner

MECHANICAL FORMS OF WORK

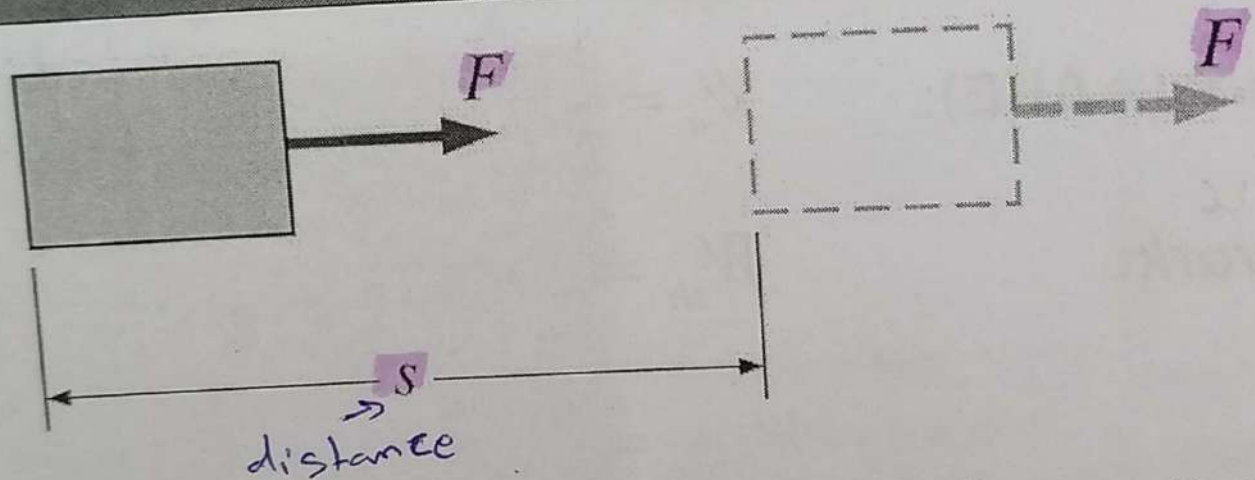
- There are two requirements for a work interaction between a system and its surroundings to exist:
  - there must be a ***force*** acting on the boundary.
  - the boundary must ***move***.

Work = Force × Distance

$$W = Fs \qquad \text{(kJ)}$$

When force is not constant

$$W = \int_1^2 F\, ds \qquad \text{(kJ)}$$



The work done is proportional to the force applied (*F*) and the distance traveled (*s*).

CamScanner الممسوحة ضوئيا بـ

قانون أوم: التيار يتناسب طردياً مع فرق الجهد أي يعني ← طاقة كهربائية

$V = IR$ ∴

Electrical Work

Electrical work — كمية الكهرباء

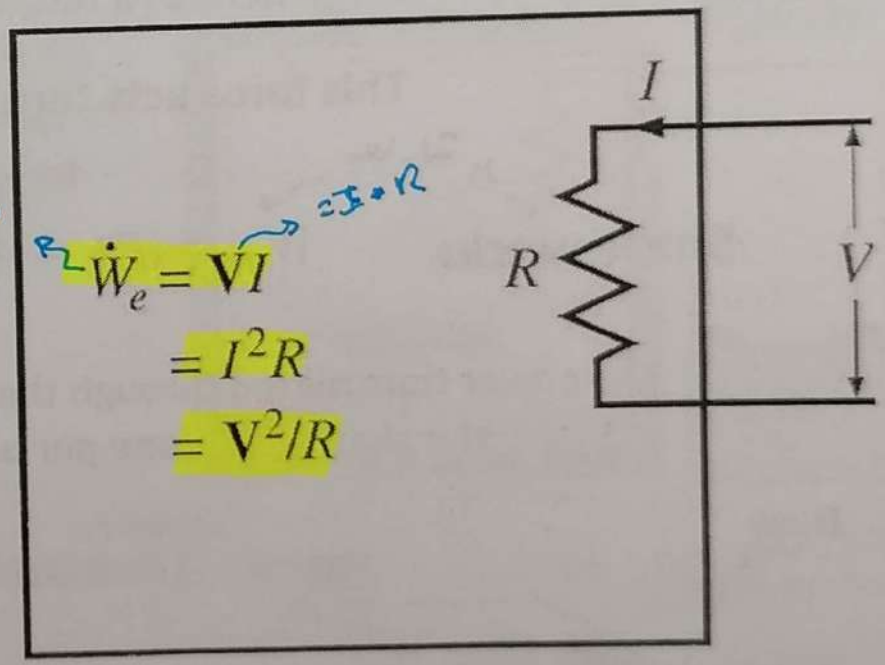
$$W_e = VN$$

V: voltage (volt)

Electrical power

$$\dot{W}_e = VI \quad (W)$$

I: current (A)



$\dot{W}_e = VI = I \cdot R$

$= I^2R$

$= V^2/R$

قسمنا على الزمن

When potential difference and current change with time

$$W_e = \int_1^2 VI\,dt \quad (kJ)$$

dt: In second

When potential difference and current remain constant

$$W_e = VI\,\Delta t \quad (kJ)$$

Electrical power in terms of resistance R, current I, and potential difference V.

→ N = coulombs of electrons move through a potential difference V

$N = I \cdot \Delta t$ ←

1 coulomb = 1 Ampere * 1 second

ohm's law: $V = I * R$

1 Joule = 1 Volt * 1 coulomb

قاس بالكولوم — قانون فاراداي: كمية الكهرباء = التيار * الزمن

$Q = I t$

[Colomb] = A * Sec

Qadar recieve

الممسوحة ضوئيا بـ CamScanner

Shaft Work

A force F acting through a moment arm r generates a torque T

$$T = Fr \quad \rightarrow \quad F = \frac{T}{r}$$

This force acts through a distance s

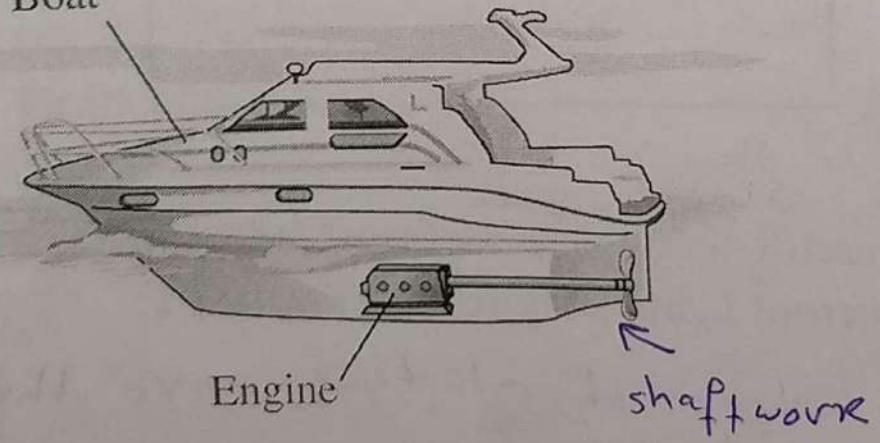
$$s = (2\pi r)n$$

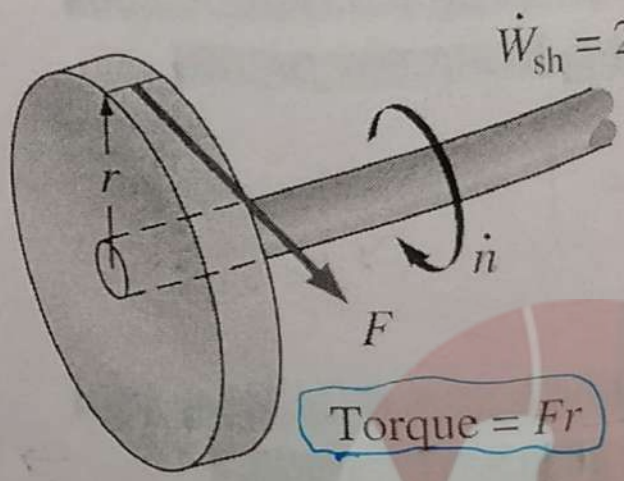
Shaft work:

$$W_{sh} = Fs = \left(\frac{T}{r}\right)(2\pi r n) = 2\pi n T \quad \text{(kJ)}$$

The power transmitted through the shaft is the shaft work done per unit time

$$\dot{W}_{sh} = 2\pi \dot{n} T \quad \text{(kW)}$$





Energy transmission through rotating shafts is commonly encountered in practice.

Shaft work is proportional to the torque applied and the number of revolutions of the shaft.

CamScanner الممسوحة ضوئيا بـ

THE FIRST LAW OF THERMODYNAMICS

- The *first law of thermodynamics* (***the conservation of energy principle***) provides a sound basis for studying the relationships among the various forms of energy and energy interactions.
- The first law states that ***energy can be neither created nor destroyed during a process; it can only change forms.***
- The *First Law*: For all adiabatic processes between two specified states of a closed system, the net work done is the same regardless of the nature of the closed system and the details of the process.

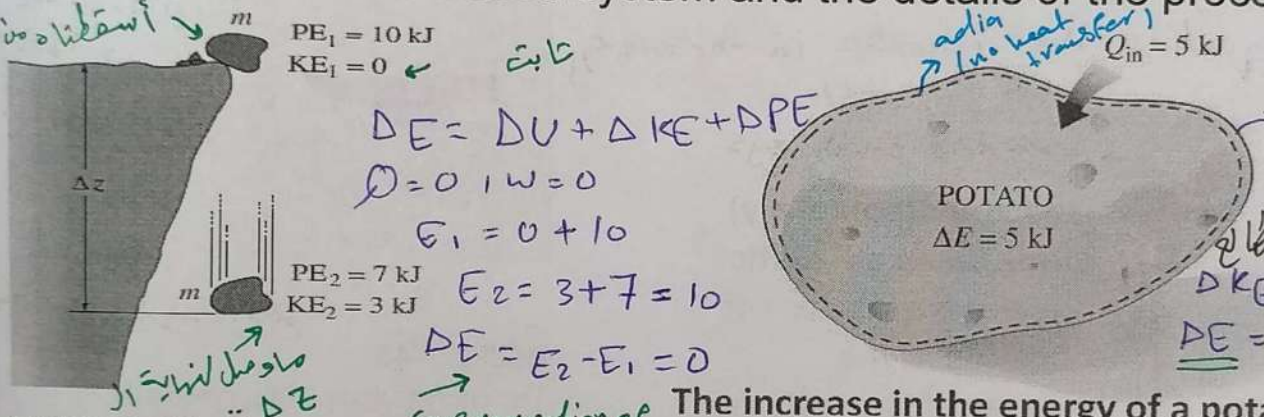
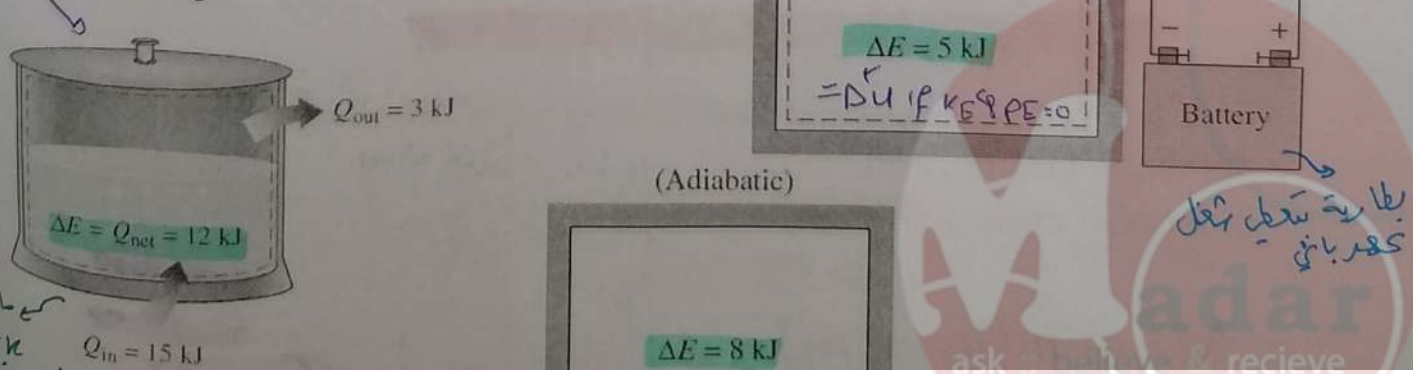


FIGURE 2–39
Energy cannot be created or destroyed; it can only change forms.

The increase in the energy of a potato in an oven is equal to the amount of heat transferred to it.

THE FIRST LAW OF THERMODYNAMICS

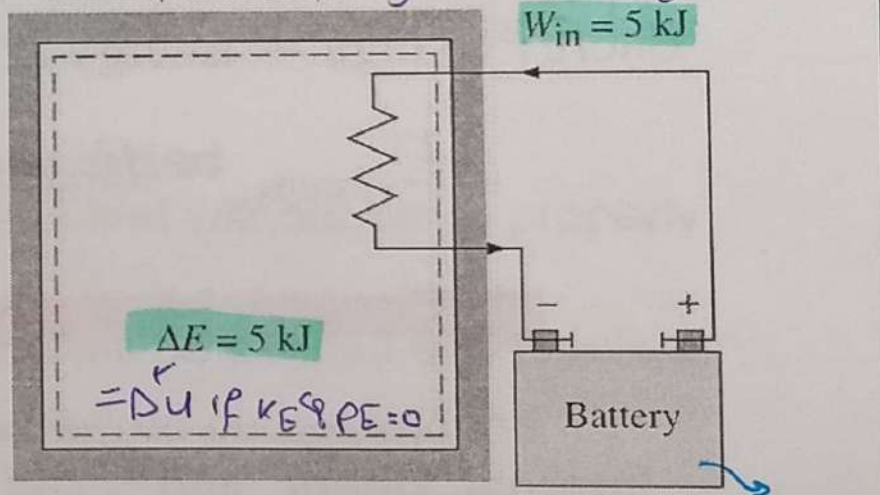
The work (electrical) done on an adiabatic system is equal to the increase in the energy of the system.



CamScanner الممسوحة ضوئيا بـ

THE FIRST LAW OF THERMODYNAMICS

The work (electrical) done on an adiabatic system is equal to the increase in the energy of the system.



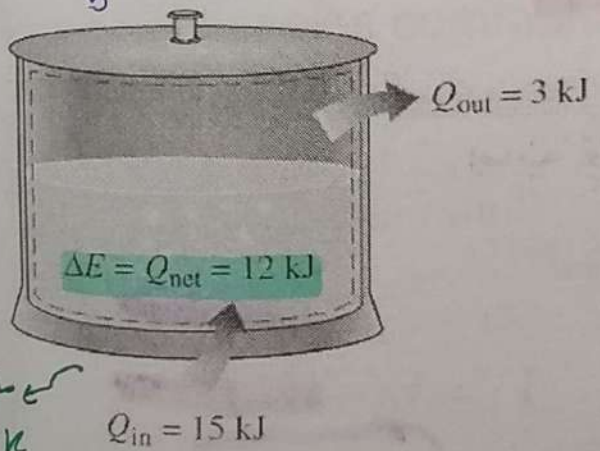
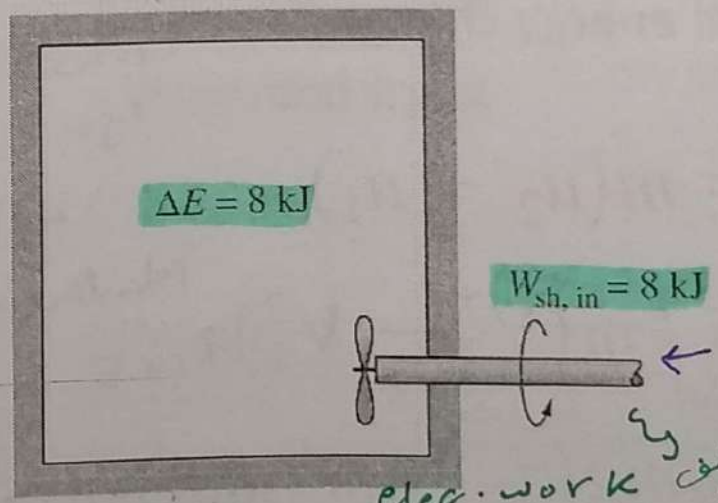


FIGURE 2–41
In the absence of any work interactions, the energy change of a system is equal to the net heat transfer.



The work (shaft) done on an adiabatic system is equal to the increase in the energy of the system.

CamScanner الممسوحة ضوئيا بـ

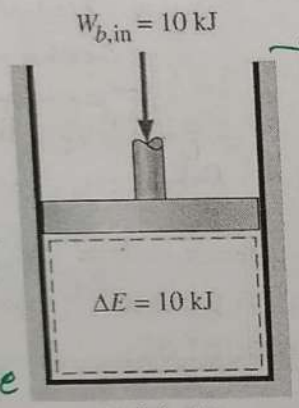
Energy Balance

*The net change (increase or decrease) in the **total energy** of the system during a process is equal to the difference between the total energy entering and the total energy leaving the system during that process.*

$$\begin{pmatrix}\text{Total energy}\\ \text{entering the system}\end{pmatrix} - \begin{pmatrix}\text{Total energy}\\ \text{leaving the system}\end{pmatrix} = \begin{pmatrix}\text{Change in the total}\\ \text{energy of the system}\end{pmatrix}$$

$$E_{in} - E_{out} = \Delta E_{system}$$

The boundary work done on an adiabatic sys is equal to the increase in the energy of the system



work done on the sys

The work (boundary) done on an adiabatic system is equal to the increase in the energy of the system.

$\Delta E = \Delta U = Q - W$

$0 - (-10) = 10$

OR: $\Delta E = \Delta U = W_{in} - W_{out}$

$= 10 - 0$

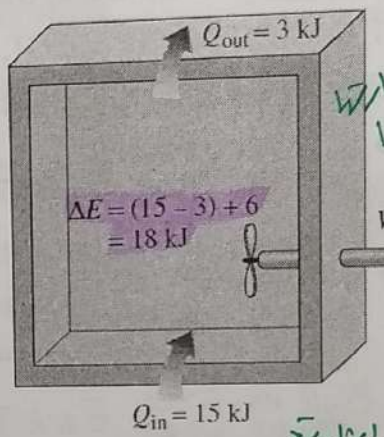


FIGURE 2–45
The energy change of a system during a process is equal to the *net* work and heat transfer between the system and its surroundings.

Energy Change of a System, ΔE_{system}

Energy change = Energy at final state − Energy at initial state

$$\Delta E_{system} = E_{final} - E_{initial} = E_2 - E_1$$

$$\Delta E = \Delta U + \Delta KE + \Delta PE$$

Internal, kinetic, and potential energy changes

$$\Delta U = m(u_2 - u_1)$$

$$\Delta KE = \frac{1}{2}m(V_2^2 - V_1^2)$$

Stationary Systems

$z_1 = z_2 \rightarrow \Delta PE = 0$

$V_1 = V_2 \rightarrow \Delta KE = 0$

$\Delta E = \Delta U$

ask recieve

الممسوحة ضوئيا بـ CamScanner

Energy Change of a System, ΔE_{system}

Energy change = Energy at final state − Energy at initial state

$$\Delta E_{system} = E_{final} - E_{initial} = E_2 - E_1$$

$$\Delta E = \Delta U + \Delta KE + \Delta PE$$

Internal, kinetic, and potential energy changes

$$\Delta U = m(u_2 - u_1)$$

$$\Delta KE = \frac{1}{2}m(V_2^2 - V_1^2)$$

$$\Delta PE = mg(z_2 - z_1)$$

Stationary Systems

$z_1 = z_2 \rightarrow \Delta PE = 0$

$V_1 = V_2 \rightarrow \Delta KE = 0$

$\Delta E = \Delta U$

Nadar ask & believe & recieve

الممسوحة ضوئيا بـ CamScanner

$\Delta = \text{In} - \text{out}$

energy balance

$\Delta T = T_2 - T_1$

$\Delta P = P_2 - P_1$

Mechanisms of Energy Transfer, E_{in} and E_{out}

$$E_{in} - E_{out} = (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass,in} - E_{mass,out}) = \Delta E_{system}$$

energy balance

1) Heat transfer
2) Work transfer
3) Mass flow

just for open sys

A closed mass involves only *heat transfer* and work.

$$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic, potential, etc., energies}} \quad \text{(kJ)}$$

الطاقة المخزنة بالجسم ونتاجة بسبب الحركة

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} \quad \text{(kW)}$$

$$Q = \dot{Q}\,\Delta t \ \text{(kJ)} \qquad W = \dot{W}\,\Delta t \qquad \Delta E = (dE/dt)\,\Delta t$$

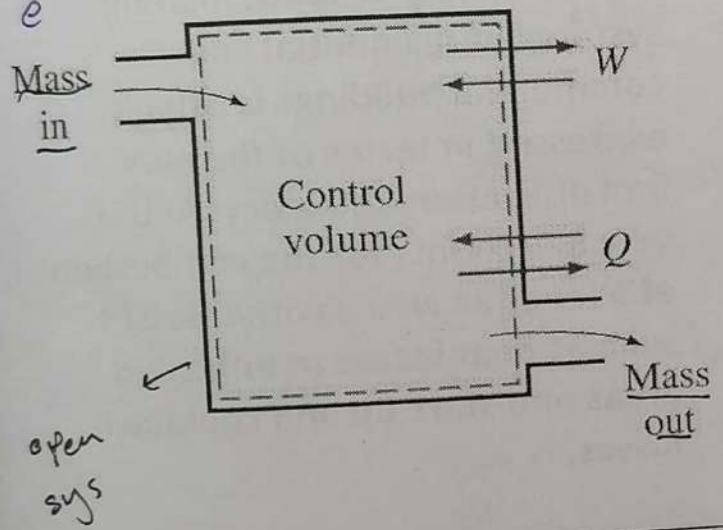
معدل تغير الـ energy

$$e_{in} - e_{out} = \Delta e_{system} \quad \text{(kJ/kg)}$$

energy per unit mass

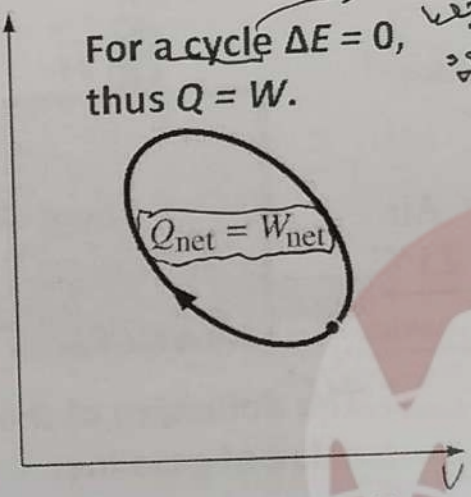
$$\delta E_{in} - \delta E_{out} = dE_{system} \qquad \delta e_{in} - \delta e_{out} = de_{system}$$

$$\dot{W}_{net,out} = \dot{Q}_{net,in} \quad \text{(for a cycle)}$$



open sys

The energy content of a control volume can be changed by mass flow as well as heat and work interactions.



For a cycle $\Delta E = 0$, thus $Q = W$.

كنا عند نقطة درجة عندما ...

ask recieve
CamScanner الممسوحة ضوئيا بـ

ENERGY CONVERSION EFFICIENCIES

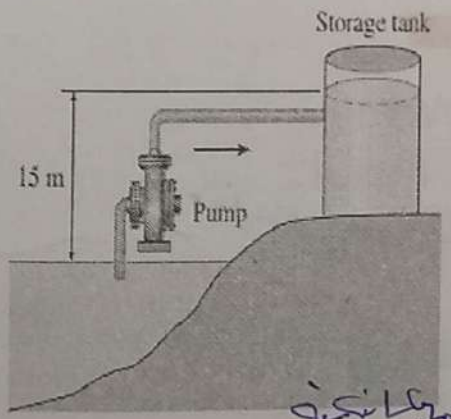
- *Efficiency* is one of the most frequently used terms in thermo-dynamics, and it indicates how well an energy conversion or transfer process is accomplished.
- *Efficiency* is also one of the most frequently misused terms in thermodynamics, because it is often used without being properly defined first.
- Some efficiencies commonly used in practice will be defined and clarified.
- *Efficiency* can be expressed in terms of the desired output and the required input as:

(In general equation) →

$$\text{Efficiency} = \frac{\text{Desired output}}{\text{Required input}}$$

← عم حطت مقارنة بالي حطيتيه

Example:



← رفعت الي من مكان لمكان عن طريق طاقة ميكانيكية

$$\eta_{\text{pump}} = \frac{\Delta \dot{E}_{\text{mech,fluid}}}{\dot{W}_{\text{shaft,in}}} = \frac{\dot{W}_{\text{pump},u}}{\dot{W}_{\text{pump}}}$$

useful

الـ shaftwork تحولت إلى طاقة ميكانيكية مخزنة بالي

ask & believe & recieve
الممسوحة ضوئيا بـ CamScanner

losses

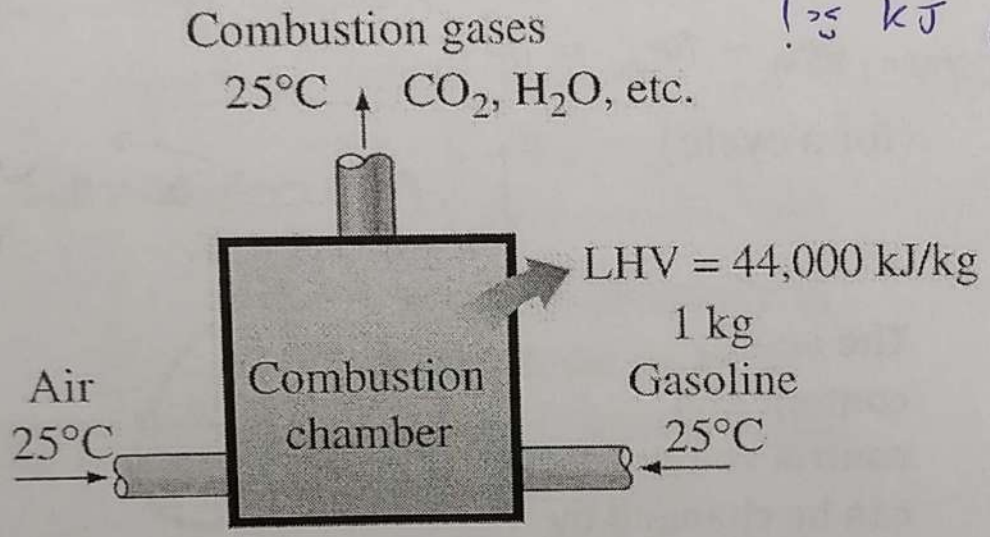
Combustion

$$\eta_{combustion} = \frac{Q}{HV} = \frac{\text{Amount of heat released during combustion}}{\text{Heating value of the fuel burned}}$$

Heating value of the fuel: The amount of heat released when a unit amount of fuel at room temperature is completely burned, and the combustion products are cooled to the room temperature.

Lower heating value (LHV): When the water leaves as a vapor.

Higher heating value (HHV): When the water in the combustion gases is completely condensed and thus the heat of vaporization is also recovered.

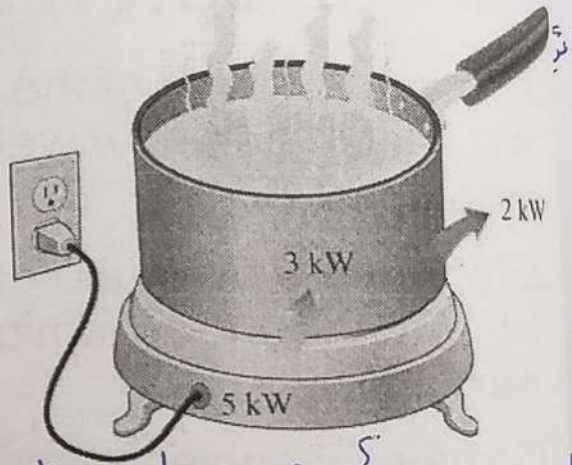


The definition of the heating value of gasoline.

The efficiency of space heating systems of residential and commercial buildings is usually expressed in terms of the annual fuel utilization efficiency (AFUE), which accounts for the combustion efficiency as well as other losses such as heat losses to unheated areas and start-up and cooldown losses.

CamScanner الممسوحة ضوئيا بـ

The efficiency of a **cooking appliance** represents the fraction of the energy supplied to the appliance that is transferred to the food.



$$\text{Efficiency} = \frac{\text{Energy utilized}}{\text{Energy supplied to appliance}}$$

$$= \frac{3\ \text{kWh}}{5\ \text{kWh}} = 0.60$$

Power Plants

- **Generator:** A device that converts mechanical energy to electrical energy.
- **Generator efficiency:** The ratio of the electrical power output to the mechanical power input.
- **Thermal efficiency of a power plant:**

  The ratio of the net electrical power output to the rate of fuel energy input:

$$\eta_{overall} = \eta_{combustion}\,\eta_{thermal}\,\eta_{generator} = \frac{\dot{W}_{net,electric}}{HHV \times \dot{m}_{fuel}}$$

$$\dot{W}_{net,mech} \times \frac{\dot{W}_{net,elect}}{\dot{W}_{net,mech}} =$$

CamScanner المسوحة ضوئيا بـ

Efficiencies of Mechanical and Electrical Devices

Mechanical efficiency

$$\eta_{mech} = \frac{\text{Mechanical energy output}}{\text{Mechanical energy input}} = \frac{E_{mech,out}}{E_{mech,in}} = 1 - \frac{E_{mech,loss}}{E_{mech,in}}$$

The effectiveness of the conversion process between the mechanical work supplied or extracted and the mechanical energy of the fluid is expressed by the pump efficiency and turbine efficiency:

$$\eta_{pump} = \frac{\text{Mechanical energy increase of the fluid}}{\text{Mechanical energy input}} = \frac{\Delta \dot{E}_{mech,fluid}}{\dot{W}_{shaft,in}} = \frac{\dot{W}_{pump,u}}{\dot{W}_{pump}}$$

$$\Delta \dot{E}_{mech,fluid} = \dot{E}_{mech,out} - \dot{E}_{mech,in}$$

$$\eta_{turbine} = \frac{\text{Mechanical energy output}}{\text{Mechanical energy decrease of the fluid}} = \frac{\dot{W}_{shaft,out}}{|\Delta \dot{E}_{mech,fluid}|} = \frac{\dot{W}_{turbine}}{\dot{W}_{turbine,e}}$$

$$|\Delta \dot{E}_{mech,fluid}| = \dot{E}_{mech,in} - \dot{E}_{mech,out}$$

$$\eta_{motor} = \frac{\text{Mechanical power output}}{\text{Electric power input}} = \frac{\dot{W}_{shaft,out}}{\dot{W}_{elect,in}}$$

Pump efficiency

$$\eta_{pump} = \frac{\dot{W}_{pump,u}}{\dot{W}_{shaft,in}} = \frac{\Delta \dot{E}_{mech,fluid}}{\dot{W}_{shaft,in}}$$

Generator efficiency

$$\eta_{generator} = \frac{\text{Electric power output}}{\text{Mechanical power input}} = \frac{\dot{W}_{elect,out}}{\dot{W}_{shaft,in}}$$

Pump-Motor overall efficiency

$$\eta_{pump-motor} = \eta_{pump}\eta_{motor} = \frac{\dot{W}_{pump,u}}{\dot{W}_{elect,in}} = \frac{\Delta \dot{E}_{mech,fluid}}{\dot{W}_{elect,in}}$$

Turbine-Generator overall efficiency

$$\eta_{turbine-gen} = \eta_{turbine}\eta_{generator} = \frac{\dot{W}_{elect,out}}{\dot{W}_{turbine,e}} = \frac{\dot{W}_{elect,out}}{|\Delta \dot{E}_{mech,fluid}|}$$

$\eta_{turbine} = 0.75 \quad \eta_{generator} = 0.97$

الممسوحة ضوئيا بـ CamScanner

$|\Delta E_{\text{mech,fluid}}|$ $E_{\text{mech,in}}$ $E_{\text{mech,out}}$

generator

useful work وبستفيد منه ... مش كل الـ shaft بعطينا

Motor efficiency

$$\eta_{\text{motor}} = \frac{\text{Mechanical power output}}{\text{Electric power input}} = \frac{\dot{W}_{\text{shaft,out}}}{\dot{W}_{\text{elect,in}}}$$

Pump efficiency

$$\eta_{\text{pump}} = \frac{\Delta \dot{E}_{\text{mech,fluid}}}{\dot{W}_{\text{shaft}}}$$

Generator efficiency

$$\eta_{\text{generator}} = \frac{\text{Electric power output}}{\text{Mechanical power input}} = \frac{\dot{W}_{\text{elect,out}}}{\dot{W}_{\text{shaft,in}}}$$

Pump-Motor overall efficiency

$$\eta_{\text{pump-motor}} = \eta_{\text{pump}}\eta_{\text{motor}} = \frac{\dot{W}_{\text{pump},u}}{\dot{W}_{\text{elect,in}}} = \frac{\Delta \dot{E}_{\text{mech,fluid}}}{\dot{W}_{\text{elect,in}}}$$

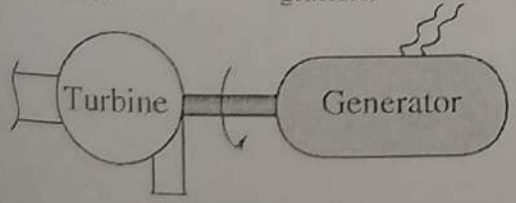
this is the system

Turbine-Generator overall efficiency

$$\eta_{\text{turbine-gen}} = \eta_{\text{turbine}}\eta_{\text{generator}} = \frac{\dot{W}_{\text{elect,out}}}{\dot{W}_{\text{turbine},e}} = \frac{\dot{W}_{\text{elect,out}}}{|\Delta \dot{E}_{\text{mech,fluid}}|}$$

flowrate — heat

$\eta_{\text{turbine}} = 0.75$ $\eta_{\text{generator}} = 0.97$



$$\eta_{\text{turbine-gen}} = \eta_{\text{turbine}}\eta_{\text{generator}} = 0.75 \times 0.97 = 0.73$$

The overall efficiency of a turbine–generator is **the product of** the efficiency of the turbine and the efficiency of the generator and represents the fraction of the mechanical energy of the fluid converted to electric energy.

working fluid ... steam

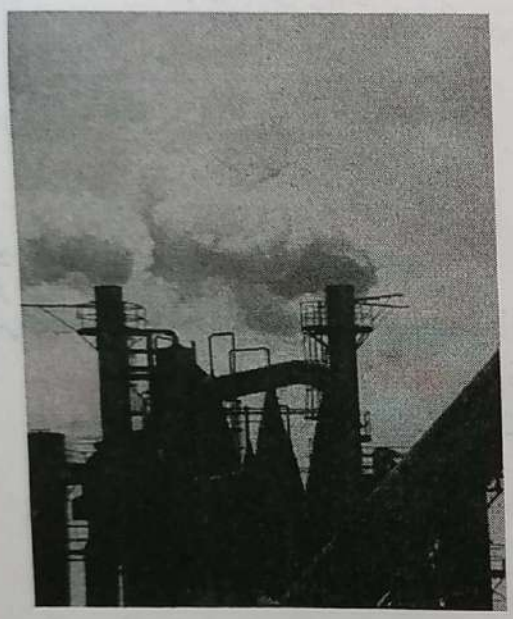
(working fluid) ما في إنتاج طاقة إلا فيه فلويد

Qadar ask · believe & recieve
الممسوحة ضوئيا بـ CamScanner

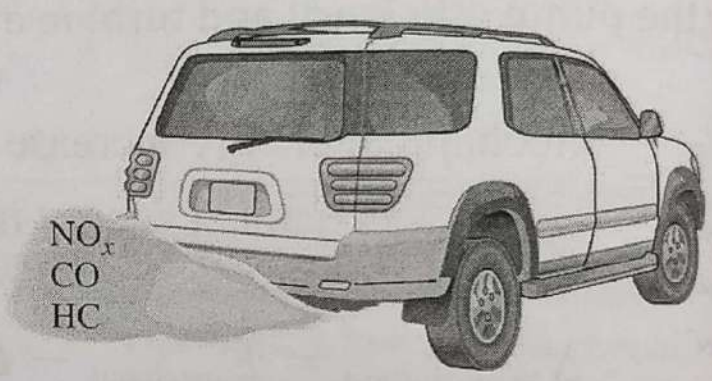
ENERGY AND ENVIRONMENT

Reading

- The conversion of energy from one form to another often affects the environment and the air we breathe in many ways, and thus the study of energy is not complete without considering its impact on the environment.
- Pollutants emitted during the combustion of fossil fuels are responsible for **smog**, **acid rain**, and **global warming**.
- The environmental pollution has reached such high levels that it became a serious threat to **vegetation**, **wildlife**, and **human health**.



Energy conversion processes are often accompanied by environmental pollution.



Motor vehicles are the largest source of air pollution.

EXAMPLE 2–2 **Wind Energy**

A site evaluated for a wind farm is observed to have steady winds at a speed of 8.5 m/s (Fig. 2–13). Determine the wind energy (*a*) per unit mass, (*b*) for a mass of 10 kg, and (*c*) for a flow rate of 1154 kg/s for air.

SOLUTION A site with a specified wind speed is considered. Wind energy per unit mass, for a specified mass, and for a given mass flow rate of air are to be determined.

Assumptions Wind flows steadily at the specified speed.

Analysis The only harvestable form of energy of atmospheric air is the kinetic energy, which is captured by a wind turbine.

(a) Wind energy per unit mass of air is

$$e = \text{ke} = \frac{V^2}{2} = \frac{(8.5\ \text{m/s})^2}{2}\left(\frac{1\ \text{J/kg}}{1\ \text{m}^2/\text{s}^2}\right) = 36.1\ \text{J/kg}$$

(b) Wind energy for an air mass of 10 kg is

الممسوحة ضوئيا بـ CamScanner

EXAMPLE 2–2 **Wind Energy**

A site evaluated for a wind farm is observed to have steady winds at a speed of 8.5 m/s (Fig. 2–13). Determine the wind energy (*a*) per unit mass, (*b*) for a mass of 10 kg, and (*c*) for a flow rate of 1154 kg/s for air.

SOLUTION A site with a specified wind speed is considered. Wind energy per unit mass, for a specified mass, and for a given mass flow rate of air are to be determined.

Assumptions Wind flows steadily at the specified speed.

Analysis The only harvestable form of energy of atmospheric air is the kinetic energy, which is captured by a wind turbine.

(a) Wind energy per unit mass of air is

$$e = \text{ke} = \frac{V^2}{2} = \frac{(8.5\ \text{m/s})^2}{2}\left(\frac{1\ \text{J/kg}}{1\ \text{m}^2/\text{s}^2}\right) = 36.1\ \text{J/kg}$$

(b) Wind energy for an air mass of 10 kg is

$$E = me = (10\ \text{kg})(36.1\ \text{J/kg}) = 361\ \text{J}$$

(c) Wind energy for a mass flow rate of 1154 kg/s is

$$\dot{E} = \dot{m}e = (1154\ \text{kg/s})(36.1\ \text{J/kg})\left(\frac{1\ \text{kW}}{1000\ \text{J/s}}\right) = 41.7\ \text{kW}$$



CamScanner الممسوحة ضوئيا بـ

EXAMPLE 2–10 Cooling of a Hot Fluid in a Tank

A rigid tank contains a hot fluid that is cooled while being stirred by a paddle wheel. Initially, the internal energy of the fluid is 800 kJ. During the cooling process, the fluid loses 500 kJ of heat, and the paddle wheel does 100 kJ of work on the fluid. Determine the final internal energy of the fluid. Neglect the energy stored in the paddle wheel.

SOLUTION A fluid in a rigid tank looses heat while being stirred. The final internal energy of the fluid is to be determined.

Assumptions 1 The tank is stationary and thus the kinetic and potential energy changes are zero, $\Delta KE = \Delta PE = 0$. Therefore, $\Delta E = \Delta U$ and internal energy is the only form of the system's energy that may change during this process. 2 Energy stored in the paddle wheel is negligible.

Analysis Take the contents of the tank as the system (Fig. 2–49). This is a *closed system* since no mass crosses the boundary during the process.

We observe that the volume of a rigid tank is constant, and thus there is no moving boundary work. Also, heat is lost from the system and shaft work is done on the system. Applying the energy balance on the system gives

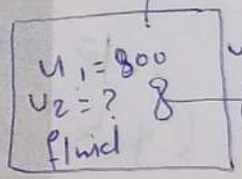
$$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic, potential, etc., energies}}$$

$$W_{sh,in} - Q_{out} = \Delta U = U_2 - U_1$$

$$100 \text{ kJ} - 500 \text{ kJ} = U_2 - 800 \text{ kJ}$$

$$U_2 = 400 \text{ kJ}$$

Therefore, the final internal energy of the system is 400 kJ.



EXAMPLE 2–15 Power Generation from a Hydroelectric Plant

Electric power is to be generated by installing a hydraulic turbine–generator at a site 70 m below the free surface of a large water reservoir that can supply water at a rate of 1500 kg/s steadily (Fig. 2–60). If the mechanical power output of the turbine is 800 kW and the electric power generation is 750 kW, determine the turbine efficiency and the combined turbine–generator efficiency of this plant. Neglect losses in the pipes.

SOLUTION A hydraulic turbine-generator installed at a large reservoir is to generate electricity. The combined turbine–generator efficiency and the turbine efficiency are to be determined.

Assumptions 1 The water elevation in the reservoir remains constant. 2 The mechanical energy of water at the turbine exit is negligible.

Analysis We take the free surface of water in the reservoir to be point 1

CamScanner الممسوحة ضوئيا بـ

EXAMPLE 2–15 Power Generation from a Hydroelectric Plant

Electric power is to be generated by installing a hydraulic turbine–generator at a site 70 m below the free surface of a large water reservoir that can supply water at a rate of 1500 kg/s steadily (Fig. 2–60). If the mechanical power output of the turbine is 800 kW and the electric power generation is 750 kW, determine the turbine efficiency and the combined turbine–generator efficiency of this plant. Neglect losses in the pipes.

SOLUTION A hydraulic turbine-generator installed at a large reservoir is to generate electricity. The combined turbine–generator efficiency and the turbine efficiency are to be determined.

Assumptions 1 The water elevation in the reservoir remains constant. 2 The mechanical energy of water at the turbine exit is negligible.

Analysis We take the free surface of water in the reservoir to be point 1 and the turbine exit to be point 2. We also take the turbine exit as the reference level ($z_2 = 0$) so that the potential energies at 1 and 2 are $pe_1 = gz_1$ and $pe_2 = 0$. The flow energy P/ρ at both points is zero since both 1 and 2 are open to the atmosphere ($P_1 = P_2 = P_{atm}$). Further, the kinetic energy at both points is zero ($ke_1 = ke_2 = 0$) since the water at point 1 is essentially motionless, and the kinetic energy of water at turbine exit is assumed to be negligible. The potential energy of water at point 1 is

adar ask · believe & recieve
الممسوحة ضوئيا بـ CamScanner

$$pe_1 = gz_1 = (9.81\ \text{m/s}^2)(70\ \text{m})\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = 0.687\ \text{kJ/kg}$$

Then the rate at which the mechanical energy of water is supplied to the turbine becomes

$$|\Delta \dot{E}_{\text{mech, fluid}}| = \dot{m}(e_{\text{mech, in}} - e_{\text{mech, out}}) = \dot{m}(pe_1 - 0) = \dot{m}pe_1$$
$$= (1500\ \text{kg/s})(0.687\ \text{kJ/kg})$$
$$= 1031\ \text{kW}$$

The combined turbine–generator and the turbine efficiency are determined from their definitions to be

$$\eta_{\text{turbine-gen}} = \frac{\dot{W}_{\text{elect, out}}}{|\Delta \dot{E}_{\text{mech, fluid}}|} = \frac{750\ \text{kW}}{1031\ \text{kW}} = 0.727 \text{ or } 72.7\%$$

$$\eta_{\text{turbine}} = \frac{\dot{W}_{\text{elect, out}}}{|\dot{E}_{\text{mech, fluid}}|} = \frac{800\text{kW}}{1031\text{kW}} = 0.776 \text{ or } 77.6\%$$

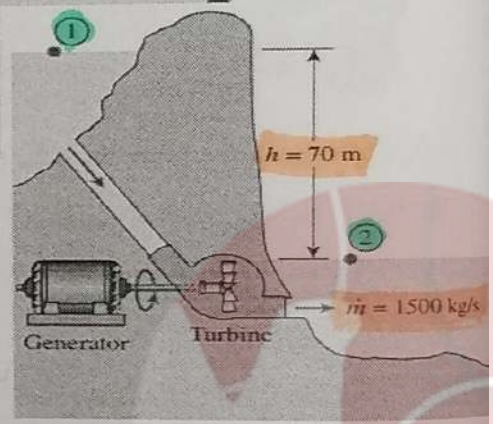


FIGURE 2-60
Schematic for Example 2-15

Mazar
ask & believe & recieve

الممسوحة ضوئيا بـ CamScanner



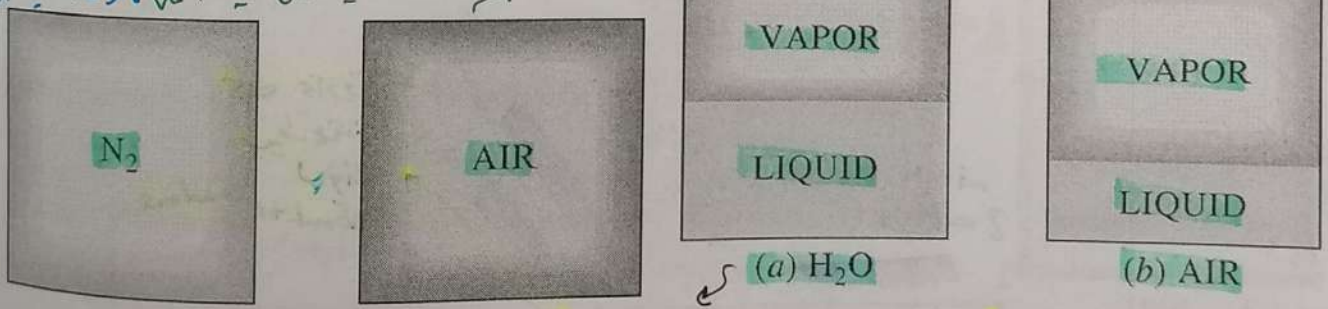
SUBSTANCES

Thermodynamics: An Engineering Approach
Yunus A. Cengel, Michael A. Boles, Mehmet Kanoglu
McGraw-Hill

Dr. Ahmad M. AbuYaghi
October 2023

PURE SUBSTANCE

- **Pure substance**: A substance that has a fixed chemical composition throughout.
- Air is a mixture of several gases, but it is considered to be a pure substance.

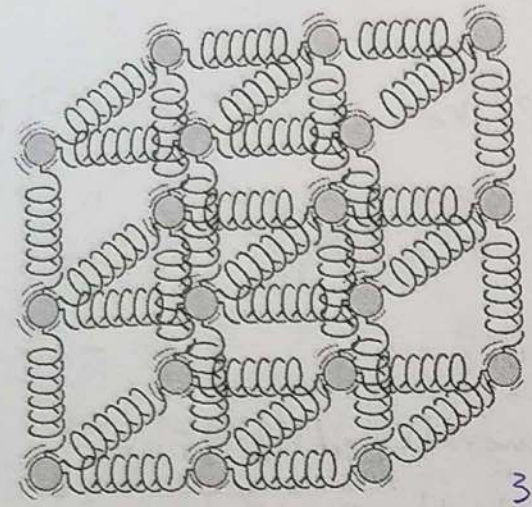


Nitrogen and gaseous air are pure substances.

A mixture of liquid and gaseous water is a pure substance, but a mixture of liquid and gaseous air is not.

* PHASES OF A PURE SUBSTANCE *

Inter & Intra molecular



The molecules in a solid are kept at their positions by the large springlike inter-molecular forces.



→ If we break it will get :-

Intramolecular $H_2O \rightarrow H_2 + \frac{1}{2} O_2$

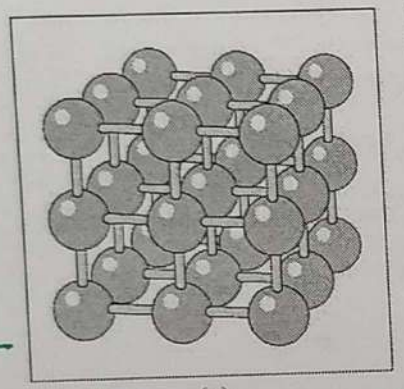
$H_2O - H_2O$ → If we break it will get s → L → g

Intermolecular

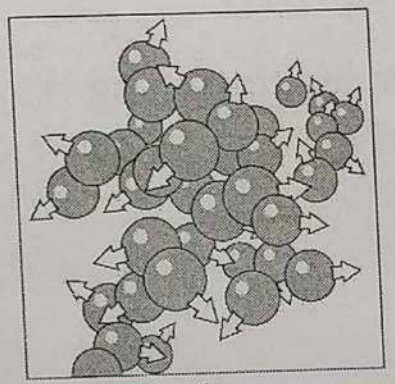
3 Types of substance :-

(3 phase change)

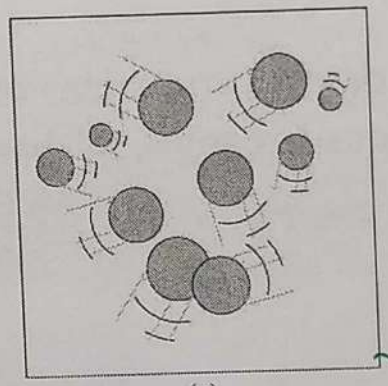
In a solid, the attractive and repulsive forces between the molecules tend to maintain them at relatively constant distances from each other.



Solid (a)



(b) liq



(c) gas

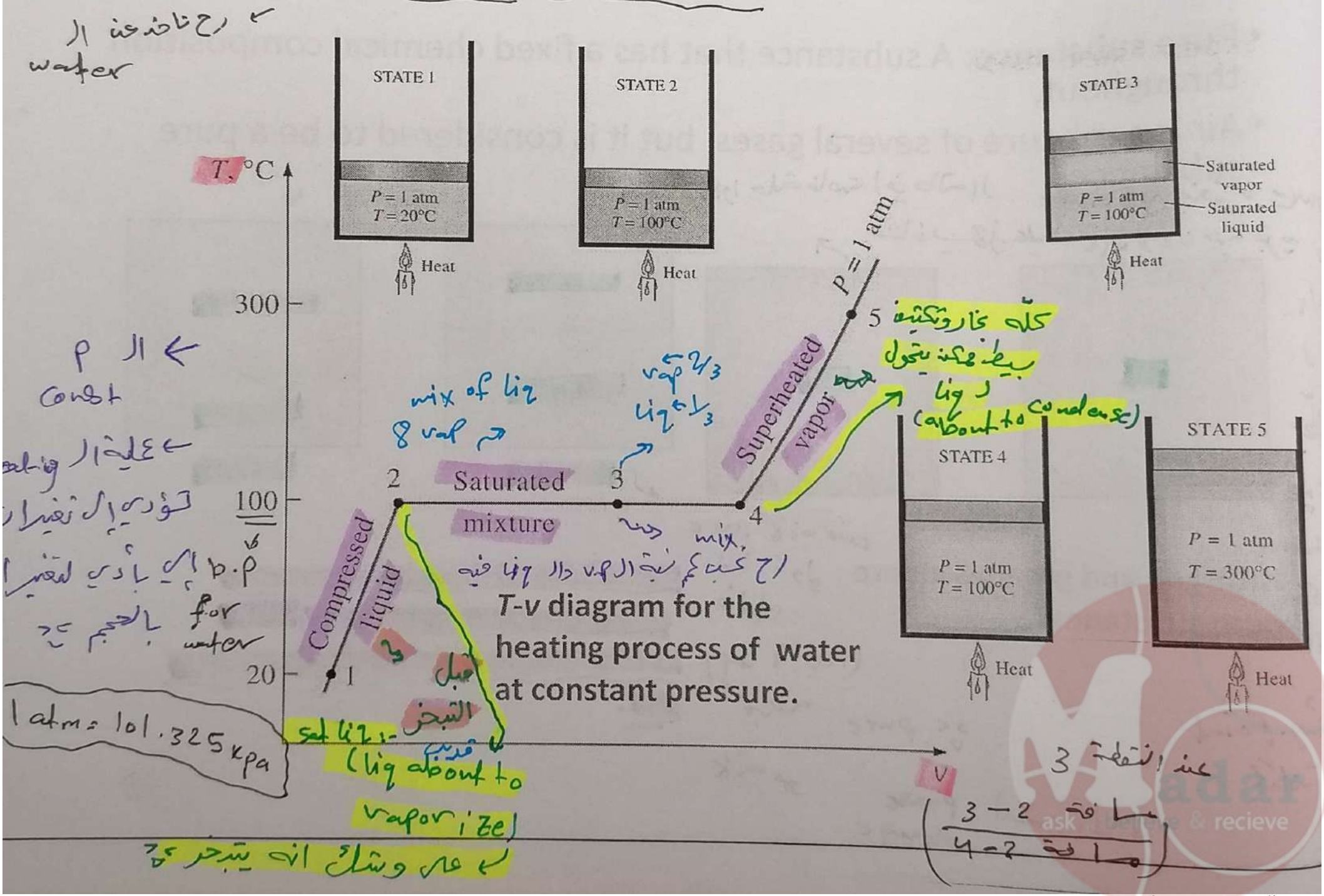
كل ما نعطي حرارة للمادة كل molecule بياخدها طاقة حركة ف بتبعد عن بعض وبتكسر الـ Intermolecular forces وبتتحول لـ liq وبعدين لـ gas

The arrangement of atoms in different phases: (*a*) molecules are at relatively fixed positions in a solid, (*b*) groups of molecules move about each other in the liquid phase, and (*c*) molecules move about at random in the gas phase.

Madar ask & believe & recieve

الممسوحة ضوئيا بـ CamScanner

PHASE-CHANGE PROCESSES OF PURE SUBSTANCES

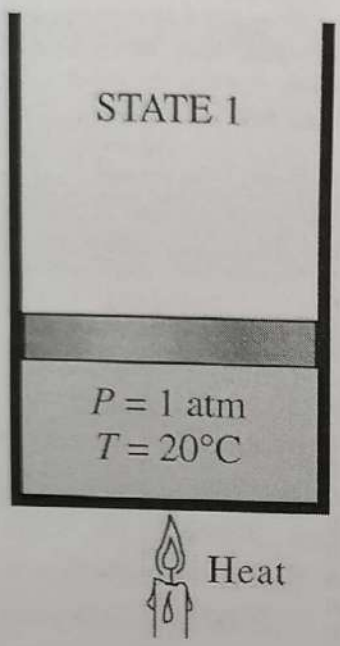


T-v diagram for the heating process of water at constant pressure.

Scanned with CamScanner
الممسوحة ضوئيا بـ CamScanner

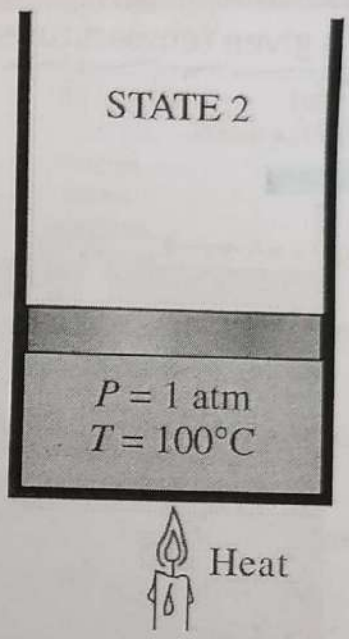
PHASE-CHANGE PROCESSES OF PURE SUBSTANCES

- **Compressed liquid (subcooled liquid)**: A substance that it is *not about to vaporize.*
- **Saturated liquid**: A liquid that is *about to vaporize.*

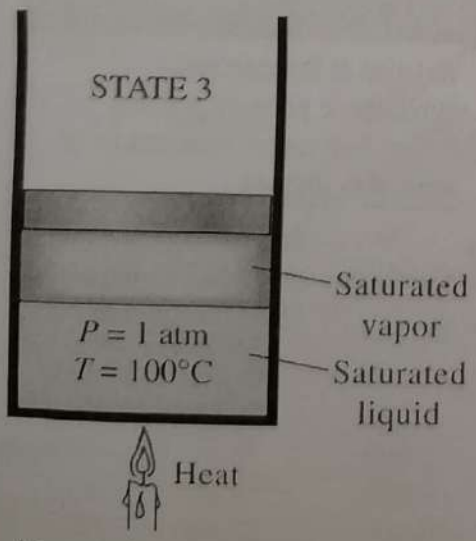


At 1 atm and 20°C, water exists in the liquid phase (***compressed liquid***).

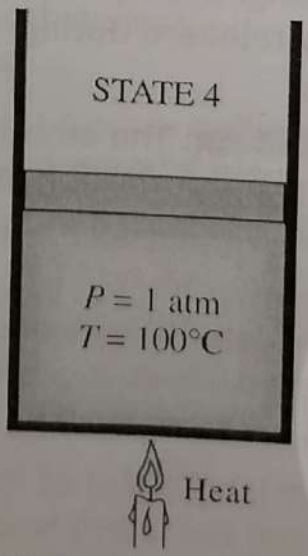
At 1 atm pressure and 100°C, water exists as a liquid that is ready to vaporize (***saturated liquid***).



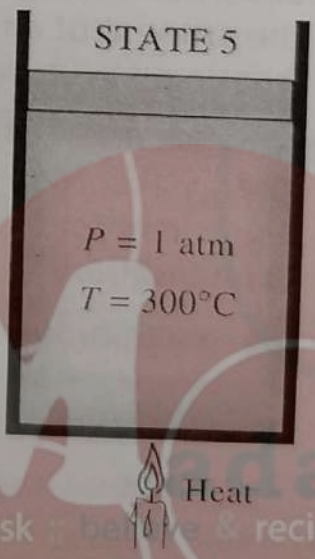
- **Saturated vapor**: A vapor that is *about to condense.*
- **Saturated liquid–vapor mixture**: The state at which the *liquid and vapor phases coexist* in equilibrium.
- **Superheated vapor**: A vapor that is *not about to condense* (i.e., not a saturated vapor).



As more heat is transferred, part of the saturated liquid vaporizes



At 1 atm pressure, the temperature remains constant

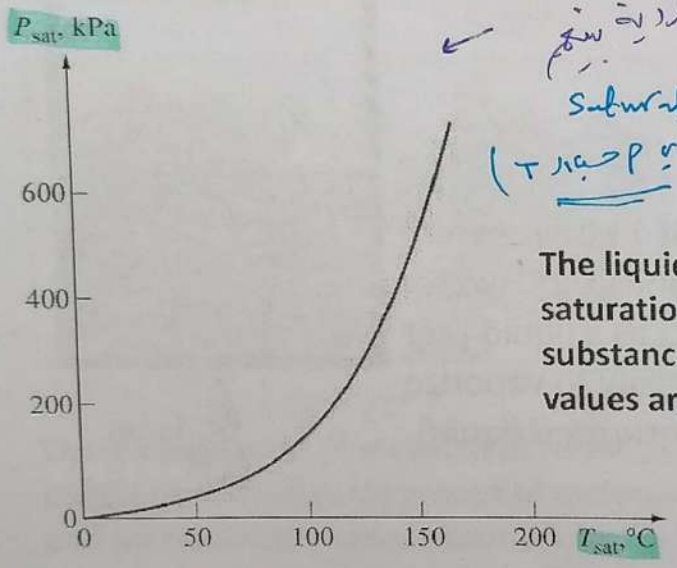


As more heat is transferred, the

ask & believe & recieve
CamScanner الممسوحة ضوئيا بـ

Saturation Temperature and Saturation Pressure

- The temperature at which water starts boiling depends on the pressure; therefore, if the pressure is fixed, so is the boiling temperature.
- Water boils at 100°C at 1 atm pressure.
- **Saturation temperature T_{sat}**: The temperature at which a pure substance changes phase at a given pressure.
- **Saturation pressure P_{sat}**: The pressure at which a pure substance changes phase at a given temperature.



The liquid–vapor saturation curve of a pure substance (numerical values are for water).

TABLE 3–1

Saturation (boiling) pressure of water at various temperatures

Temperature, T, °C	Saturation pressure, P_{sat}, kPa
−10	0.26
−5	0.40
0	0.61
5	0.87
10	1.23
15	1.71
20	2.34
25	3.17
30	4.25
40	7.39
50	12.35
100	101.4
150	476.2
200	1555
250	3976
300	8588

- **Latent heat**: The amount of energy absorbed or released during a phase-change process.
- **Latent heat of fusion**: The amount of energy absorbed during melting. It is equivalent to the amount of energy released during freezing.
- **Latent heat of vaporization**: The amount of energy absorbed during vaporization, and it is equivalent to the energy released during condensation.
- The magnitudes of the latent heats depend on the temperature or pressure at which the phase change occurs.
- At 1 atm pressure, the latent heat of fusion of water is 333.7 kJ/kg and the latent

TABLE 3–2

Variation of the standard atmospheric pressure and the boiling (saturation) temperature of water with altitude

Elevation, m	Atmospheric pressure, kPa	Boiling temperature, °C
0	101.33	100.0
1,000	89.55	96.5
2,000		

CamScanner الممسوحة ضوئيا بـ

- **Latent heat**: The amount of energy absorbed or released during a phase-change process.
- **Latent heat of fusion**: The amount of energy absorbed during melting. It is equivalent to the amount of energy released during freezing.
- **Latent heat of vaporization**: The amount of energy absorbed during vaporization, and it is equivalent to the energy released during condensation.
- The magnitudes of the latent heats depend on the temperature or pressure at which the phase change occurs.
- At 1 atm pressure, the latent heat of fusion of water is 333.7 kJ/kg and the latent heat of vaporization is 2256.5 kJ/kg.
- The atmospheric pressure, and thus the boiling temperature of water, decreases with elevation.

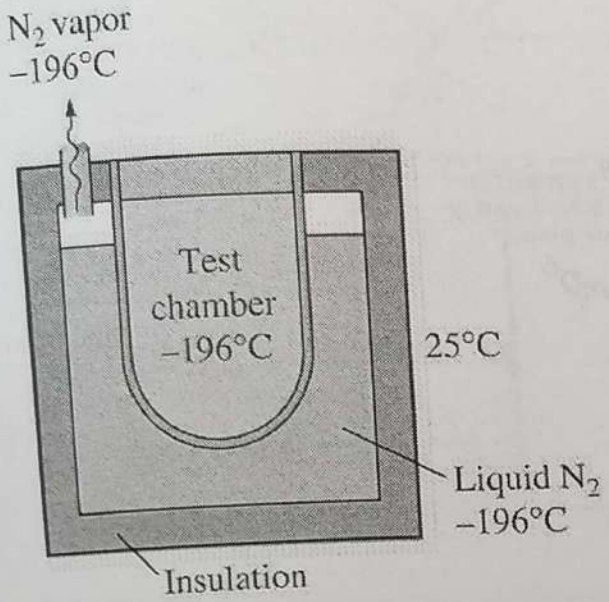
TABLE 3–2

Variation of the standard atmospheric pressure and the boiling (saturation) temperature of water with altitude

Elevation, m	Atmospheric pressure, kPa	Boiling temperature, °C
0	101.33	100.0
1,000	89.55	96.5
2,000	79.50	93.3
5,000	54.05	83.3
10,000	26.50	66.3
20,000	5.53	34.7

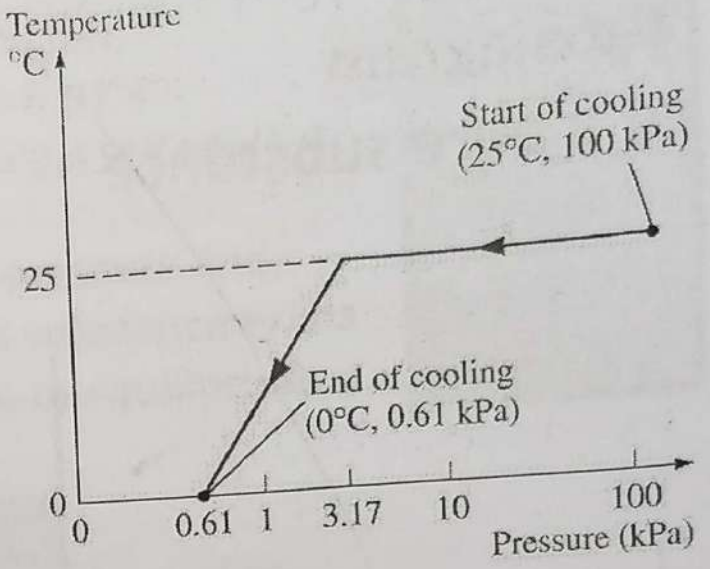
CamScanner الممسوحة ضوئيا بـ

Some Consequences of T_{sat} and P_{sat} Dependence

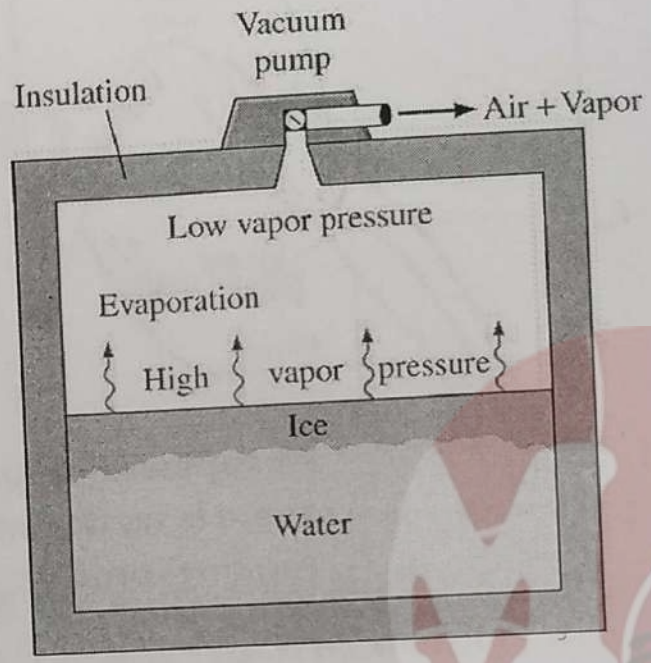


The temperature of liquid nitrogen exposed to the atmosphere remains constant at 196°C, and thus it maintains the test chamber at 196°C.

The variation of the temperature of fruits and vegetables with pressure during vacuum cooling from 25°C to 0°C.



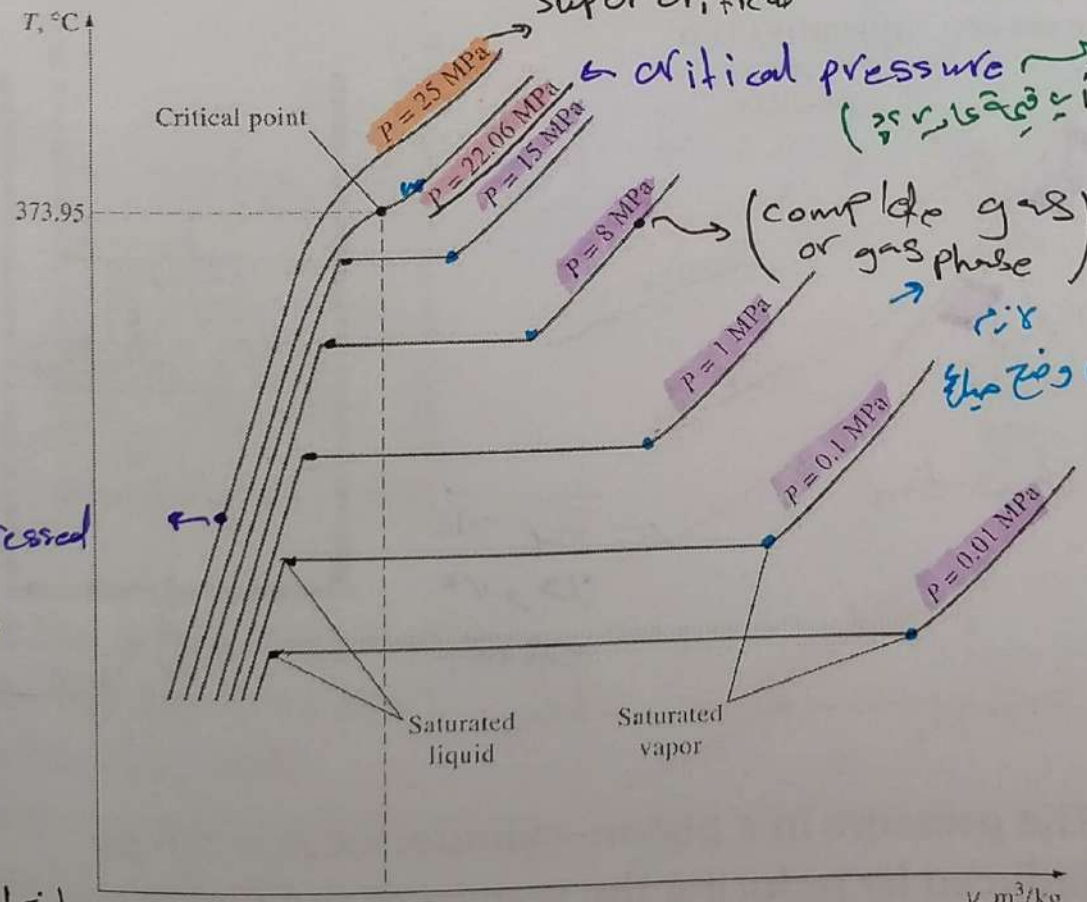
In 1775, ice was made by evacuating the air space in a water tank.



CamScanner الممسوحة ضوئيا بـ

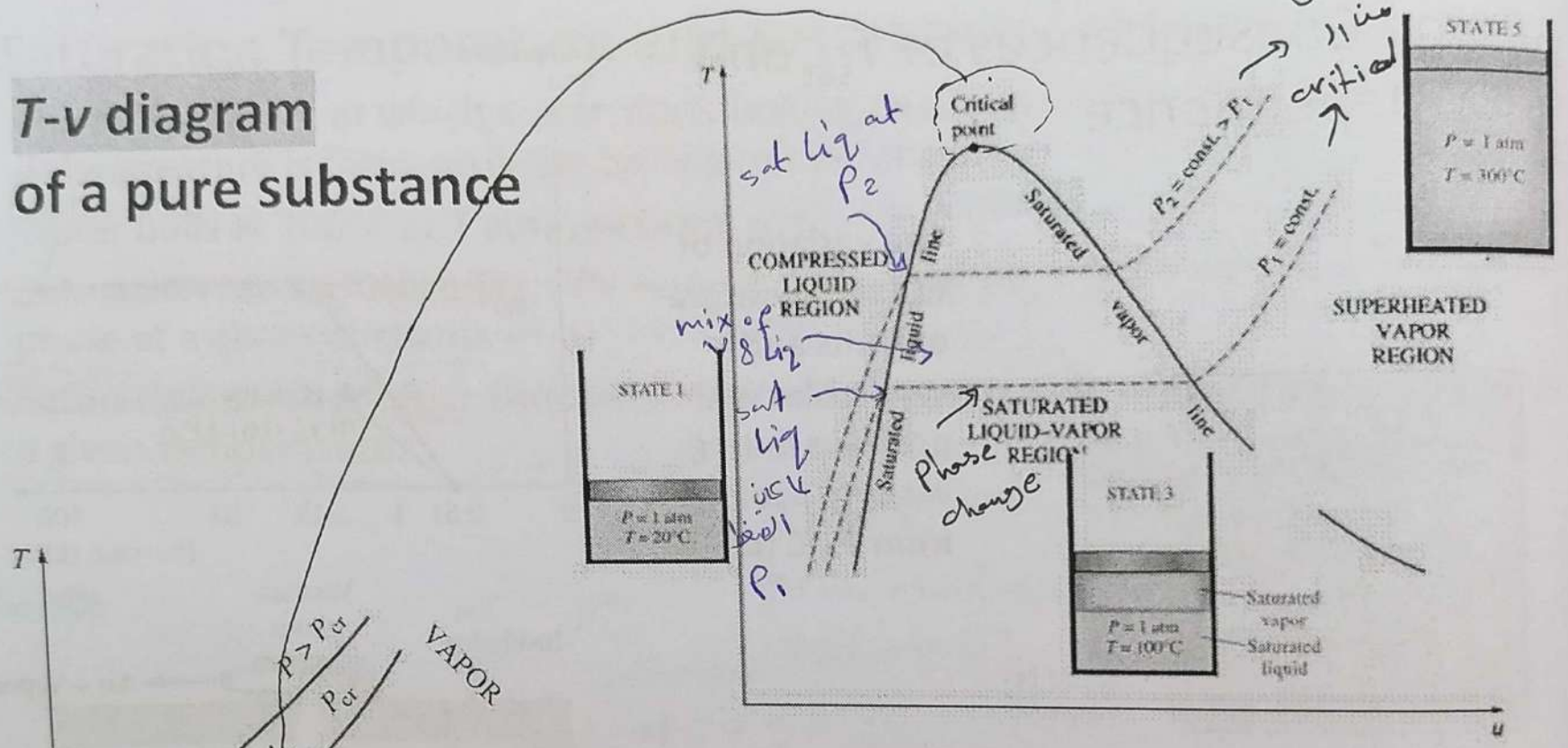
PROPERTY DIAGRAMS FOR PHASE-CHANGE PROCESSES

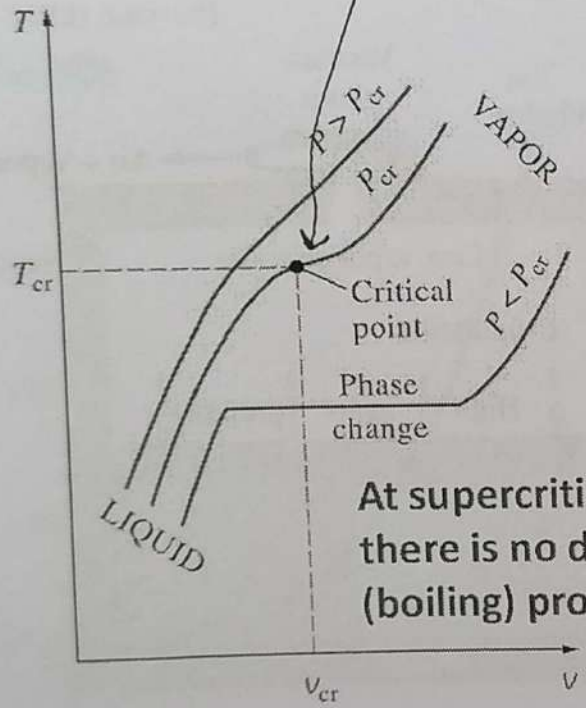
- The variations of properties during phase-change processes are best studied and understood with the help of property diagrams such as the ***T-v*, *P-v*, and *P-T* diagrams** for pure substances.



T-v diagram of constant-pressure phase-change processes of a pure substance at various pressures (numerical values are for water).

T-v diagram of a pure substance





At supercritical pressures ($P > P_{cr}$), there is no distinct phase-change (boiling) process.

Critical point: The point at which the saturated liquid and saturated vapor states are identical.

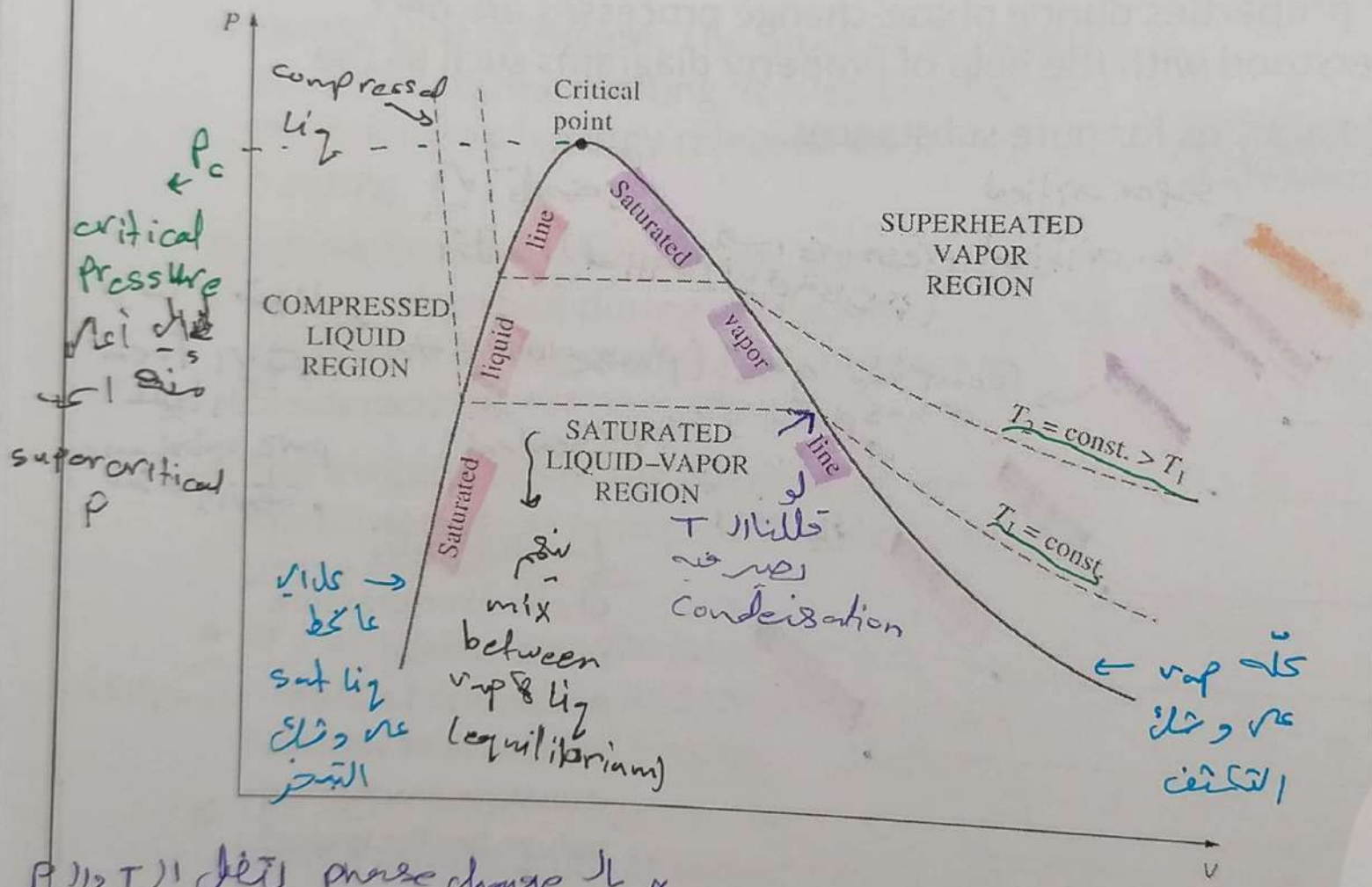
For water

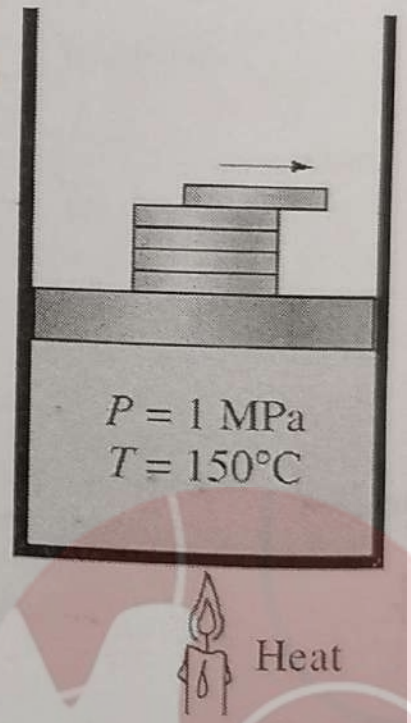
$T_c = 374\ c^\circ$

$P_c = 22.06\ MPa \simeq 22000\ KPa$

الممسوحة ضوئيا بـ CamScanner

P-v diagram of a pure substance.



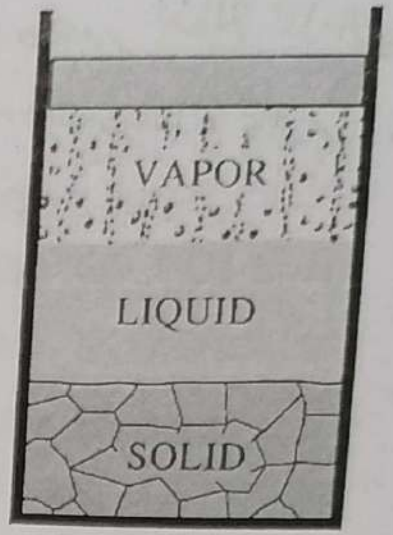


The pressure in a piston–cylinder device can be reduced by reducing the weight of the piston.

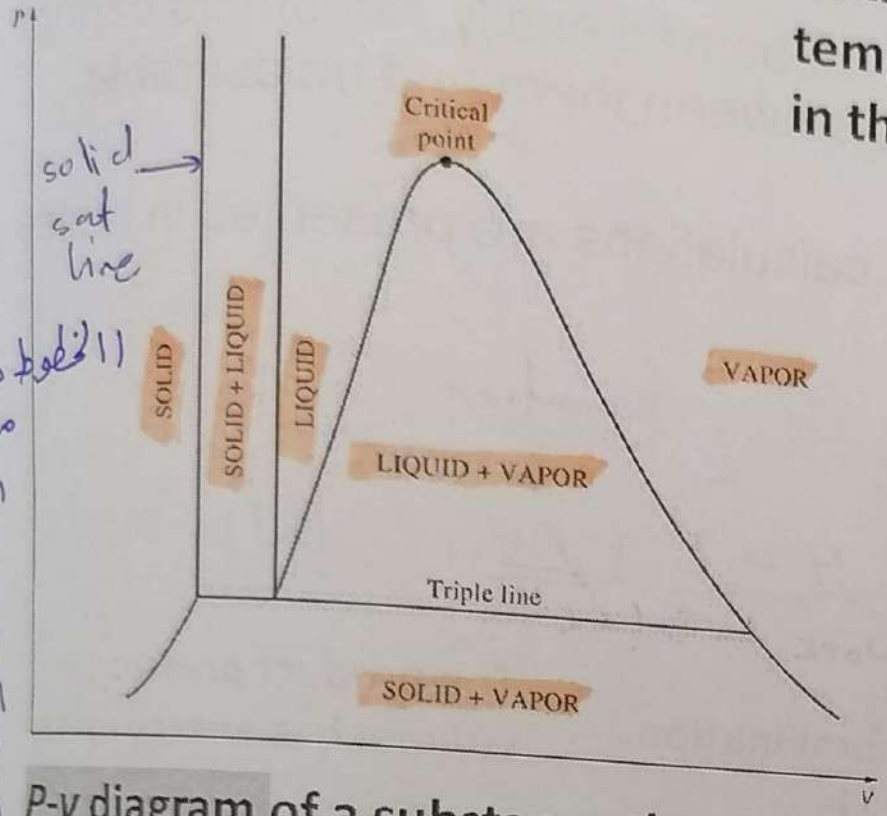
CamScanner الممسوحة ضوئيا بـ

Extending Diagrams to Include Solid Phase

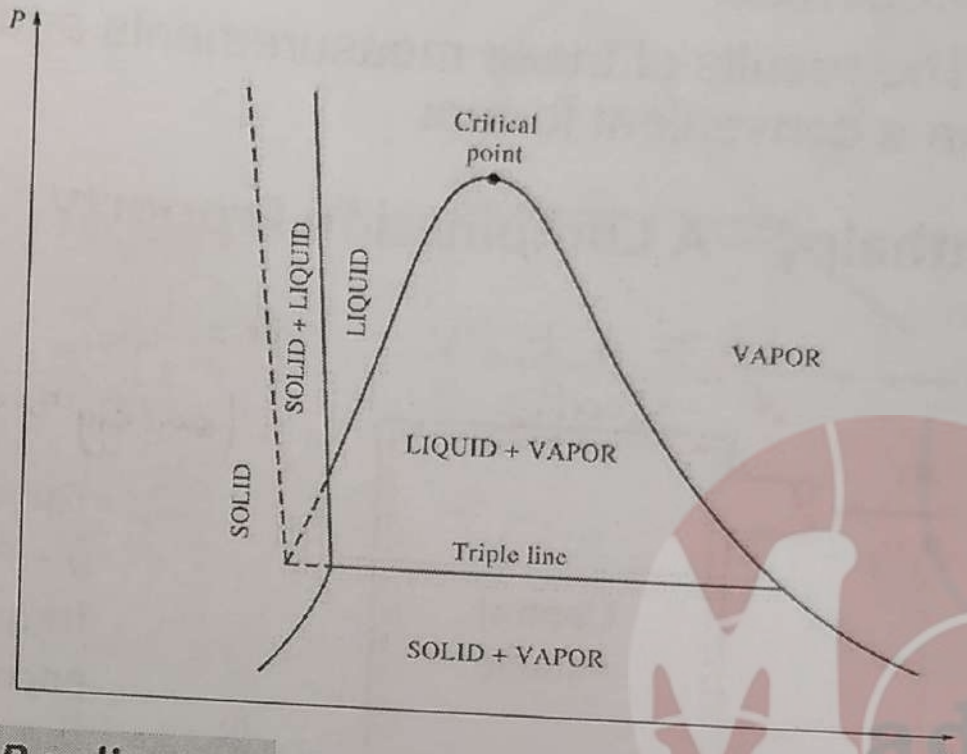
For water,
$T_{tp} = 0.01°C$
$P_{tp} = 0.6117$ kPa



At triple-point pressure and temperature, a substance exists in three phases in equilibrium.



P-v diagram of a substance that contracts on freezing.

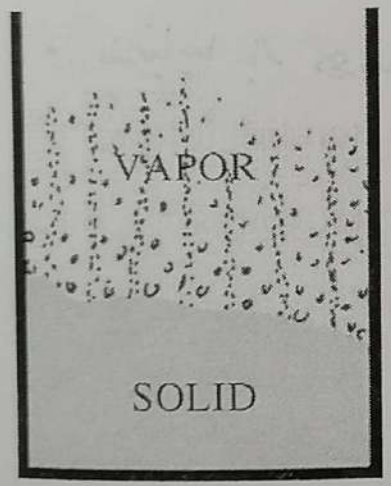


P-v diagram of a substance that expands on freezing (such as water).

CamScanner الممسوحة ضوئيا بـ

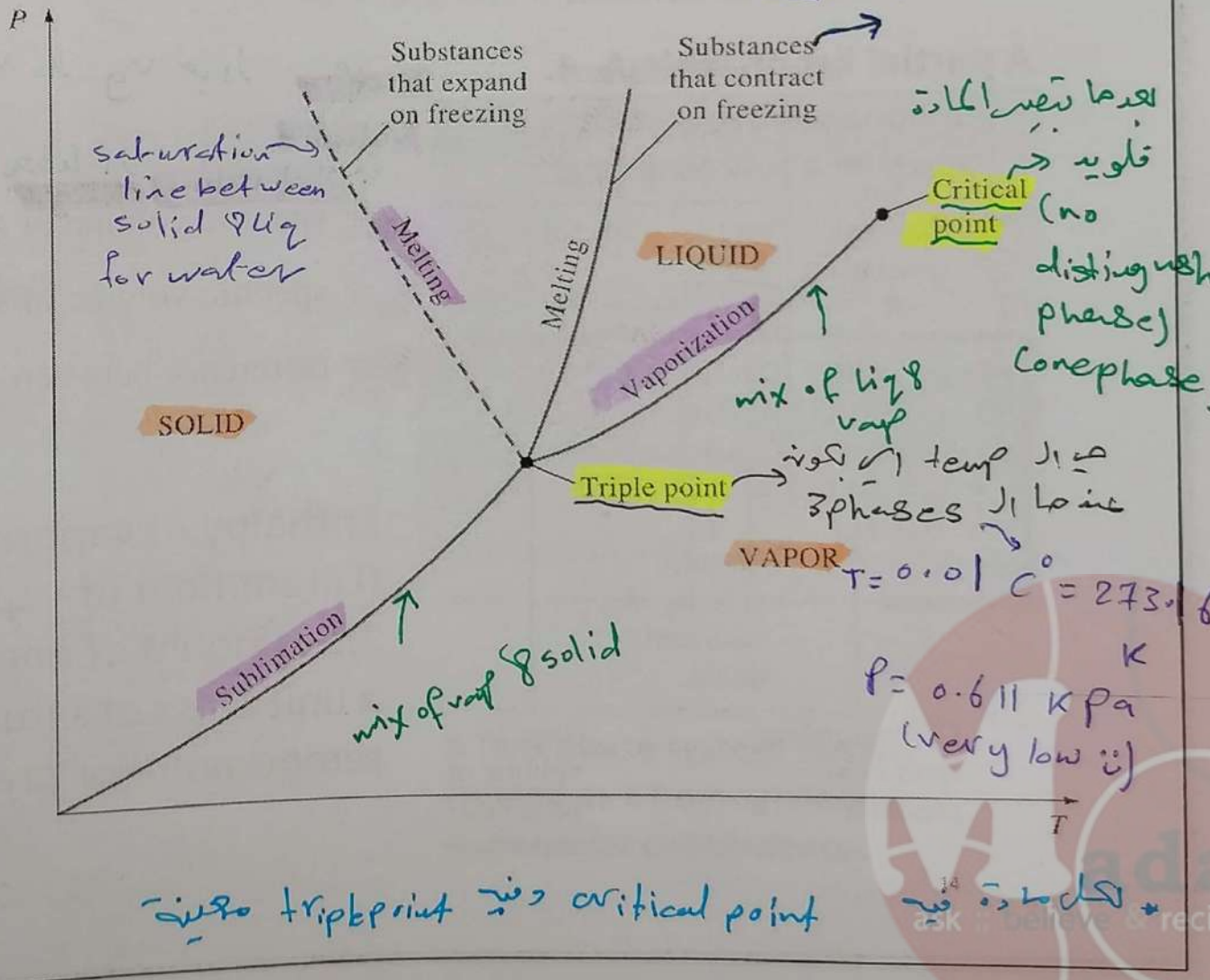
the first graph for study

Sublimation:
Passing from the solid phase directly into the vapor phase.



At low pressures (**below the triple-point value**), solids evaporate without melting first (*sublimation*).

P-T diagram of pure substances



هاد الخط لمعظم المواد ما عدا الـ H_2O

saturation line between solid & liq for water

بعدها بتصير المادة غازية (no distinguish phase/ one phase)

mix of liq & vap

عند هاد الـ temp بتكون 3 phases

$T = 0.01\ C^\circ = 273.16\ K$

$P = 0.611\ kPa$ (very low)

mix of vap & solid

* لكل مادة triple point و critical point معينة

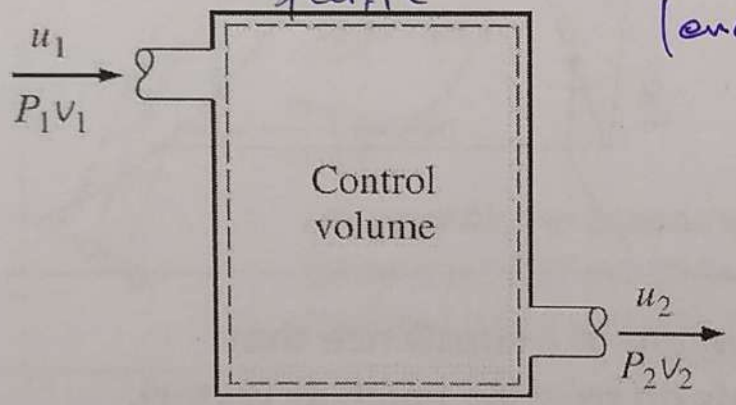
CamScanner الممسوحة ضوئيا بـ

PROPERTY TABLES

- For most substances, the relationships among thermodynamic properties are too complex to be expressed by simple equations.
- Therefore, properties are frequently presented in the form of tables.
- Some thermodynamic properties can be measured easily, but others cannot and are calculated by using the relations between them and measurable properties.
- The results of these measurements and calculations are presented in tables in a convenient format.

Enthalpy—A Combination Property

$$h = u + Pv \quad (\text{kJ/kg}) \qquad H = U + PV \quad (\text{kJ})$$



The combination *u + Pv* is frequently encountered in the analysis of control volumes.

The product *pressure* × *volume* has energy units.

$$\text{kPa} \cdot \text{m}^3 \equiv \text{kJ}$$
$$\text{kPa} \cdot \text{m}^3/\text{kg} \equiv \text{kJ/kg}$$
$$\text{bar} \cdot \text{m}^3 \equiv 100\ \text{kJ}$$
$$\text{MPa} \cdot \text{m}^3 \equiv 1000\ \text{kJ}$$

CamScanner الممسوحة ضوئيا بـ

24/10

Saturated Liquid and Saturated Vapor States

- **Table A–4**: Saturation properties of water under temperature.
- **Table A–5**: Saturation properties of water under pressure.

A partial list of Table A–4.

Temp. °C T	Sat. press. kPa P_{sat}	Specific volume m^3/kg Sat. liquid v_f	Sat. vapor v_g
85	57.868	0.001032	2.8261
90	70.183	0.001036	2.3593
95	84.609	0.001040	1.9808

Specific temperature

Corresponding saturation pressure

Specific volume of saturated liquid

Specific volume of saturated vapor

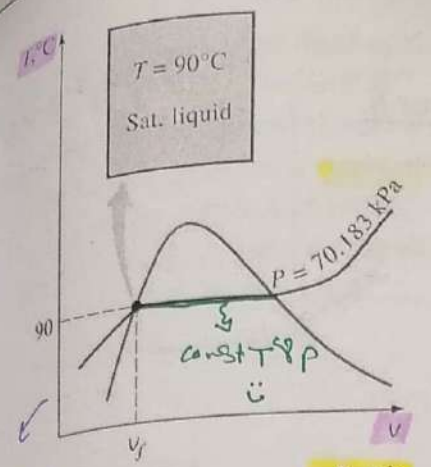
v_f = specific volume of saturated liquid

v_g = specific volume of saturated vapor

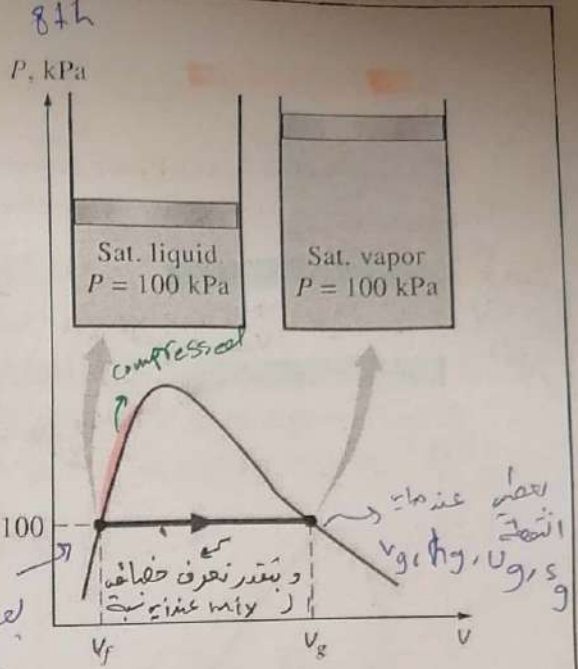
v_{fg} = difference between v_g and v_f (that is, $v_{fg} = v_g - v_f$)

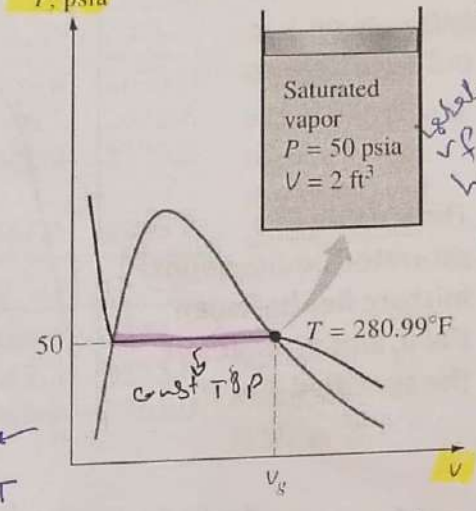
Enthalpy of vaporization, h_{fg} (Latent heat of vaporization): The amount of energy needed to vaporize a unit mass of saturated liquid at a given temperature or pressure.

ask & believe & recieve
الممسوحة ضوئيا بـ CamScanner



Examples: Saturated liquid and saturated vapor states of water on *T*-*v* and *P*-*v* diagrams.





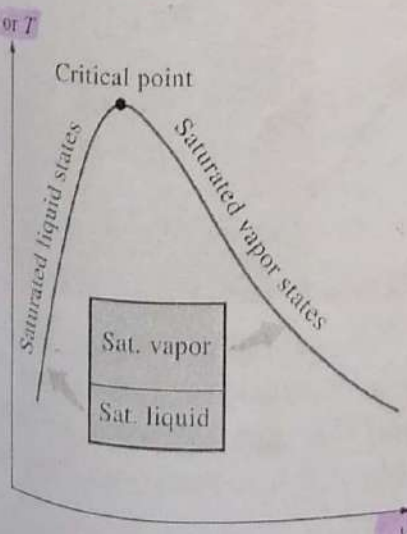
Saturated Liquid–Vapor Mixture

Quality, *x* : The ratio of the mass of vapor to the total mass of the mixture. Quality is between 0 and 1 **0: sat. liquid, 1: sat. vapor.**

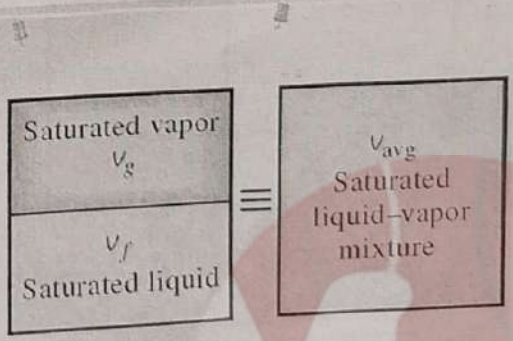
The properties of the saturated liquid are the same whether it exists alone or in a mixture with saturated vapor.

$$x = \frac{m_{\text{vapor}}}{m_{\text{total}}} \qquad m_{\text{total}} = m_{\text{liquid}} + m_{\text{vapor}} = m_f + m_g$$

Temperature and pressure are dependent properties for a mixture.



The relative amounts of liquid and vapor phases in a saturated mixture are specified by the *quality x*.



A two-phase system can be treated as a homogeneous mixture for convenience.

CamScanner الممسوحة ضوئيا بـ

$$v_{avg} = v_f + x v_{fg} \quad (m^3/kg)$$

$$x = m_g/m_t \qquad x = \frac{v_{avg} - v_f}{v_{fg}}$$

fraction of vap

$$u_{avg} = u_f + x u_{fg} \quad (kJ/kg)$$

$$h_{avg} = h_f + x h_{fg} \quad (kJ/kg)$$

combe

$y \rightarrow v, u, \text{or } h.$

$$y_{avg} = y_f + x y_{fg}$$

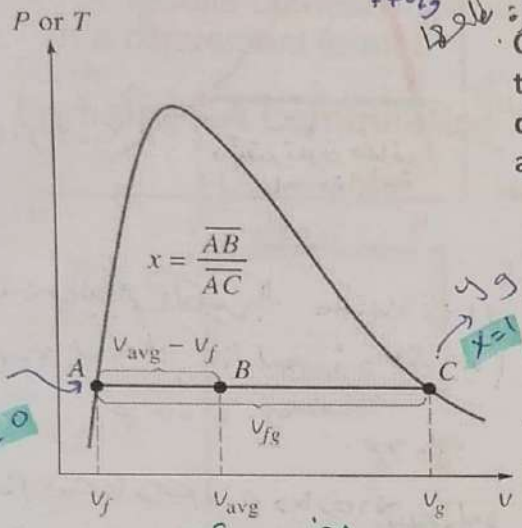
$$y_f \le y_{avg} \le y_g$$

من الجدول

If $x = 0 \rightarrow$ sat liq

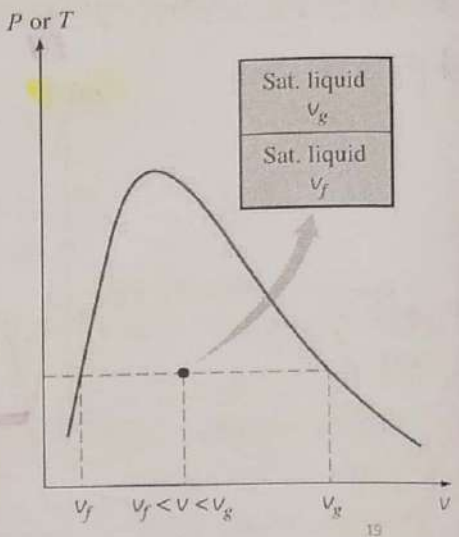
If $x = 1 \rightarrow$ sat vap

$0 < x < 1$



Quality is related to the horizontal distances on *P-v* and *T-v* diagrams.

The *v* value of a saturated liquid–vapor mixture lies between the v_f and v_g values at the specified *T* or *P*.

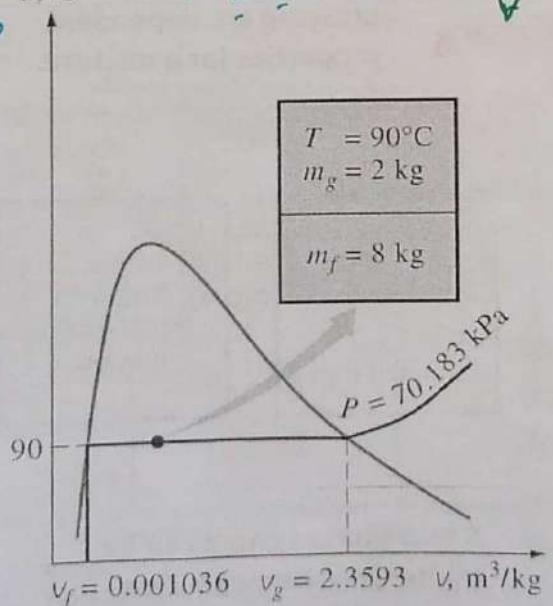


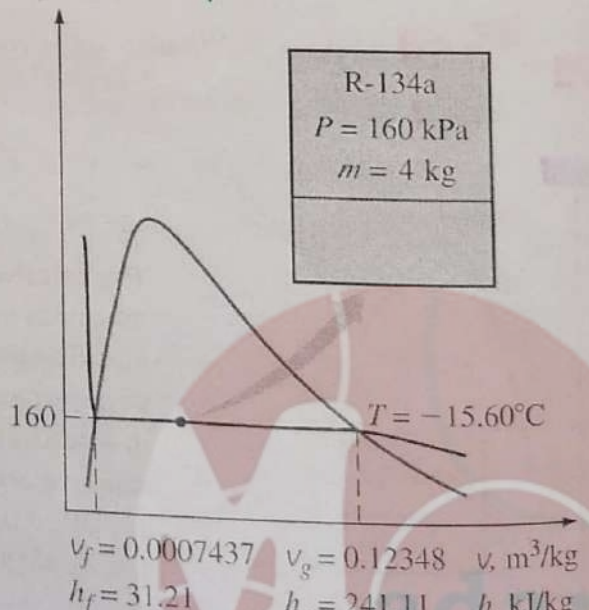
$v_{fg} = v_g - v_f$

$u_{fg} = u_g - u_f$

Examples:

Saturated liquid-vapor mixture states on *T-v* and *P-v* diagrams.





ask : believe & recieve
CamScanner الممسوحة ضوئيا بـ

Superheated Vapor

In the region to the right of the saturated vapor line and at temperatures above the critical point temperature, a substance exists as superheated vapor. In this region, temperature and pressure are independent properties.

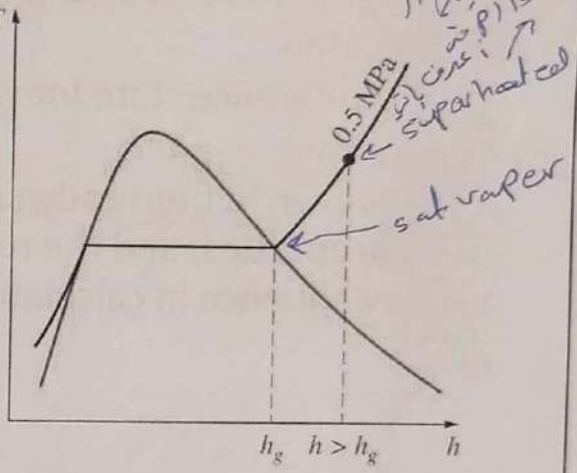
Compared to saturated vapor, superheated vapor is characterized by

- Lower pressures ($P < P_{sat}$ at a given T)
- Higher tempreatures ($T > T_{sat}$ at a given P)
- Higher specific volumes ($v > v_g$ at a given P or T)
- Higher internal energies ($u > u_g$ at a given P or T)
- Higher enthalpies ($h > h_g$ at a given P or T)

T, °C	v m³/kg	u kJ/kg	h kJ/kg
	$P = 0.1$ MPa (99.61°C)		
Sat.	1.6941	2505.6	2675.0
100	1.6959	2506.2	2675.8
150	1.9367	2582.9	2776.6
⋮	⋮	⋮	⋮
1300	7.2605	4687.2	5413.3
	$P = 0.5$ MPa (151.83°C)		
Sat.	0.37483	2560.7	2748.1
200	0.42503	2643.3	2855.8
250	0.47443	2723.8	2961.0

A partial listing of Table A–6.

At a specified P, superheated vapor exists at a higher h than the saturated vapor.



Compressed Liquid

The compressed liquid properties depend on temperature much more strongly than they do on pressure.

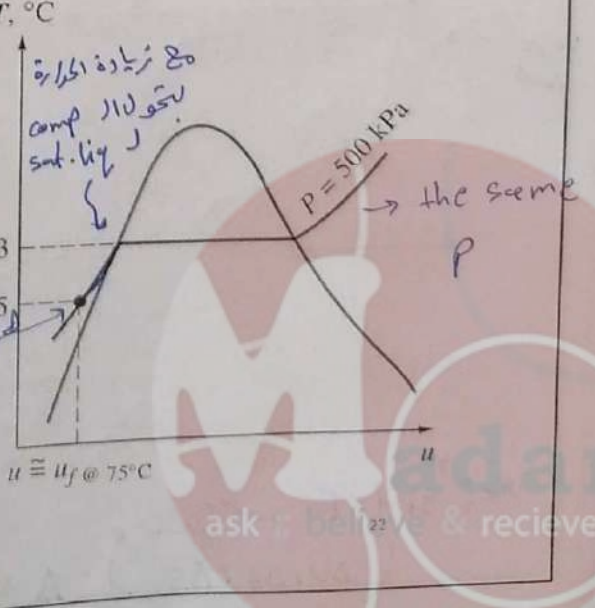
$y \cong y_{f\,@\,T}$ $\quad y \rightarrow v, u,$ or h

A more accurate relation for h

$$h \cong h_{f\,@\,T} + v_{f\,@\,T}(P - P_{sat\,@\,T})$$

Compressed liquid is characterized by

Higher pressures ($P > P_{sat}$ at a given T)
Lower tempreatures ($T < T_{sat}$ at a given P)
Lower specific volumes ($v < v_f$ at a given P or T)
Lower internal energies ($u < u_f$ at a given P or T)
Lower enthalpies ($h < h_f$ at a given P or T)



Given: P and T

$v \cong v_{f\,@T}$
$u \cong u_{f\,@T}$
$h \cong h_{f\,@T}$

A compressed liquid may be approximated as a saturated liquid at the given temperature.

At a given P and T, a pure substance will exist as a compressed liquid if $T < T_{sat\,@\,P}$

CamScanner الممسوحة ضوئيا بـ

13th

Reference State and Reference Values

- The values of ***u***, ***h***, and ***s*** cannot be measured directly, and they are calculated from measurable properties using the relations between properties.
- Those relations give the ***changes* in properties**, not the values of properties at specified states.
- Therefore, we need to choose a convenient ***reference state*** and assign a value of ***zero*** for a convenient property or properties at that state.
- The reference state for water is 0.01°C and for R-134a is -40°C in tables.
- However, In thermodynamics we are concerned with the ***changes* in properties,** and the reference state chosen is of no consequence in calculations.

14th

Reference State and Reference Values

Saturated water—Temperature table

Temp., T °C	Sat. press., P_{sat} kPa	Specific volume, m³/kg: Sat. liquid, v_f	Specific volume, m³/kg: Sat. vapor, v_g	Internal energy, kJ/kg: Sat. liquid, u_f	Internal energy, kJ/kg: Evap., u_{fg}	Internal energy, kJ/kg: Sat. vapor, u_g	Enthalpy, kJ/kg: Sat. liquid, h_f	Enthalpy, kJ/kg: Evap., h_{fg}	Enthalpy, kJ/kg: Sat. vapor, h_g	Entropy, kJ/kg · K: Sat. liquid, s_f	Entropy, kJ/kg · K: Evap., s_{fg}	Entropy, kJ/kg · K: Sat. vapor, s_g
0.01	0.6117	0.001000	206.00	0.000	2374.9	2374.9	0.001	2500.9	2500.9	0.0000	9.1556	9.1556
5	0.8725	0.001000	147.03	21.019	2360.8	2381.8	21.020	2489.1	2510.1	0.0763	8.9487	9.0249

triple point

Saturated refrigerant-134a—Temperature table

Temp., T °C	Sat. press., P_{sat} kPa	Specific volume, m³/kg: Sat. liquid, v_f	Specific volume, m³/kg: Sat. vapor, v_g	Internal energy, kJ/kg: Sat. liquid, u_f	Internal energy, kJ/kg: Evap., u_{fg}	Internal energy, kJ/kg: Sat. vapor, u_g	Enthalpy, kJ/kg: Sat. liquid, h_f	Enthalpy, kJ/kg: Evap., h_{fg}	Enthalpy, kJ/kg: Sat. vapor, h_g	Entropy, kJ/kg · K: Sat. liquid, s_f	Entropy, kJ/kg · K: Evap., s_{fg}	Entropy, kJ/kg · K: Sat. vapor, s_g
−40	51.25	0.0007054	0.36081	−0.036	207.40	207.37	0.000	225.86	225.86	0.00000	0.96866	0.96866

Ref state for reffrence

(ΔU، ΔH، ΔS) Δ وحتى لو ما كانة فيه reff نعتبرها الدلتا بالنيرو state

CamScanner الممسوحة ضوئيا بـ

THE IDEAL-GAS EQUATION OF STATE

- Equation of state: Any equation that relates the pressure, temperature, and specific volume of a substance.
- The simplest and best-known equation of state for substances in the gas phase is the ideal-gas equation of state. This equation predicts the *P-v-T* behavior of a gas quite accurately within some properly selected region.

$$P = R\left(\frac{T}{v}\right) \quad Pv = RT$$

Ideal gas equation of state

$$R = \frac{R_u}{M} \qquad (\text{kJ/kg} \cdot \text{K or kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})$$

R: gas constant
M: molar mass (kg/kmol)
R_u: universal gas constant

$R_u =$
- 8.31447 kJ/kmol · K
- 8.31447 kPa · m³/kmol · K
- 0.0831447 bar · m³/kmol · K
- 1.98588 Btu/lbmol · R
- 10.7316 psia · ft³/lbmol · R
- 1545.37 ft · lbf/lbmol · R

Substance	R, kJ/kg·K
Air	0.2870
Helium	2.0769
Argon	0.2081
Nitrogen	0.2968

Different substances have different gas constants.

$$w = \int_{v_1}^{v_2} P\,dv$$

Mass = Molar mass × Mole number

$$m = MN \quad (\text{kg})$$

$$V = mv \longrightarrow \boxed{PV = mRT}$$

$$mR = (MN)R = NR_u \longrightarrow PV = NR_uT$$

$$V = N\bar{v} \longrightarrow P\bar{v} = R_uT$$

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

Ideal gas equation at two states for a fixed mass

Various expressions of ideal gas equation

Per unit mass	Per unit mole
v, m³/kg	$\bar{v}$, m³/kmol
u, kJ/kg	$\bar{u}$, kJ/kmol
h, kJ/kg	$\bar{h}$, kJ/kmol

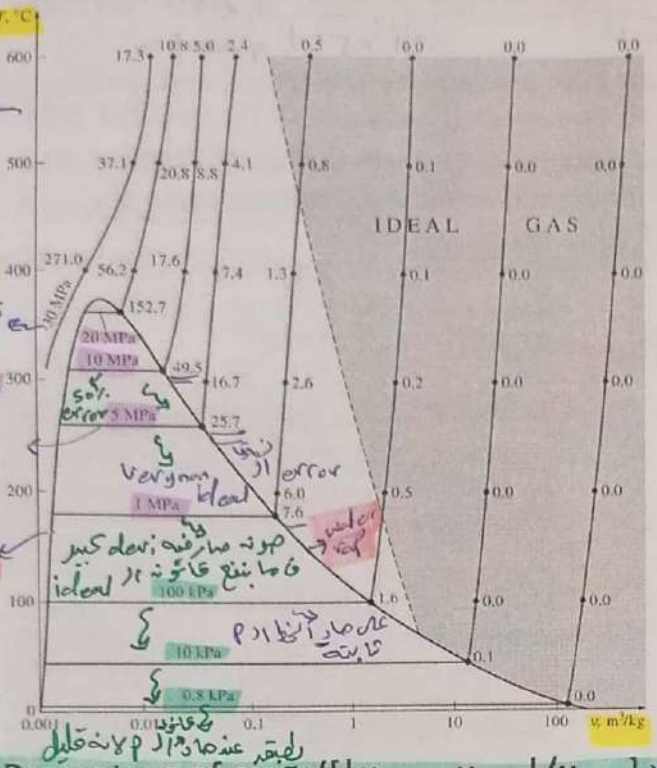
Properties per unit mole are denoted with a bar on the top.

- Real gases behave as an ideal gas at low densities (i.e., low pressure, high temperature).
- The ideal-gas relation often is not applicable to real gases; thus, care should be exercised when using it.

CamScanner الممسوحة ضوئيا بـ

17th

Is Water Vapor an Ideal Gas?



- At pressures below 10 kPa, water vapor can be treated as an ideal gas, regardless of its temperature, with negligible error (less than 0.1 percent).
- At higher pressures, however, the ideal gas assumption yields unacceptable errors, particularly in the vicinity of the critical point and the saturated vapor line.
- In air-conditioning applications, the water vapor in the air can be treated as an ideal gas. Why?
- In steam power plant applications, however, the pressures involved are usually very high; therefore, ideal-gas relations should not be used.

Percentage of error ($[|v_{table} - v_{ideal}|/v_{table}] \times 100$) involved in assuming steam to be an ideal gas, and the region where steam can be treated as an ideal gas with less than 1 percent error.

27

18th

COMPRESSIBILITY FACTOR—A MEASURE OF DEVIATION FROM IDEAL-GAS BEHAVIOR

Compressibility factor Z A factor that accounts for the deviation of real gases from ideal-gas behavior at a given temperature and pressure.

$$Pv = ZRT$$

$$Z = \frac{Pv}{RT} \qquad Z = \frac{V_{actual}}{V_{ideal}}$$

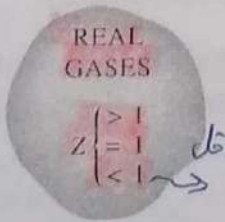
The farther away Z is from unity, the more the gas deviates from ideal-gas behavior.

Gases behave as an ideal gas at low densities (i.e., low pressure, high temperature).

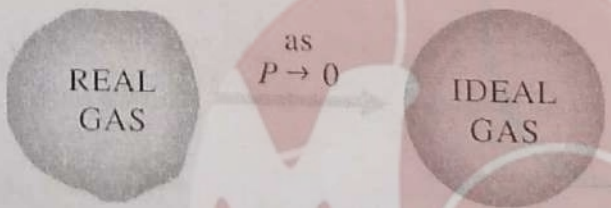
Question: **What is the criteria for low pressure and high temperature?**

Answer: **The pressure or temperature of a gas is high or low relative to its critical temperature or pressure.**





The compressibility factor is unity for ideal gases.



At very low pressures, all gases approach ideal-gas behavior (regardless of their temperature).

28

CamScanner الممسوحة ضوئيا بـ

Reduced Properties

Reduced pressure

$$P_R = \frac{P}{P_{cr}}$$

P_{cr} ← critical point pressure

Reduced temperature

$$T_R = \frac{T}{T_{cr}}$$

T ← actual condition point

T_{cr} ← critical point temp

Pseudo-reduced specific volume

$$v_R = \frac{v_{actual}}{RT_{cr}/P_{cr}}$$

- The Z factor is approximately the same for all gases at the same reduced temperature and reduced pressure, which are defined as

$$T_R = \frac{T}{T_{cr}} \quad \text{and} \quad P_R = \frac{P}{P_{cr}}$$

where P_{cr} and T_{cr} are the critical pressure and temperature, respectively.

- This is known as the *principle of corresponding states*.

Compressibility factor

The pvT properties of a component are expressed in terms of compressibility factor (Z) and Z can be related to p, T, and v (or V) as below:

$$Z = \frac{pV}{nRT} \qquad Z = \frac{pv}{RT} \quad (n = 1)$$

For ideal gas: $Z = 1.0$

For liquids: $Z = 0.01$ to 0.2 [9]

Z at the critical point is usually in the range of 0.27 to 0.29. For most substances, Z_c is 0.27.

$$\left.\begin{aligned} P_R &= \frac{P}{P_{cr}} \\ v_R &= \frac{v}{RT_{cr}/P_{cr}} \end{aligned}\right\} Z = \ldots \text{ (Fig. A–15)}$$

Z can also be determined from a knowledge of P_R and v_R.

Comparison of Z Factors for Various Gases

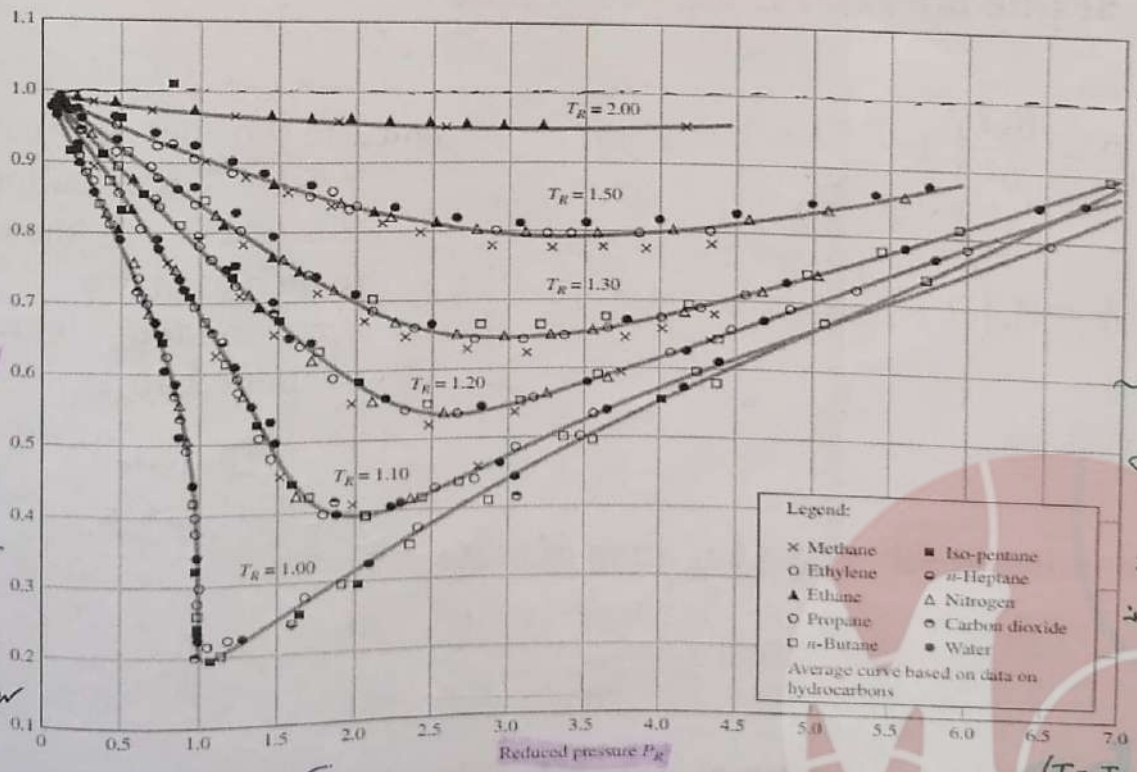


FIGURE 3–47
Comparison of Z factors for various gases.
Source: Gour-Jen Su, "Modified Law of Corresponding States," Ind. Eng. Chem. (International ed.) 38 (1946), p. 803.

CamScanner الممسوحة ضوئيا بـ

OTHER EQUATIONS OF STATE

Several equations have been proposed to represent the ***P-v-T*** behavior of substances accurately over a larger region with no limitations.

van der Waals
Berthelet
Redlich-Kwang
Beattie-Bridgeman
Benedict-Webb-Rubin
Strobridge
Virial

Van der Waals Equation of State

$$\left(P + \frac{a}{v^2}\right)(v - b) = RT$$

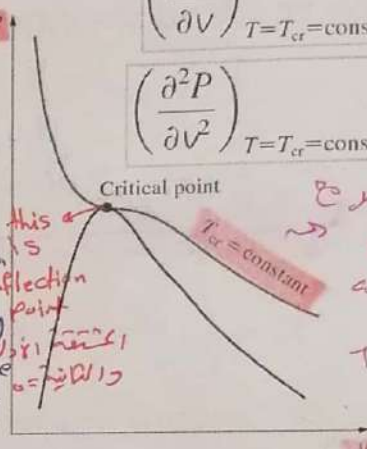
$$a = \frac{27R^2T_{cr}^2}{64P_{cr}} \qquad b = \frac{RT_{cr}}{8P_{cr}}$$

This model includes two effects not considered in the ideal-gas model: the *intermolecular attraction forces* and the *volume occupied by the molecules themselves*. The accuracy of the van der Waals equation of state is often inadequate.

Critical isotherm of a pure substance has an inflection point at the critical state.

$$\left(\frac{\partial P}{\partial v}\right)_{T=T_{cr}=\text{const}} = 0$$

$$\left(\frac{\partial^2 P}{\partial v^2}\right)_{T=T_{cr}=\text{const}} = 0$$



Beattie-Bridgeman Equation of State

$$P = \frac{R_u T}{\bar{v}^2}\left(1 - \frac{c}{\bar{v}T^3}\right)(\bar{v} + B) - \frac{A}{\bar{v}^2}$$

$$A = A_0\left(1 - \frac{a}{\bar{v}}\right) \qquad B = B_0\left(1 - \frac{b}{\bar{v}}\right)$$

The constants are given in Table 3–4 for various substances. It is known to be reasonably accurate for densities up to about $0.8\rho_{cr}$.

Benedict-Webb-Rubin Equation of State

$$P = \frac{R_u T}{\bar{v}} + \left(B_0 R_u T - A_0 - \frac{C_0}{T^2}\right)\frac{1}{\bar{v}^2} + \frac{bR_u T - a}{\bar{v}^3} + \frac{a\alpha}{\bar{v}^6} + \frac{c}{\bar{v}^3 T^2}\left(1 + \frac{\gamma}{\bar{v}^2}\right)e^{-\gamma/\bar{v}^2}$$

The constants are given in Table 3–4. This equation can handle substances at densities up to about 2.5 ρ_{cr}.

ask & believe & recieve
CamScanner الممسوحة ضوئيا بـ

Examples

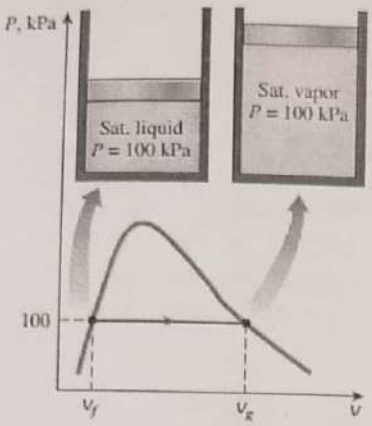


FIGURE 3–30
Schematic and *P-v* diagram for Example 3–3.

EXAMPLE 3–3 Volume and Energy Change during Evaporation

A mass of 200 g of saturated liquid water is completely vaporized at a constant pressure of 100 kPa. Determine (*a*) the volume change and (*b*) the amount of energy transferred to the water.

SOLUTION Saturated liquid water is vaporized at constant pressure. The volume change and the energy transferred are to be determined.

Analysis (*a*) The process described is illustrated on a *P-v* diagram in Fig. 3–30. The volume change per unit mass during a vaporization process is v_{fg}, which is the difference between v_g and v_f. Reading these values from Table A–5 at 100 kPa and substituting yield

$$v_{fg} = v_g - v_f = 1.6941 - 0.001043 = 1.6931 \text{ m}^3/\text{kg}$$

Thus,

$$\Delta V = mv_{fg} = (0.2 \text{ kg})(1.6931 \text{ m}^3/\text{kg}) = 0.3386 \text{ m}^3$$

(*b*) The amount of energy needed to vaporize a unit mass of a substance at a given pressure is the enthalpy of vaporization at that pressure, which is h_{fg} = 2257.5 kJ/kg for water at 100 kPa. Thus, the amount of energy transferred is

$$mh_{fg} = (0.2 \text{ kg})(2257.5 \text{ kJ/kg}) = 451.5 \text{ kJ}$$

Discussion Note that we have considered the first four decimal digits of v_{fg} and disregarded the rest. This is because v_g has significant numbers to the first four decimal places only, and we do not know the numbers in the other decimal places. Copying all the digits from the calculator would mean that we are assuming v_g = 1.694100, which is not necessarily the case. It could very well be that v_g = 1.694138 since this number, too, would truncate to 1.6941. All the digits in our result (1.6931) are significant. But if we did not truncate the result, we would obtain v_{fg} = 1.693057, which falsely implies that our result is accurate to the sixth decimal place.

EXAMPLE 3–4 Pressure and Volume of a Saturated Mixture

A rigid tank contains 10 kg of water at 90°C. If 8 kg of the water is in the liquid form and the rest is in the vapor form, determine (*a*) the pressure in the tank and (*b*) the volume of the tank.

SOLUTION A rigid tank contains saturated mixture. The pressure and the volume of the tank are to be determined.

Analysis (*a*) The state of the saturated liquid–vapor mixture is shown in Fig. 3–35. Since the two phases coexist in equilibrium, we have a saturated mixture, and the pressure must be the saturation pressure at the given temperature:

$$P = P_{\text{sat @ 90°C}} = 70.183 \text{ kPa} \qquad \text{(Table A–4)}$$

(*b*) At 90°C, we have v_f = 0.001036 m³/kg and v_g = 2.3593 m³/kg (Table A–4). One way of finding the volume of the tank is to determine the volume occupied by each phase and then add them:

$$V = V_f + V_g = m_f v_f + m_g v_g$$
$$= (8 \text{ kg})(0.001036 \text{ m}^3/\text{kg}) + (2 \text{ kg})(2.3593 \text{ m}^3/\text{kg})$$
$$= 4.73 \text{ m}^3$$

Another way is to first determine the quality *x*, then the average specific volume *v*, and finally the total volume:

$$x = \frac{m_g}{m_t} = \frac{2 \text{ kg}}{10 \text{ kg}} = 0.2$$

$$v = v_f + xv_{fg}$$
$$= 0.001036 \text{ m}^3/\text{kg} + (0.2)[(2.3593 - 0.001036) \text{ m}^3/\text{kg}]$$
$$= 0.473 \text{ m}^3/\text{kg}$$

and

$$V = mv = (10 \text{ kg})(0.473 \text{ m}^3/\text{kg}) = 4.73 \text{ m}^3$$

Discussion The first method appears to be easier in this case since the masses of each phase are given. In most cases, however, the masses of each phase are not available, and the second method becomes more convenient.

CamScanner الممسوحة ضوئيا بـ

EXAMPLE 3–5 **Properties of Saturated Liquid–Vapor Mixture**

An 80-L vessel contains 4 kg of refrigerant-134a at a pressure of 160 kPa. Determine (*a*) the temperature, (*b*) the quality, (*c*) the enthalpy of the refrigerant, and (*d*) the volume occupied by the vapor phase.

SOLUTION A vessel is filled with refrigerant-134a. Some properties of the refrigerant are to be determined.

Analysis (*a*) The state of the saturated liquid–vapor mixture is shown in Fig. 3–36. At this point we do not know whether the refrigerant is in the compressed liquid, superheated vapor, or saturated mixture region. This can be determined by comparing a suitable property to the saturated liquid and saturated vapor values. From the information given, we can determine the specific volume:

$$v = \frac{V}{m} = \frac{0.080\ \text{m}^3}{4\ \text{kg}} = 0.02\ \text{m}^3/\text{kg}$$

At 160 kPa, we read

$$v_f = 0.0007435\ \text{m}^3/\text{kg}$$
$$v_g = 0.12355\ \text{m}^3/\text{kg} \qquad \text{(Table A–12)}$$

Obviously, $v_f < v < v_g$, and, the refrigerant is in the saturated mixture region. Thus, the temperature must be the saturation temperature at the specified pressure:

$$T = T_{\text{sat @ 160 kPa}} = -15.60°\text{C}$$

(*b*) Quality can be determined from

$$x = \frac{v - v_f}{v_{fg}} = \frac{0.02 - 0.0007435}{0.12355 - 0.0007435} = 0.157$$

(*c*) At 160 kPa, we also read from Table A–12 that $h_f = 31.18$ kJ/kg and $h_{fg} = 209.96$ kJ/kg. Then,

$$h = h_f + xh_{fg}$$
$$= 31.18\ \text{kJ/kg} + (0.157)(209.96\ \text{kJ/kg})$$
$$= 64.1\ \text{kJ/kg}$$

(*d*) The mass of the vapor is

$$m_g = xm_t = (0.157)(4\ \text{kg}) = 0.628\ \text{kg}$$

and the volume occupied by the vapor phase is

$$V_g = m_g v_g = (0.628\ \text{kg})(0.12355\ \text{m}^3/\text{kg}) = 0.0776\ \text{m}^3\ (\text{or } 77.6\ \text{L})$$

The rest of the volume (2.4 L) is occupied by the liquid.

CamScanner الممسوحة ضوئيا بـ

EXAMPLE 3–11 The Use of Generalized Charts

Determine the specific volume of refrigerant-134a at 1 MPa and 50°C, using (a) the ideal-gas equation of state and (b) the generalized compressibility chart. Compare the values obtained to the actual value of 0.021796 m^3/kg and determine the error involved in each case.

SOLUTION The specific volume of refrigerant-134a is to be determined assuming ideal- and nonideal-gas behavior.

Analysis The gas constant, the critical pressure, and the critical temperature of refrigerant-134a are determined from Table A–1 to be

$$R = 0.0815 \text{ kPa·m}^3/\text{kg·K}$$
$$P_{cr} = 4.059 \text{ MPa}$$
$$T_{cr} = 374.2 \text{ K}$$

(a) The specific volume of refrigerant-134a under the ideal-gas assumption is

$$v = \frac{RT}{P} = \frac{(0.0815 \text{ kPa·m}^3/\text{kg·K})(323 \text{ K})}{1000 \text{ kPa}} = 0.026325 \text{ m}^3/\text{kg}$$

Therefore, treating the refrigerant-134a vapor as an ideal gas would result in an error of (0.026325 − 0.021796)/0.021796 = 0.208, or 20.8 percent in this case.

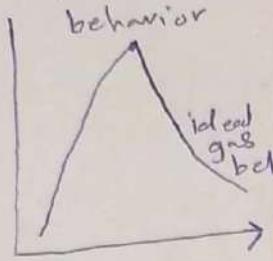
(b) To determine the correction factor Z from the compressibility chart, we first need to calculate the reduced pressure and temperature:

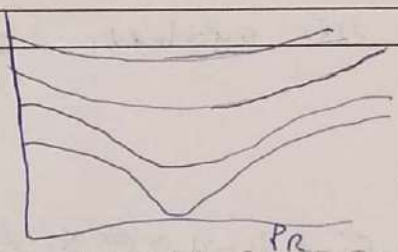
$$P_R = \frac{P}{P_{cr}} = \frac{1 \text{ MPa}}{4.059 \text{ MPa}} = 0.246$$
$$T_R = \frac{T}{T_{cr}} = \frac{323 \text{ K}}{374.2 \text{ K}} = 0.863$$
$$\Rightarrow Z = 0.84$$

Thus

$$v = Zv_{ideal} = (0.84)(0.026325 \text{ m}^3/\text{kg}) = 0.022113 \text{ m}^3/\text{kg}$$

Discussion The error in this result is less than 2 percent. Therefore, in the absence of tabulated data, the generalized compressibility chart can be used with confidence.





Exercises

3–23 Complete this table for H_2O:

T, °C	P, kPa	v, m³/kg	Phase description
140		0.05	
	550		Saturated liquid
125	750		
500		0.140	

3–26 Complete this table for refrigerant-134a:

T, °C	P, kPa	v, m³/kg	Phase description
−4	320		
10		0.0065	
	850		Saturated vapor
90	600		

CamScanner الممسوحة ضوئيا بـ

31 + 36 + 37 + 38 + 39 + 40 + 41 + 43

T(°C)	P(kPa)	U(kJ/kg)	phase composition
143.61	400	1450	Sat mix (because $U_f < U < U_g$)
220	2319.6	2801.3	Sat. vap
190	2500	805.05	compressed liq
466.2	4000	3040	superheated

* إذا أعطاني P لحال ← طلع الـ T (إذا كانت sat) والعكس (لأنه فيه dependency)
(في حالة الـ sat)

* أما إذا أعطاني (T و P) مع بعض في حال ← sat يكون
(يعني حالة one phase) ↳ Sup or compressed
(مش حالة mix)

← بالنسبة للحالة اللي جاية ندور إما على الـ super أو الـ compressed.

بنروح على A-6 عند الـ superheated عند الـ 190 والـ 2.5 ← بناءً على انه الحرارة أكبر من الـ 190 و الـ P أكبر من 2.5 MPa
(so not applicable)

← بنروح على A-7 ← بناءً على انه الـ P أكبر من 2.5 بنلاقي فعلاً (لأنه تقريباً) الـ compressed الـ P مش كتير بتأثر على الـ T (بتأثر بشكل كبير)

we interpolate in 3rd one

Radar
ask : believe & recieve
الممسوحة ضوئيا بـ CamScanner



Chapter 4

ENERGY ANALYSIS OF CLOSED SYSTEMS (Control Mass)

Thermodynamics: An Engineering Approach
Yunus A. Cengel, Michael A. Boles, Mehmet Kanoglu
McGraw-Hill

شو الفرق بين الـ E_{in} والـ E_{out} والـ ΔE !

Dr. Ahmad M. AbuYaghi
October 2023

MOVING BOUNDARY WORK

صوأ حدأ نواعي الـ work المرتبط بالحركة (moving boundary) زي الغاز لما يتمدد (كل ذرة بتضغط عالذرة اللي جنبها ت)

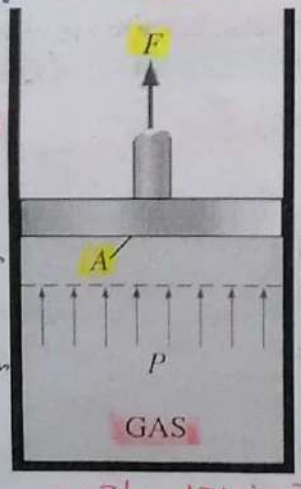
Moving boundary work (*P dV* work):
The expansion and compression work in a piston-cylinder device.

Quasi-equilibrium process:
A process during which the system remains nearly in equilibrium at all times.

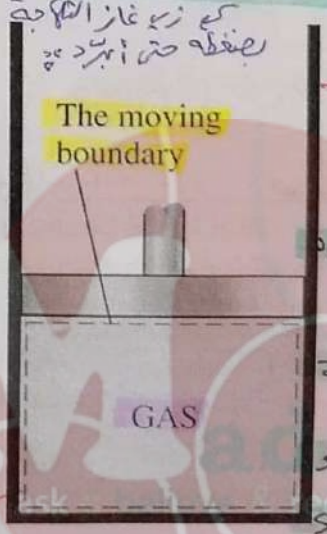
$$\delta W_b = F\,ds = PA\,ds = P\,dV$$

$$W_b = \int_1^2 P\,dV \quad (\text{kJ})$$

W_b is positive → for expansion
W_b is negative → for compression

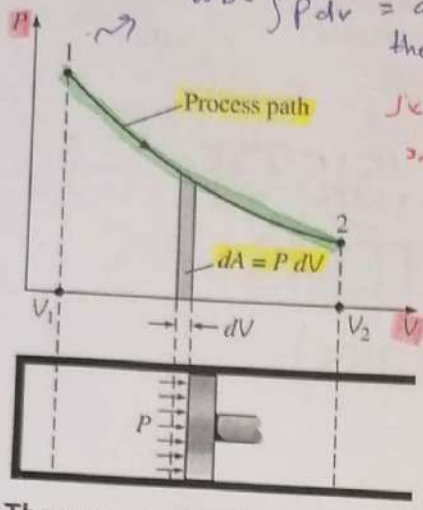


A gas does a differential amount of work δW_b as it forces the piston to move by a differential amount *ds*.



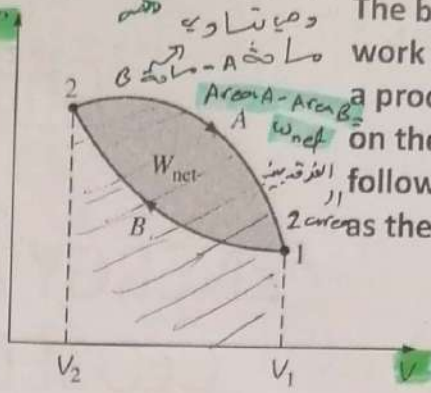
The work associated with a moving boundary is called *boundary work*.

الممسوحة ضوئيا بـ CamScanner

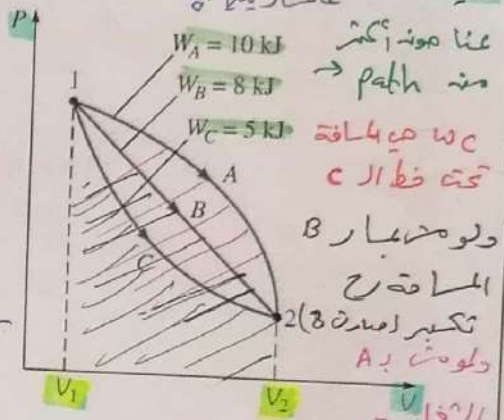


The area under the process curve on a *P-V* diagram represents the boundary work.

$$\text{Area} = A = \int_1^2 dA = \int_1^2 P\,dV$$



The boundary work done during a process depends on the path followed as well as the end states.



The net work done during a cycle is the difference between the work done by the system and the work done on the system.

Polytropic, Isothermal, and Isobaric processes

Polytropic process: C, n (polytropic exponent) constants

$$P = CV^{-n}$$

$$W_b = \int_1^2 P\,dV = \int_1^2 CV^{-n}\,dV = C\frac{V_2^{-n+1} - V_1^{-n+1}}{-n+1} = \frac{P_2V_2 - P_1V_1}{1-n}$$

Polytropic and for ideal gas

$$W_b = \frac{mR(T_2 - T_1)}{1-n}$$

When $n = 1$ (isothermal process)

$$W_b = \int_1^2 P\,dV = \int_1^2 CV^{-1}\,dV = RV\ln\left(\frac{V_2}{V_1}\right)$$

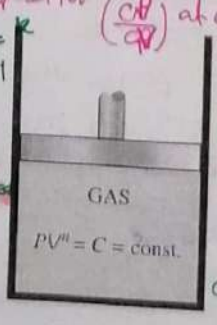
Constant pressure process

$$W_b = \int_1^2 P\,dV = P_0\int_1^2 dV = P_0(V_2 - V_1)$$

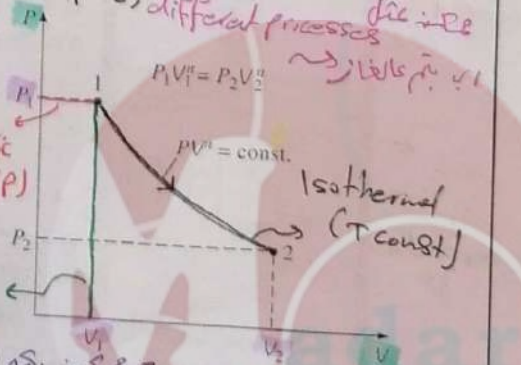
Q: What is the boundary work for a constant-volume process? equal zero

$$W_b = 0$$

because $W_b = \int P\Delta V$



Schematic and *P-V* diagram for a polytropic process.



الممسوحة ضوئيا بـ CamScanner

ENERGY BALANCE FOR CLOSED SYSTEMS

$$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic, potential, etc., energies}} \quad \text{(kJ)}$$

Energy balance for any system undergoing any process

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} \quad \text{(kW)}$$

Energy balance in the rate form

The total quantities are related to the quantities per unit time is:

$$Q = \dot{Q}\Delta t, \quad W = \dot{W}\Delta t, \quad \text{and} \quad \Delta E = (dE/dt)\Delta t \quad \text{(kJ)}$$

$$e_{in} - e_{out} = \Delta e_{system} \quad \text{(kJ/kg)}$$

Energy balance per unit mass basis

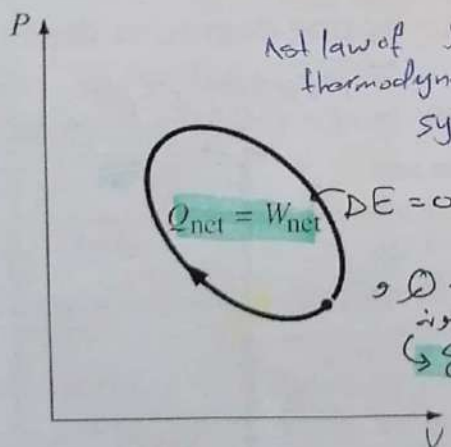
$$W_{net,out} = Q_{net,in} \quad \text{or} \quad \dot{W}_{net,out} = \dot{Q}_{net,in}$$

Energy balance for a cycle

$$Q_{net,in} - W_{net,out} = \Delta E_{system} \quad \text{or} \quad Q - W = \Delta E$$

$$Q = Q_{net,in} = Q_{in} - Q_{out}$$
$$W = W_{net,out} = W_{out} - W_{in}$$

Energy balance when sign convention is used (i.e., heat input and work output are positive; heat output and work input are negative).



For a cycle $\Delta E = 0$, thus $Q = W$.

General	$Q - W = \Delta E$
Stationary systems	$Q - W = \Delta U$
Per unit mass	$q - w = \Delta e$
Differential form	$\delta q - \delta w = de$

Various forms of the first-law relation for closed systems when sign convention is used.

The first law cannot be proven mathematically, but no process in nature is known to have violated the first law, and this should be taken as sufficient proof.

CamScanner الممسوحة ضوئيا بـ

Energy balance for a constant-pressure expansion or compression process

General analysis for a closed system undergoing a quasi-equilibrium constant-pressure process. *Q* is *to* the system and *W* is *from* the system.

$$E_{in} - E_{out} = \Delta E_{system}$$

Net energy transfer by heat, work, and mass = Change in internal, kinetic, potential, etc., energies

$$Q - W = \Delta U + \Delta KE^{0} + \Delta PE^{0}$$

$$Q - W_{other} - W_b = U_2 - U_1$$

$$Q - W_{other} - P_0(V_2 - V_1) = U_2 - U_1$$

$$Q - W_{other} = (U_2 + P_2V_2) - (U_1 + P_1V_1)$$

$H = U + PV$ ← H = U+PV ال by definition

$$Q - W_{other} = H_2 - H_1$$

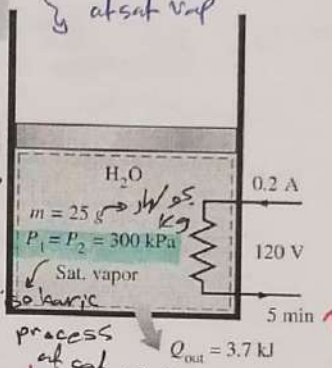
For a constant-pressure expansion or compression process:

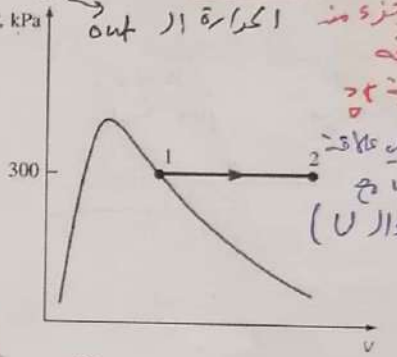
$$\Delta U + W_b = \Delta H$$

An example of constant-pressure process

$$W_{e,in} - Q_{out} - W_b = \Delta U$$

$$W_{e,in} - Q_{out} = \Delta H = m(h_2 - h_1)$$

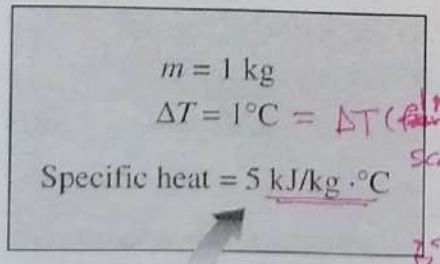




SPECIFIC HEATS

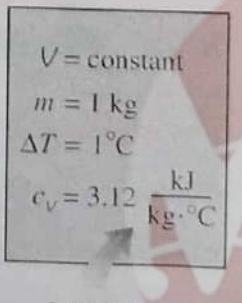
Specific heat at constant volume, c_v: The energy required to raise the temperature of the unit mass of a substance by one degree as the volume is maintained constant.

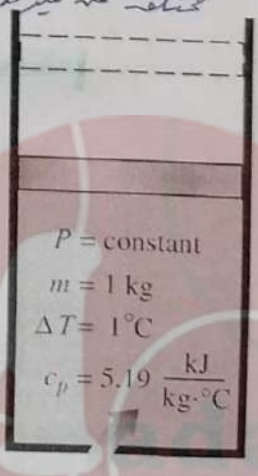
Specific heat at constant pressure, c_p: The energy required to raise the temperature of the unit mass of a substance by one degree as the pressure is maintained constant.



Specific heat is the energy required to raise the temperature of a unit mass of a substance by one degree in a specified way.

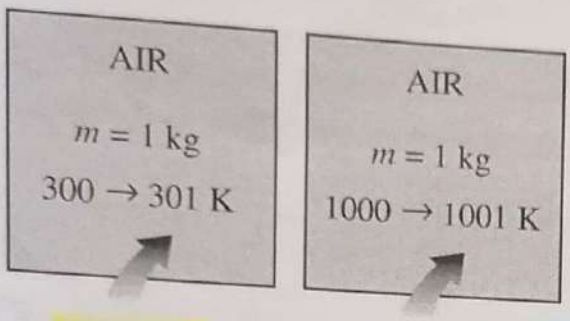
Constant-volume and constant-pressure specific heats c_v and c_p (values are for helium gas).





CamScanner الممسوحة ضوئيا بـ

- The equations in the figure are valid for *any* substance undergoing *any* process.
- c_v and c_p are properties.
- c_v is related to the changes in *internal energy* and c_p to the changes in *enthalpy*.
- A common unit for specific heats is kJ/kg · °C or kJ/kg · K. ***Are these units identical?***



0.718 kJ 0.855 kJ

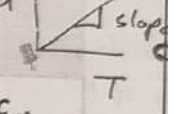
The specific heat of a substance changes with temperature.

Q: True or False:
c_p is always greater than c_v

$\Delta U = \int c_v dT$

$c_v = \left(\frac{\partial u}{\partial T}\right)_v$ = the change in internal energy with temperature at constant volume

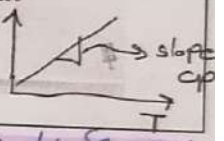
معدل تغير الـ internal energy بالنسبة لدرجة الحرارة عند حجم ثابت



Formal definitions of c_v and c_p.

$c_p = \left(\frac{\partial h}{\partial T}\right)_p$ = the change in enthalpy with temperature at constant pressure

معدل تغير الـ enthalpy مع درجة الحرارة عند ضغط ثابت



$c_p > c_v$ always

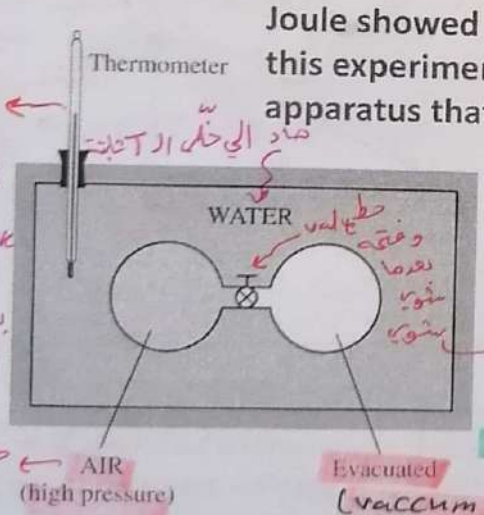
$R = c_p - c_v$ (only on ideal gas) because $h = u + pv$ so $h > u$

$\frac{dh}{dT} > \frac{du}{dT} \rightarrow c_p > c_v$

In real gas it differ ; * In liq & solid $c_p = c_v = c$ (because they are incompressible)

INTERNAL ENERGY, ENTHALPY, and SPECIFIC HEATS OF IDEAL GASES

Joule showed using this experimental apparatus that $u = u(T)$



$$\left.\begin{aligned} h &= u + Pv \\ Pv &= RT \end{aligned}\right\} \quad h = u + RT$$

$u = u(T)$ $h = h(T)$ تبين ان الـ Internal E & enth تعتمد على الحرارة

also c_v & c_p depend on Temp (not depend on P)

$du = c_v(T)\,dT$ $dh = c_p(T)\,dT$

$\Delta u = u_2 - u_1 = \int_1^2 c_v(T)\,dT$ change in Internal E

$\Delta h = h_2 - h_1 = \int_1^2 c_p(T)\,dT$ change in enth

$\Delta H = \int_{T_1}^{T_2} c_p dT = \int_{T_1}^{T_2} (a + bT + cT^2 + dT^3)\,dT$

$\Delta H = \left(a\,dT + bT\,dT + cT^2\,dT\right)\Big]_{T_1}^{T_2}$

$\Delta H = aT + b\frac{T^2}{2} + c\frac{T^3}{3}\Big]_{T_1}^{T_2}$

$c_v(T)$ $c_p(T)$

Δu & ΔH هو طول بحيث ان c_v دالة c_p تقدر تطلع من التكامل

ما تغيرت بالـ T ما تغير الـ U (Internal E) ما تغير

$u = u(T)$
$h = h(T)$
$c_v = c_v(T)$
$c_p = c_p(T)$

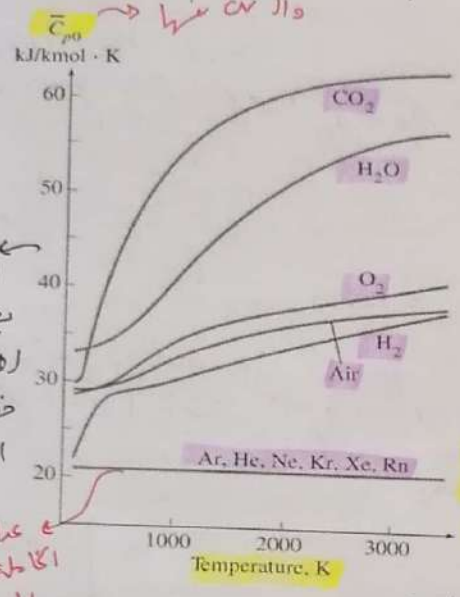
For ideal gases, u, h, c_v, and c_p vary with temperature only.

Internal energy and enthalpy change of an ideal gas because they are fun on T

c_p جامدة دائما بتكون أصغر من c_v بمقدار ثابت

الممسوحة ضوئيا بـ CamScanner

- At low pressures, all real gases approach ideal-gas behavior, and therefore their specific heats depend on temperature only.
- The specific heats of real gases at low pressures are called *ideal-gas specific heats*, or *zero-pressure specific heats*, and are often denoted c_{p0} and c_{v0}.



Ideal-gas constant-pressure specific heats for some gases (see Table A–2c for c_p equations).

- u and h data for a number of gases have been tabulated.
- These tables are obtained by choosing an arbitrary reference point and performing the integrations by treating state 1 as the reference state.

AIR

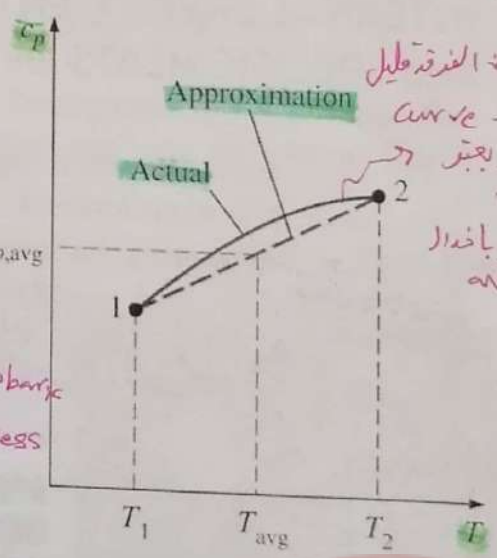
T, K	u, kJ/kg	h, kJ/kg
0	0	0
.	.	.
.	.	.
300	214.07	300.19
310	221.25	310.24
.	.	.
.	.	.

In the preparation of ideal-gas tables, 0 K is chosen as the reference temperature.

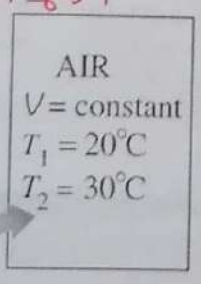
Internal energy and enthalpy change when specific heat is taken constant at an average value:

$$\Delta u = u_2 - u_1 = c_{v,\text{avg}}(T_2 - T_1) \quad \text{(kJ/kg)}$$

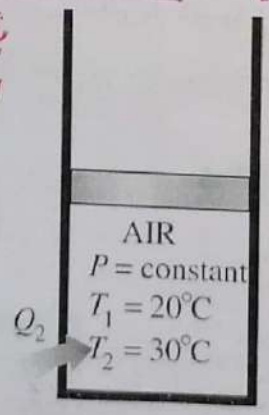
$$\Delta h = h_2 - h_1 = c_{p,\text{avg}}(T_2 - T_1)$$



For small temperature intervals, the specific heats may be assumed to vary linearly with temperature.



$\Delta u = c_v \Delta T = 7.18$ kJ/kg



$\Delta u = c_v \Delta T = 7.18$ kJ/kg

The relation $\Delta u = c_v \Delta T$ is valid for any kind of process, constant-volume or not.

CamScanner الممسوحة ضوئيا بـ

Three ways of calculating Δu and Δh

1. By using the tabulated u and h data. This is the easiest and ***most accurate*** way when tables are readily available.
2. By using the c_v or c_p relations (Table A-2c) as a function of temperature and performing the integrations. This is very inconvenient for hand calculations but quite desirable for computerized calculations. The results obtained are ***very accurate.***
3. By using average specific heats. This is very simple and certainly very convenient when property tables are not available. The results obtained are ***reasonably accurate*** if the temperature interval is not very large.

$$\Delta u = u_2 - u_1 \text{ (table)}$$

$$\Delta u = \int_1^2 c_v(T)\, dT$$

$$\Delta u \cong c_{v,\text{avg}}\, \Delta T$$

Three ways of calculating Δu.

13

Specific Heat Relations of Ideal Gases

$$h = u + RT \quad (R = \text{const})$$

$$dh = du + R\,dT$$

$dh = c_p dT$ and $du = c_v dT$

The relationship between c_p, c_v and R

$$c_p = c_v + R \qquad (\text{kJ/kg} \cdot \text{K})$$

On a molar basis

$$\bar{c}_p = \bar{c}_v + R_u \qquad (\text{kJ/kmol} \cdot \text{K})$$

Specific heat ratio:

$$k = \frac{c_p}{c_v}$$

AIR at 300 K

$$\left.\begin{aligned} c_v &= 0.718 \text{ kJ/kg} \cdot \text{K} \\ R &= 0.287 \text{ kJ/kg} \cdot \text{K} \end{aligned}\right\} c_p = 1.005 \text{ kJ/kg} \cdot \text{K}$$

or

$$\left.\begin{aligned} \bar{c}_v &= 20.80 \text{ kJ/kmol} \cdot \text{K} \\ R_u &= 8.314 \text{ kJ/kmol} \cdot \text{K} \end{aligned}\right\} \bar{c}_p = 29.114 \text{ kJ/kmol} \cdot \text{K}$$

The c_p of an ideal gas can be determined from a knowledge of c_v and R.

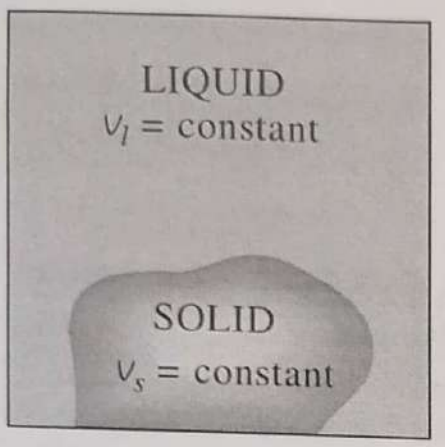
- The specific ratio varies with temperature, but this variation is very mild.
- For monatomic gases (helium, argon, etc.), its value is essentially constant at 1.667.
- Many diatomic gases, including air, have a specific heat ratio of about 1.4 at room temperature.

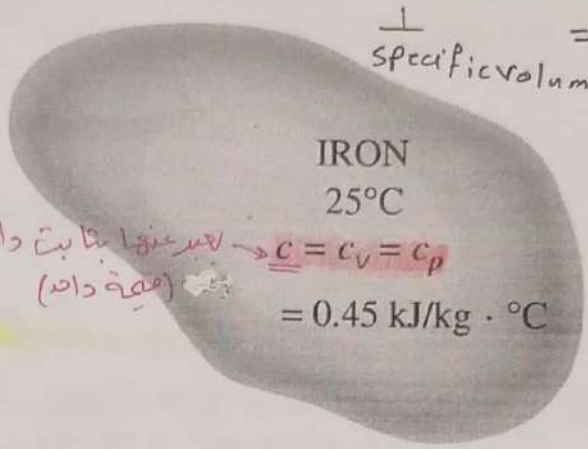
CamScanner الممسوحة ضوئيا بـ

INTERNAL ENERGY, ENTHALPY, and SPECIFIC HEATS OF SOLIDS AND LIQUIDS

Incompressible substance: A substance whose specific volume (or density) is constant. **Solids and liquids** are incompressible substances.

density = $\frac{1}{\text{specific volume}}$





يعبر عنها بثابت واحد (حجمة واحد)

The specific volumes of incompressible substances remain constant during a process.

The c_v and c_p values of incompressible substances are identical and are denoted by c. 15

Internal Energy Changes

$$du = c_v\,dT = c(T)\,dT$$

إذا لاحظنا في فرق بال C هو ال c_{avg} بناخد temp

$$\Delta u = u_2 - u_1 = \int_1^2 c(T)\,dT \qquad \text{(kJ/kg)}$$

واذا ما في بتكون ثابتة

$$\Delta u \cong c_{avg}(T_2 - T_1) \qquad \text{(kJ/kg)}$$

إما بتكون Const أو c_{avg}

Enthalpy Changes

$$h = u + Pv \quad \text{(for all substances)}$$

$$dh = du + v\,dP + P\,dv = du + v\,dP$$

$$\Delta h = \Delta u + v\,\Delta P \cong c_{avg}\,\Delta T + v\,\Delta P \qquad \text{(kJ/kg)}$$

(for liq & solid) no change in v

$h = u + Pv$

$dh = du + d(Pv)$

$= (v\,dP + P\,dv)$

For *solids*, the term $v\,\Delta P$ is insignificant and thus $\Delta h = \Delta u \cong c_{avg}\Delta T$. For *liquids*, two special cases are commonly encountered:

1. *Constant-pressure processes*, as in heaters ($\Delta P = 0$): $\Delta h = \Delta u \cong c_{avg}\Delta T$
2. *Constant-temperature processes*, as in pumps ($\Delta T = 0$): $\Delta h = v\,\Delta P$

$$h_{@P,T} \cong h_{f@T} + v_{f@T}(P - P_{sat@T})$$

The enthalpy of a compressed liquid

A more accurate relation than $h_{@P,T} \cong h_{f@T}$ (compressed ← saturated)

Qadar ask & believe & recieve

الممسوحة ضوئيا بـ CamScanner

EXAMPLE 4–1 Boundary Work for a Constant-Volume Process

A rigid tank contains air at 500 kPa and 150°C. As a result of heat transfer to the surroundings, the temperature and pressure inside the tank drop to 65°C and 400 kPa, respectively. Determine the boundary work done during this process.

SOLUTION Air in a rigid tank is cooled, and both the pressure and temperature drop. The boundary work done is to be determined.

Analysis A sketch of the system and the *P-V* diagram of the process are shown in Fig. 4–6. The boundary work can be determined from Eq. 4–2 to be

$$W_b = \int_1^2 P\,dV = 0$$

Discussion This is expected since a rigid tank has a constant volume and $dV = 0$ in this equation. Therefore, there is no boundary work done during this process. That is, the boundary work done during a constant-volume process is always zero. This is also evident from the *P-V* diagram of the process (the area under the process curve is zero).

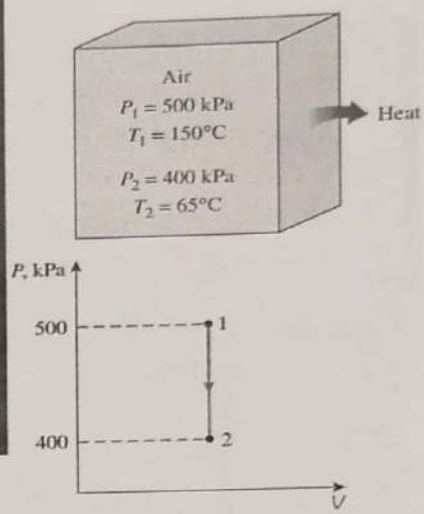


FIGURE 4–6
Schematic and *P-V* diagram for Example 4–1.

EXAMPLE 4–3 Isothermal Compression of an Ideal Gas

A piston–cylinder device initially contains 0.4 m^3 of air at 100 kPa and 80°C. The air is now compressed to 0.1 m^3 in such a way that the temperature inside the cylinder remains constant. Determine the work done during this process.

SOLUTION Air in a piston–cylinder device is compressed isothermally. The boundary work done is to be determined.

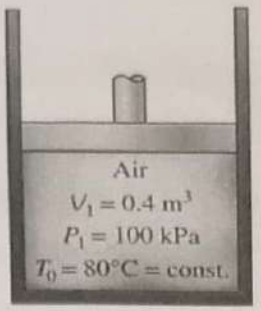
Analysis A sketch of the system and the *P-V* diagram of the process are shown in Fig. 4–8.

Assumptions 1 The compression process is quasi-equilibrium. 2 At specified conditions, air can be considered to be an ideal gas since it is at a high temperature and low pressure relative to its critical-point values.

Analysis For an ideal gas at constant temperature T_0,

$$PV = mRT_0 = C \quad \text{or} \quad P = \frac{C}{V}$$

CamScanner الممسوحة ضوئيا بـ



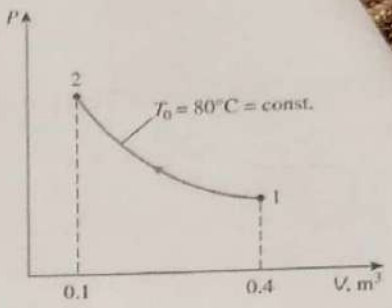


FIGURE 4–8
Schematic and *P-V* diagram for Example 4–3.

where C is a constant. Substituting this into Eq. 4–2, we have

$$W_b = \int_1^2 P\,dV = \int_1^2 \frac{C}{V}\,dV = C\int_1^2 \frac{dV}{V} = C \ln \frac{V_2}{V_1} = P_1V_1 \ln \frac{V_2}{V_1} \qquad (4\text{–}7)$$

In Eq. 4–7, P_1V_1 can be replaced by P_2V_2 or mRT_0. Also, V_2/V_1 can be replaced by P_1/P_2 for this case since $P_1V_1 = P_2V_2$.

Substituting the numerical values into Eq. 4–7 yields

$$W_b = (100\ \text{kPa})(0.4\ \text{m}^3)\left(\ln \frac{0.1}{0.4}\right)\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right)$$

$$= -55.5\ \text{kJ}$$

Discussion The negative sign indicates that this work is done on the system (a work input), which is always the case for compression processes.

EXAMPLE 4–5 Electric Heating of a Gas at Constant Pressure

A piston–cylinder device contains 25 g of saturated water vapor that is maintained at a constant pressure of 300 kPa. A resistance heater within the cylinder is turned on and passes a current of 0.2 A for 5 min from a 120-V source. At the same time, a heat loss of 3.7 kJ occurs. (*a*) Show that for a closed system the boundary work W_b and the change in internal energy ΔU in the first-law relation can be combined into one term, ΔH, for a constant-pressure process. (*b*) Determine the final temperature of the steam.

SOLUTION Saturated water vapor in a piston–cylinder device expands at constant pressure as a result of heating. It is to be shown that $\Delta U + W_b = \Delta H$, and the final temperature is to be determined.

Assumptions 1 The tank is stationary and thus the kinetic and potential energy changes are zero, $\Delta KE = \Delta PE = 0$. Therefore, $\Delta E = \Delta U$ and internal energy is the only form of energy of the system that may change during this process. 2 Electrical wires constitute a very small part of the system, and thus the energy change of the wires can be neglected.

Analysis We take the contents of the cylinder, including the resistance wires, as the *system* (Fig. 4–13). This is a *closed system* since no mass crosses the system boundary during the process. We observe that a piston–cylinder device typically involves a moving boundary and thus boundary work W_b. The pressure remains constant during the process and thus $P_2 = P_1$. Also, heat is lost from the system and electrical work W_e is done on the system.

CamScanner الممسوحة ضوئيا بـ

(*a*) This part of the solution involves a general analysis for a closed system undergoing a quasi-equilibrium constant-pressure process, and thus we consider a general closed system. We take the direction of heat transfer Q to be to the system and the work W to be done by the system. We also express the work as the sum of boundary and other forms of work (such as electrical and shaft). Then, the energy balance can be expressed as

$$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic, potential, etc., energies}}$$

$$Q - W = \Delta U + \Delta KE^{\nearrow 0} + \Delta PE^{\nearrow 0}$$

$$Q - W_{other} - W_b = U_2 - U_1$$

For a constant-pressure process, the boundary work is given as $W_b = P_0(V_2 - V_1)$. Substituting this into the preceding relation gives

$$Q - W_{other} - P_0(V_2 - V_1) = U_2 - U_1$$

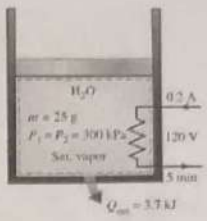
However,

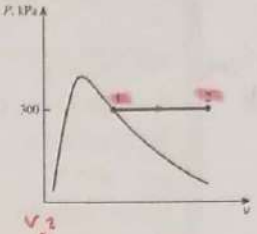
$$P_0 = P_2 = P_1 \rightarrow Q - W_{other} = (U_2 + P_2V_2) - (U_1 + P_1V_1)$$

Also $H = U + PV$, and thus

$$Q - W_{other} = H_2 - H_1 \quad \text{(kJ)} \qquad \textbf{(4–18)}$$

which is the desired relation (Fig. 4–14). This equation is very convenient to use in the analysis of closed systems undergoing a ***constant-pressure quasi-equilibrium process*** since the boundary work is automatically taken care of by the enthalpy terms, and one no longer needs to determine it separately.





$\rightarrow w_b = \int_{v_1}^{v_2} P\,dv = P(v_2 - v_1)$ ln Isobaric

$\rightarrow w_b = \int_{v_1}^{v_2} P\,dv$ (Isothermal)

ln Isothermal Ideal gas law

$PV = mRT \rightarrow$ const $= C$ ($PV = C$)

So $P_1V_1 = P_2V_2 \Rightarrow \frac{V_2}{V_1} = \frac{P_1}{P_2}$

$\rightarrow w_b = \int_{v_1}^{v_2} P\,dv = \int_{v_1}^{v_2} \frac{C}{V}\,dv$

$w_b = C\int \frac{dv}{v}$

$\therefore w_b = P_1V_1 \ln\frac{V_2}{V_1} = P_2V_2 \ln\frac{V_2}{V_1}$

$= \ln\frac{P_1}{P_2}$

(*b*) The only other form of work in this case is the electrical work, which can be determined from

$$W_e = VI\Delta t = (120\text{ V})(0.2\text{ A})(300\text{ s})\left(\frac{1\text{ kJ/s}}{1000\text{ VA}}\right) = 7.2\text{ kJ}$$

State 1: $\left.\begin{matrix} P_1 = 300\text{ kPa} \\ \text{sat. vapor} \end{matrix}\right\} h_1 = h_{g\,@\,300\text{ kPa}} = 2724.9\text{ kJ/kg}$ (Table A–5)

The enthalpy at the final state can be determined directly from Eq. 4–18 by expressing heat transfer from the system and work done on the system as negative quantities (since their directions are opposite to the assumed directions). Alternately, we can use the general energy balance relation with the simplification that the boundary work is considered automatically by replacing ΔU by ΔH for a constant-pressure expansion or compression process:

$$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic, potential, etc., energies}}$$

$$W_{e,in} - Q_{out} - W_b = \Delta U$$

$$W_{e,in} - Q_{out} = \Delta H = m(h_2 - h_1) \quad \text{(since } P = \text{constant)}$$

$$7.2\text{ kJ} - 3.7\text{ kJ} = (0.025\text{ kg})(h_2 - 2724.9)\text{ kJ/kg}$$

$$h_2 = 2864.9\text{ kJ/kg}$$

Now the final state is completely specified since we know both the pressure and the enthalpy. The temperature at this state is

State 2: $\left.\begin{matrix} P_2 = 300\text{ kPa} \\ h_2 = 2864.9\text{ kJ/kg} \end{matrix}\right\} T_2 = 200°\text{C}$ (Table A–6)

Therefore, the steam will be at 200°C at the end of this process.

CamScanner الممسوحة ضوئيا بـ

EXAMPLE 4–7 Evaluation of the Δu of an Ideal Gas

Air at 300 K and 200 kPa is heated at constant pressure (isobaric) to 600 K. Determine the change in internal energy of air per unit mass, using (*a*) data from the air table (Table A–17), (*b*) the functional form of the specific heat (Table A–2*c*), and (*c*) the average specific heat value (Table A–2*b*).

SOLUTION The internal energy change of air is to be determined in three different ways.

Assumptions At specified conditions, air can be considered to be an ideal gas since it is at a high temperature and low pressure relative to its critical-point values.

Analysis The internal energy change Δu of ideal gases depends on the initial and final temperatures only, and not on the type of process. Thus, the following solution is valid for any kind of process.

(*a*) One way of determining the change in internal energy of air is to read the u values at T_1 and T_2 from Table A–17 and take the difference:

$$u_1 = u_{@\,300\,K} = 214.07 \text{ kJ/kg}$$

$$u_2 = u_{@\,600\,K} = 434.78 \text{ kJ/kg}$$

Thus,

$$\Delta u = u_2 - u_1 = (434.78 - 214.07) \text{ kJ/kg} = 220.71 \text{ kJ/kg}$$

(*b*) The $\bar{c}_p(T)$ of air is given in Table A–2*c* in the form of a third-degree polynomial expressed as

$$\bar{c}_p(T) = a + bT + cT^2 + dT^3$$

where $a = 28.11$, $b = 0.1967 \times 10^{-2}$, $c = 0.4802 \times 10^{-5}$, and $d = -1.966 \times 10^{-9}$. From Eq. 4–30,

$$\bar{c}_v(T) = \bar{c}_p - R_u = (a - R_u) + bT + cT^2 + dT^3$$

From Eq. 4–25,

$$\Delta \bar{u} = \int_1^2 \bar{c}_v(T)\, dT = \int_{T_1}^{T_2} [(a - R_u) + bT + cT^2 + dT^3]\, dT$$

Performing the integration and substituting the values, we obtain

$$\Delta \bar{u} = 6447 \text{ kJ/kmol}$$

The change in the internal energy on a unit-mass basis is determined by dividing this value by the molar mass of air (Table A–1):

$$\Delta u = \frac{\Delta \bar{u}}{M} = \frac{6447 \text{ kJ/kmol}}{28.97 \text{ kg/kmol}} = 222.5 \text{ kJ/kg}$$

which differs from the tabulated value by 0.8 percent.

(*c*) The average value of the constant-volume specific heat $c_{v,\text{avg}}$ is determined from Table A–2*b* at the average temperature of $(T_1 + T_2)/2 = 450$ K to be

$$c_{v,\text{avg}} = c_{v\,@\,450\,K} = 0.733 \text{ kJ/kg·K}$$

Thus,

$$\Delta u = c_{v,\text{avg}}(T_2 - T_1) = (0.733 \text{ kJ/kg·K})[(600 - 300)\text{K}] = 220 \text{ kJ/kg}$$

EXAMPLE 4–11 **Enthalpy of Compressed Liquid**

Determine the enthalpy of liquid water at 100°C and 15 MPa (*a*) by using compressed liquid tables, (*b*) by approximating it as a saturated liquid, and (*c*) by using the correction given by Eq. 4–38.

SOLUTION The enthalpy of liquid water is to be determined exactly and approximately.

Analysis At 100°C, the saturation pressure of water is 101.42 kPa, and since $P > P_{sat}$, the water exists as a compressed liquid at the specified state.

(*a*) From compressed liquid tables, we read

$$\left.\begin{matrix} P = 15\ \text{MPa} \\ T = 100°\text{C} \end{matrix}\right\} \quad h = 430.39\ \text{kJ/kg} \qquad \text{(Table A–7)}$$

This is the exact value.

(*b*) Approximating the compressed liquid as a saturated liquid at 100°C, as is commonly done, we obtain

$$h \cong h_{f\,@\,100°\text{C}} = 419.17\ \text{kJ/kg}$$

This value is in error by about 2.6 percent.

(*c*) From Eq. 4–38,

$$h_{@P,T} \cong h_{f\,@\,T} + v_{f\,@\,T}(P - P_{sat\,@\,T})$$

$$= (419.17\ \text{kJ/kg}) + (0.001\ \text{m}^3/\text{kg})[(15{,}000 - 101.42)\ \text{kPa}]\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right)$$

$$= 434.07\ \text{kJ/kg}$$

Discussion Note that the correction term reduced the error from 2.6 to about 1 percent in this case. However, this improvement in accuracy is often not worth the extra effort involved.

CamScanner الممسوحة ضوئيا بـ



Chapter 5

MASS AND ENERGY ANALYSIS OF OPEN SYSTEMS (Control Volumes)

Thermodynamics: An Engineering Approach
Yunus A. Cengel, Michael A. Boles, Mehmet Kanoglu
McGraw-Hill

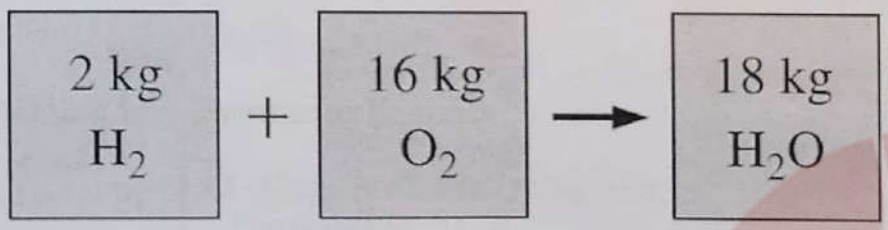
Dr. Ahmad M. AbuYaghi
October 2023

CONSERVATION OF MASS

Conservation of mass: Mass, like energy, is a conserved property, and it cannot be created or destroyed during a process.

Closed systems: The mass of the system remain constant during a process.

Control volumes: Mass can cross the boundaries, and so we must keep track of the amount of mass entering and leaving the control volume.



Mass is conserved even during chemical reactions.

Mass m and energy E can be converted to each other according to

$$E = mc^2$$

where c is the speed of light in a vacuum, which is $c = 2.9979 \times 10^8$ m/s.

The mass change due to energy change is absolutely negligible.

CamScanner الممسوحة ضوئيا بـ

Mass and Volume Flow Rates

$$\delta \dot{m} = \rho V_n \, dA_c$$

$$\dot{m} = \int_{A_c} \delta \dot{m} = \int_{A_c} \rho V_n \, dA_c$$

$$\dot{m} = \rho V_{\text{avg}} A_c \qquad (\text{kg/s})$$

$$V_{\text{avg}} = \frac{1}{A_c} \int_{A_c} V_n \, dA_c$$

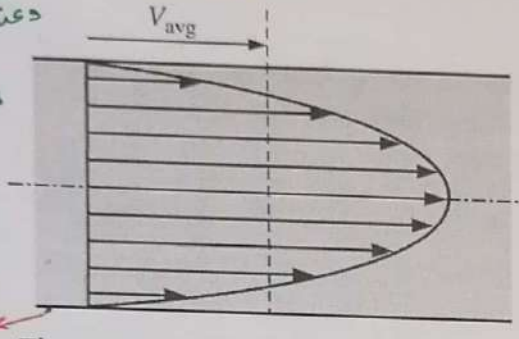
Definition of average velocity

Volume flow rate

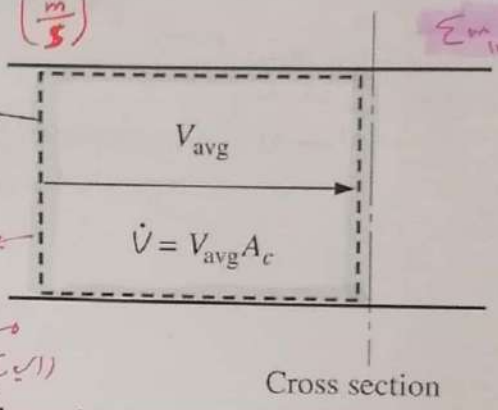
$$\dot{V} = \int_{A_c} V_n \, dA_c = V_{\text{avg}} A_c = VA_c \qquad (\text{m}^3/\text{s})$$

$$\dot{m} = \rho \dot{V} = \frac{\dot{V}}{v}$$

Mass flow rate



The average velocity V_{avg} is defined as the average speed through a cross section.



The volume flow rate is the volume of fluid flowing through a cross section per unit time.

Conservation of Mass Principle

The conservation of mass principle for a control volume: **The net mass transfer to or from a control volume during a time interval Δt is equal to the net change (increase or decrease) in the total mass within the control volume during Δt.**

$$\begin{pmatrix}\text{Total mass entering}\\ \text{the CV during } \Delta t\end{pmatrix} - \begin{pmatrix}\text{Total mass leaving}\\ \text{the CV during } \Delta t\end{pmatrix} = \begin{pmatrix}\text{Net change in mass}\\ \text{within the CV during } \Delta t\end{pmatrix}$$

$$m_{\text{in}} - m_{\text{out}} = \Delta m_{\text{CV}} \qquad (\text{kg})$$

$$\dot{m}_{\text{in}} - \dot{m}_{\text{out}} = dm_{\text{CV}}/dt \qquad (\text{kg/s})$$

General conservation of mass

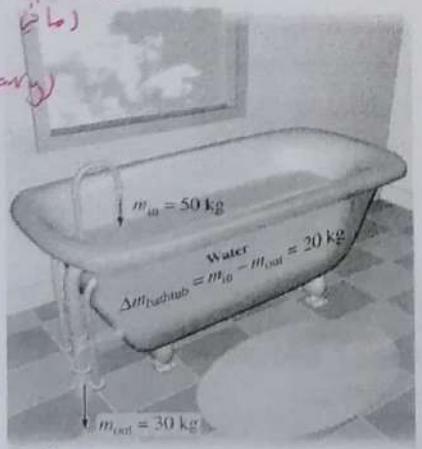
$$\frac{d}{dt}\int_{\text{CV}} \rho \, dV + \int_{\text{CS}} \rho(\vec{V} \cdot \vec{n}) \, dA = 0$$

General conservation of mass in rate form

$$\frac{d}{dt}\int_{\text{CV}} \rho \, dV = \sum_{\text{in}} \dot{m} - \sum_{\text{out}} \dot{m}$$

or

$$\frac{dm_{\text{CV}}}{dt} = \sum_{\text{in}} \dot{m} - \sum_{\text{out}} \dot{m}$$

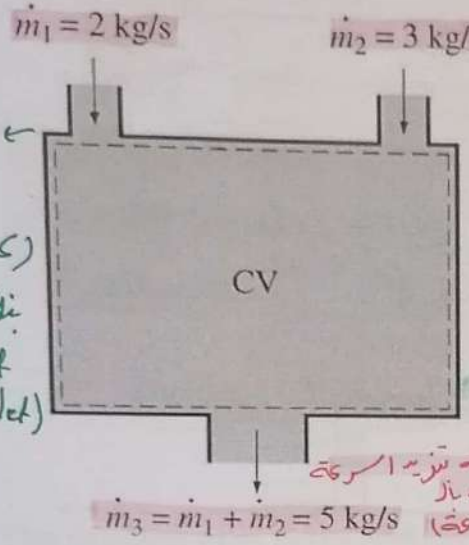


Conservation of mass principle for an ordinary bathtub.

Mass Balance for Steady-Flow Processes

During a steady-flow process, the total amount of mass contained within a control volume does not change with time (m_{CV} = constant).

Then the conservation of mass principle requires that the total amount of mass entering a control volume equal the total amount of mass leaving it.



Conservation of mass principle for a two-inlet–one-outlet steady-flow system.

For steady-flow processes, we are interested in the amount of mass flowing per unit time, that is, *the mass flow rate.*

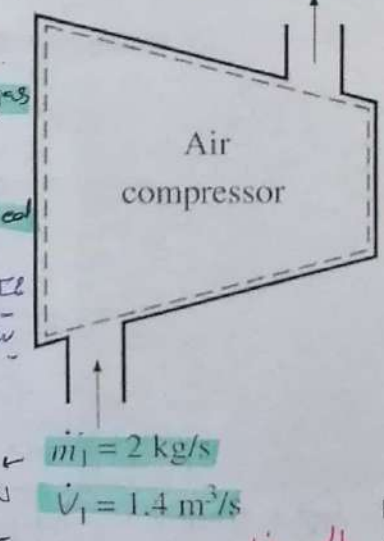
$$\sum_{in} \dot{m} = \sum_{out} \dot{m} \quad (kg/s)$$ Multiple inlets and exits

$$\dot{m}_1 = \dot{m}_2 \rightarrow \rho_1 V_1 A_1 = \rho_2 V_2 A_2$$ Single stream

Many engineering devices such as nozzles, diffusers, turbines, compressors, and pumps involve a single stream (only one inlet and one outlet).

Special Case: Incompressible Flow

The conservation of mass relations can be simplified even further when the fluid is incompressible, which is usually the case for liquids.



$$\sum_{in} \dot{V} = \sum_{out} \dot{V} \quad (m^3/s)$$ Steady, incompressible

$$\dot{V}_1 = \dot{V}_2 \rightarrow V_1 A_1 = V_2 A_2$$ Steady, incompressible flow (single stream)

- **There is no such thing as a "conservation of volume" principle.**
- **However, for steady flow of liquids, the volume flow rates, as well as the mass flow rates, remain constant since liquids are essentially incompressible substances.**

During a steady-flow process, volume flow rates are not necessarily conserved although mass flow rates are.

CamScanner الممسوحة ضوئيا بـ

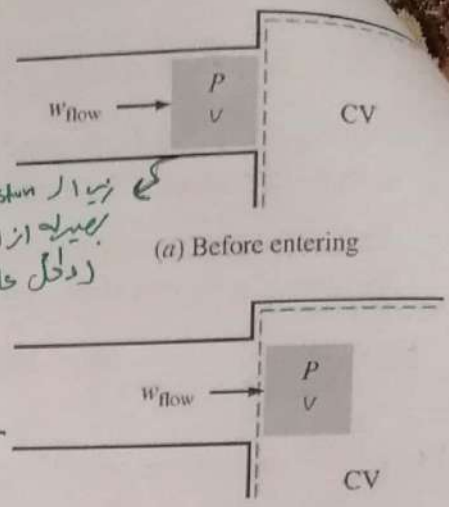
FLOW WORK AND THE ENERGY OF A FLOWING FLUID

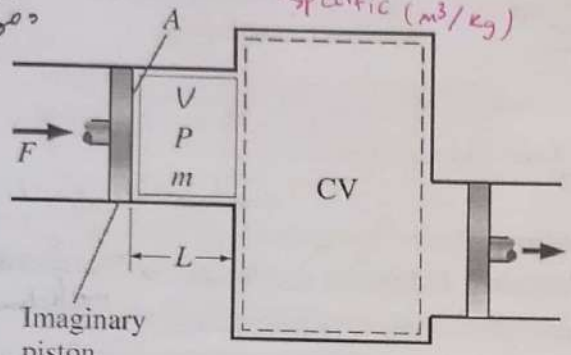
Flow work, or flow energy: The work (or energy) required to push the mass into or out of the control volume. This work is necessary for maintaining a continuous flow through a control volume.

$$F = PA$$

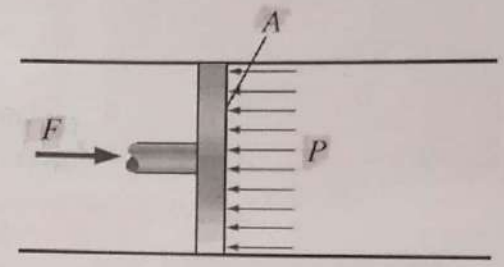
$$W_{flow} = FL = PAL = PV \quad \text{(kJ)}$$

$$w_{flow} = Pv \quad \text{(kJ/kg)}$$





Schematic for flow work.



In the absence of acceleration, the force applied on a fluid by a piston is equal to the force applied on the piston by the fluid.

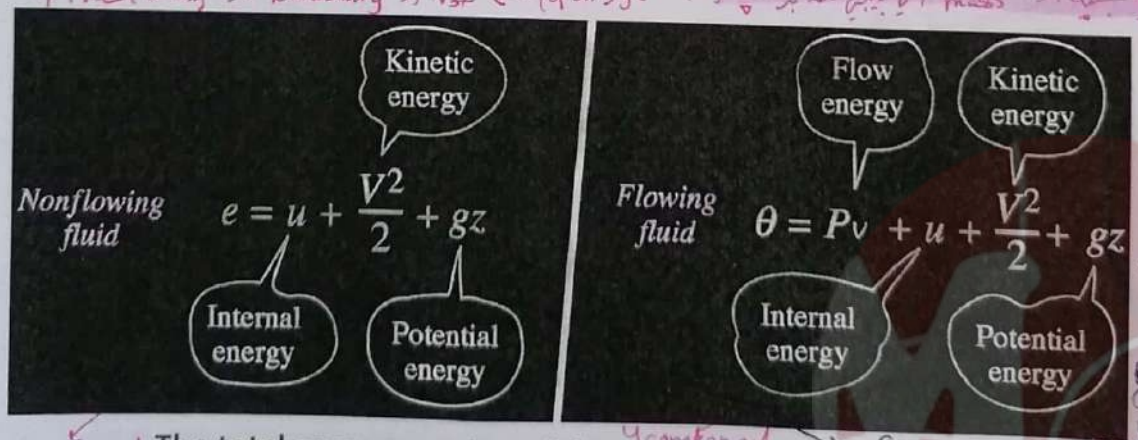
Total Energy of a Flowing Fluid

$$e = u + \text{ke} + \text{pe} = u + \frac{V^2}{2} + gz \quad \text{(kJ/kg)}$$

$$\theta = Pv + e = Pv + (u + \text{ke} + \text{pe}) \qquad h = u + Pv$$

$$\theta = h + \text{ke} + \text{pe} = h + \frac{V^2}{2} + gz \quad \text{(kJ/kg)}$$

The flow energy is automatically taken care of by enthalpy. In fact, this is the main reason for defining the property enthalpy.

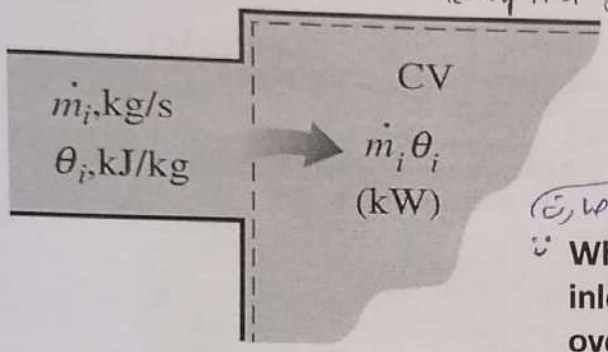


The total energy consists of three parts for a nonflowing fluid and four parts for a flowing fluid.

Energy Transport by Mass

Amount of energy transport: $E_{\text{mass}} = m\theta = m\left(h + \frac{V^2}{2} + gz\right)$ (kJ)

Rate of energy transport: $\dot{E}_{\text{mass}} = \dot{m}\theta = \dot{m}\left(h + \frac{V^2}{2} + gz\right)$ (kW)



When the kinetic and potential energies of a fluid stream are negligible

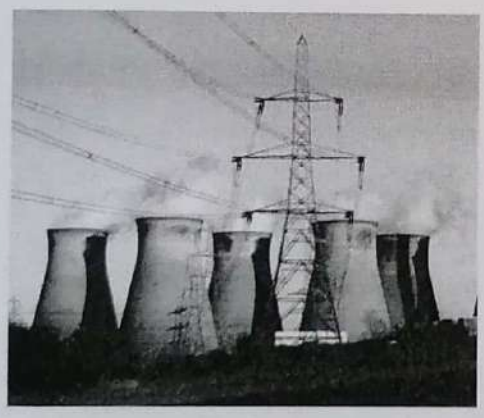
$$E_{\text{mass}} = mh \qquad \dot{E}_{\text{mass}} = \dot{m}h$$

When the properties of the mass at each inlet or exit change with time as well as over the cross section

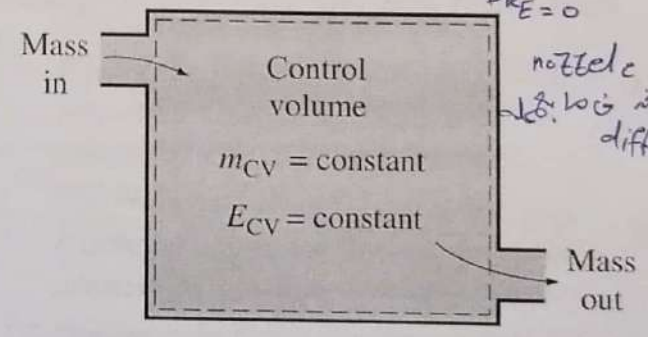
$$E_{\text{in,mass}} = \int_{m_i} \theta_i\, \delta m_i = \int_{m_i} \left(h_i + \frac{V_i^2}{2} + gz_i\right) \delta m_i$$

The product $\dot{m}_i\theta_i$ is the energy transported into control volume by mass per unit time.

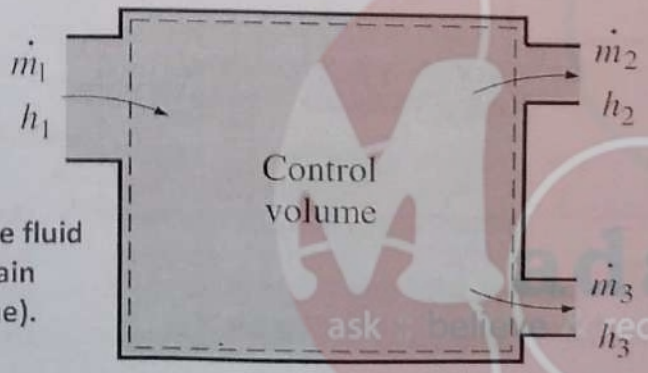
ENERGY ANALYSIS OF STEADY-FLOW SYSTEMS



Many engineering systems such as power plants operate under steady conditions.



Under steady-flow conditions, the mass and energy contents of a control volume remain constant.

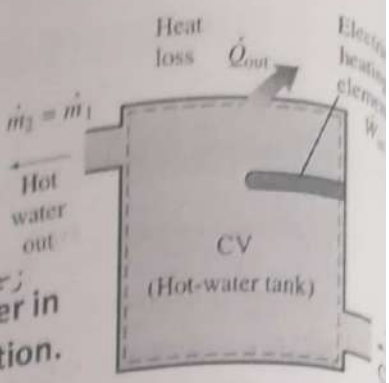


Under steady-flow conditions, the fluid properties at an inlet or exit remain constant (do not change with time).

CamScanner الممسوحة ضوئيا بـ

Mass and Energy balances for a steady-flow process

$$\sum_{in} \dot{m} = \sum_{out} \dot{m} \quad (kg/s)$$



A water heater in steady operation.

Mass balance

$$\dot{m}_1 = \dot{m}_2 \quad \text{(single in \& out)}$$

$$\rho_1 V_1 A_1 = \rho_2 V_2 A_2$$

Energy balance

$$\dot{E}_{in} - \dot{E}_{out} = \underbrace{dE_{system}/dt}_{0 \text{ (steady)}} = 0$$

$\dot{E}_{in} - \dot{E}_{out}$: Rate of net energy transfer by heat, work, and mass

dE_{system}/dt: Rate of change in internal, kinetic, potential, etc., energies

$$\dot{E}_{in} = \dot{E}_{out} \quad (kW)$$

$\dot{E}_{in}$: Rate of net energy transfer in by heat, work, and mass

$\dot{E}_{out}$: Rate of net energy transfer out by heat, work, and mass

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m}\left(h + \frac{V^2}{2} + gz\right) = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m}\left(h + \frac{V^2}{2} + g\right)$$

for each inlet → energy carried by the mass

for each exit

Energy balance relations with sign conventions (i.e., heat input and work output are positive)

$$\dot{Q} - \dot{W} = \sum_{out} \dot{m}\left(h + \frac{V^2}{2} + gz\right) - \sum_{in} \dot{m}\left(h + \frac{V^2}{2} + gz\right)$$

for each exit — for each inlet

$$\dot{Q} - \dot{W} = \dot{m}\left[h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right] \quad \text{(for single In \& out)}$$

$\dot{Q}$, $\dot{W}$: kJ/s — $\dot{m}$: kg/s

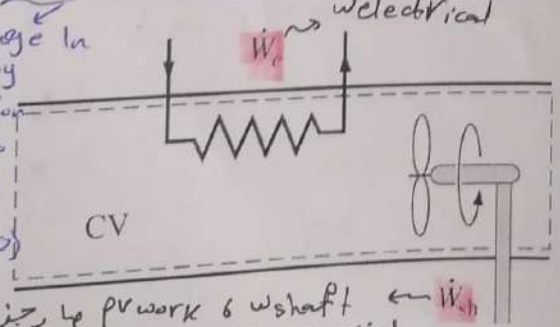
$$q - w = h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$

q, w: kJ/kg

$$q - w = h_2 - h_1 \quad q = \dot{Q}/\dot{m} \quad w = \dot{W}/\dot{m}$$

$$\frac{J}{kg} \equiv \frac{N \cdot m}{kg} \equiv \left(kg\frac{m}{s^2}\right)\frac{m}{kg} \equiv \frac{m^2}{s^2}$$

$$\left(\text{Also, } \frac{Btu}{lbm} \equiv 25{,}037\ \frac{ft^2}{s^2}\right)$$



Under steady operation, shaft work and electrical work are the only forms of work a simple compressible system may involve.

Some energy unit equivale

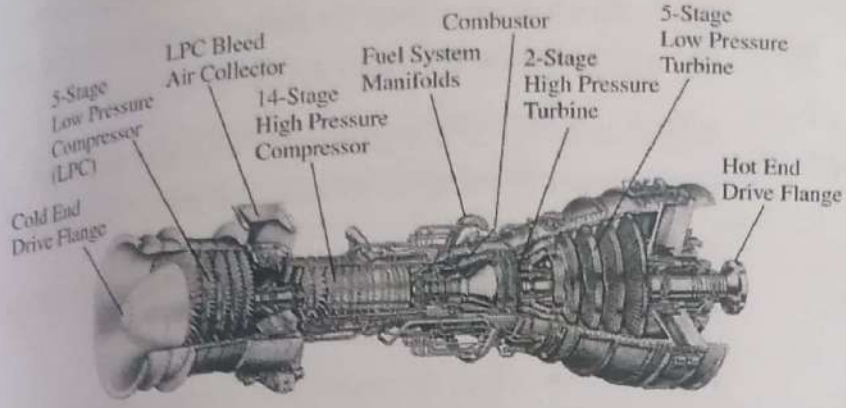
St.st applications: turbines, Power plant, Pipes, nozzles, compressors, throttling, mixing ch

when kinetic and potential energy changes are negligible

الممسوحة ضوئيا بـ CamScanner

SOME STEADY-FLOW ENGINEERING DEVICES

Many engineering devices operate essentially under the same conditions for long periods of time. The components of a steam power plant (turbines, compressors, heat exchangers, and pumps), for example, operate nonstop for months before the system is shut down for maintenance. Therefore, these devices can be conveniently analyzed as steady-flow devices.

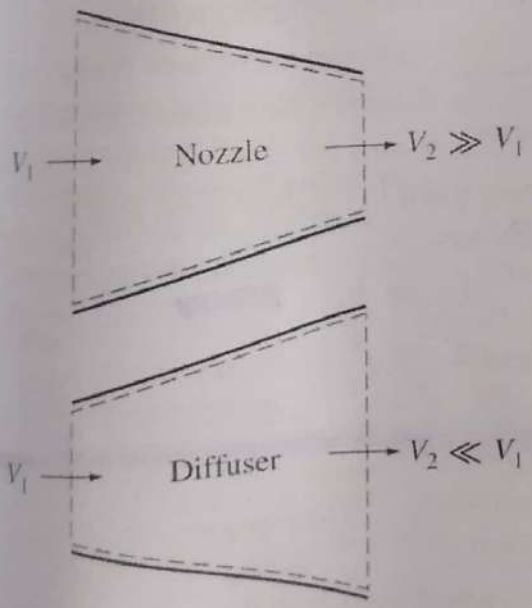


A modern land-based gas turbine used for electric power production. This is a General Electric LM5000 turbine. It has a length of 6.2 m, it weighs 12.5 tons, and produces 55.2 MW at 3600 rpm with steam injection.

V_1 m/s	V_2 m/s	Δke kJ/kg
0	45	1
50	67	1
100	110	1
200	205	1
500	502	1

At very high velocities, even small changes in velocities can cause significant changes in the kinetic energy of the fluid.

Nozzles and Diffusers



Nozzles and diffusers are commonly utilized in jet engines, rockets, spacecraft, and even garden hoses.

A nozzle is a device that *increases the velocity of a fluid* at the expense of pressure.

A diffuser is a device that *increases the pressure of a fluid* by slowing it down.

The cross-sectional area of a nozzle decreases in the flow direction for subsonic flows and increases for supersonic flows. The reverse is true for diffusers.

Nozzles and diffusers are shaped so that they cause large changes in fluid velocities and thus kinetic energies.

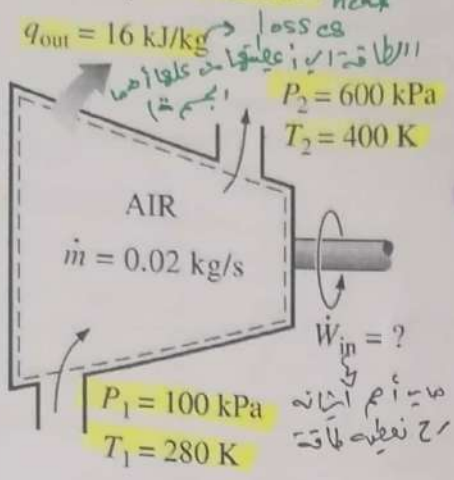
Energy balance for a nozzle or diffuser:

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}\left(h_1 + \frac{V_1^2}{2}\right) = \dot{m}\left(h_2 + \frac{V_2^2}{2}\right)$$

(since $\dot{Q} \cong 0$, $\dot{W} = 0$, and $\Delta pe \cong 0$)

Turbines and Compressors



Energy balance for the compressor in this figure:

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{W}_{in} + \dot{m}h_1 = \dot{Q}_{out} + \dot{m}h_2$$

(since $\Delta ke = \Delta pe \cong 0$)

Turbine drives the electric generator In s
gas, or hydroelectric power plants.

As the fluid passes through the turbine, wo
done against the blades, which are attache
the shaft. As a result, the shaft rotates, and
turbine produces work.

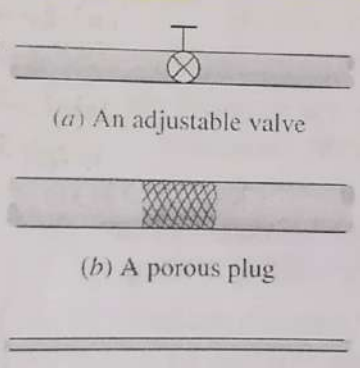
Compressors, as well as **pumps** and f
are devices used to increase the pressure o
fluid. Work is supplied to these devices fro
external source through a rotating shaft.

A ***fan*** increases the pressure of a gas slight
and is mainly used to mobilize a gas.

A ***compressor*** is capable of compressing
gas to very high pressures.

Pumps work very much like compressors
except that they handle liquids instead of ga

Throttling valves



Throttling valves are *any kind of flow-restricting devic*
that cause a significant pressure drop in the fluid.

What is the difference between a turbine and a throttling valve?

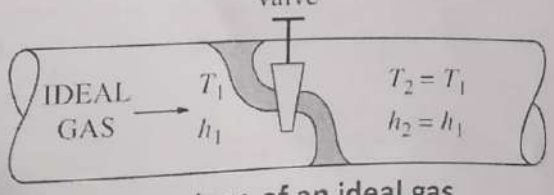
The pressure drop in the fluid is often accompanied b
large drop in temperature, and for that reason throttli
devices are commonly used in refrigeration and air-
conditioning applications.

Energy balance

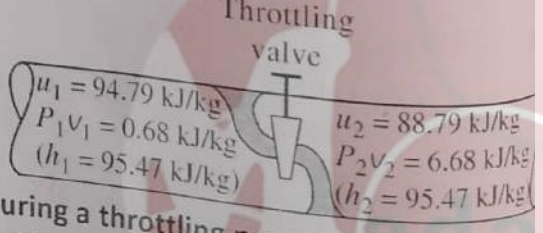
$$h_2 \cong h_1$$

$$u_1 + P_1v_1 = u_2 + P_2v_2$$

Internal energy + Flow energy = Consta



The temperature of an ideal gas does not change during a throttling (h = constant) process since $h = h(T)$.



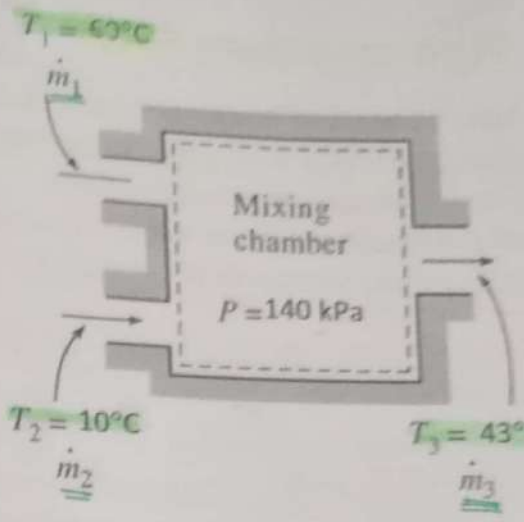
During a throttling process, the enthalpy o
fluid remains constant. But internal and flo
energies may be converted to each other.

الممسوحة ضوئيا بـ CamScanner

Mixing chambers

to mix 2 fluids

- In engineering applications, the section where the mixing process takes place is commonly referred to as a mixing chamber.



Energy balance for the adiabatic mixing chamber in the figure is:

we have 2 inlets & one outlet

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$$

$\dot{m}_1 + \dot{m}_2 = \dot{m}_3$

Then, $Q_1 = mc_p \Delta T \rightarrow = T_3 - T_1$

$Q_2 = mc_p \Delta T \rightarrow = T_3 - T_2$

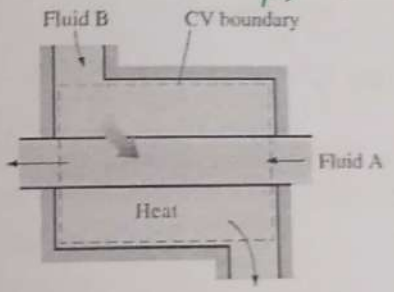
Then, $h = c_p \Delta T$

Assumption (insulated) (since $\dot{Q} \cong 0$, $\dot{W} = 0$, ke $\cong$ pe $\cong 0$)

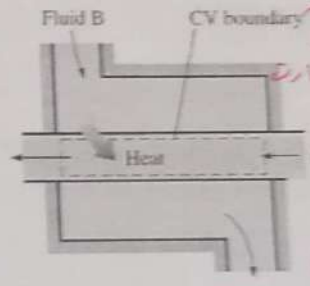
no electrical or fans

Heat exchangers

Heat exchangers are devices where two moving fluid streams exchange heat without mixing. Heat exchangers are widely used in various industries, and they come in various designs.

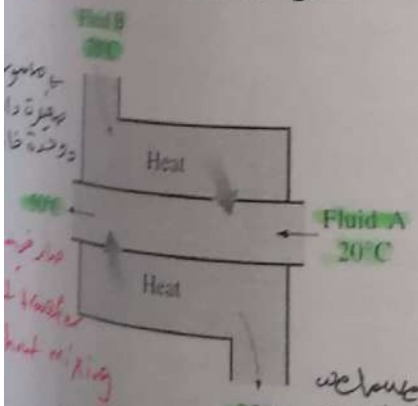


(a) System: Entire heat exchanger ($Q_{CV} = 0$)



(b) System: Fluid A ($Q_{CV} \neq 0$)

The heat transfer associated with a heat exchanger may be zero or nonzero depending on how the control volume is selected.



A heat exchanger can be as simple as two concentric pipes.

Mass and energy balances for the adiabatic heat exchanger in the figure is:

we have 2 inlet & 2 outlet

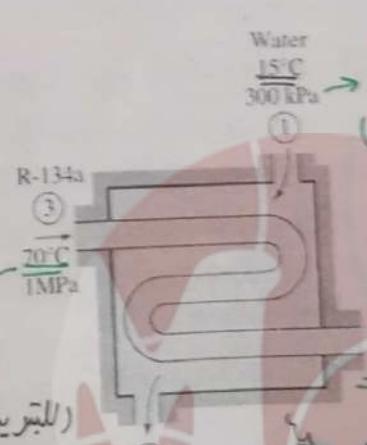
$$\dot{m}_1 = \dot{m}_2 = \dot{m}_w \quad \text{for water}$$

$$\dot{m}_3 = \dot{m}_4 = \dot{m}_R \quad \text{for refrigerant}$$

for st.st $\dot{E}_{in} = \dot{E}_{out}$

$$\dot{m}_1 h_1 + \dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_4 h_4$$

input = outlet



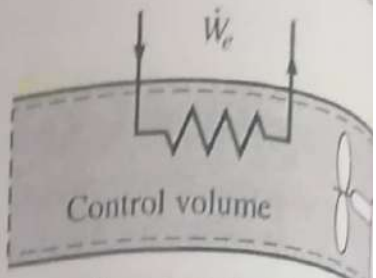
Shell & tube H.E

for sys → Q = 0 = KE = PE = 0

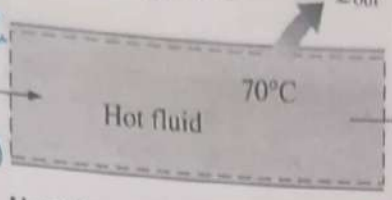
CamScanner الممسوحة ضوئيا بـ

Pipe and duct fow

The transport of liquids or gases in pipes and ducts is of great importance in many engineering applications. Flow through a pipe or a duct usually satisfies the steady-flow conditions.



Pipe or duct flow may involve more than one form of work at the same time.



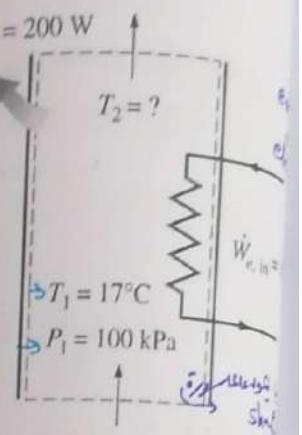
Heat losses from a hot fluid flowing through an uninsulated pipe or duct to the cooler environment may be very significant.

Energy balance for the pipe flow shown in the figure is:

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{W}_{e,in} + \dot{m}h_1 = \dot{Q}_{out} + \dot{m}h_2$$

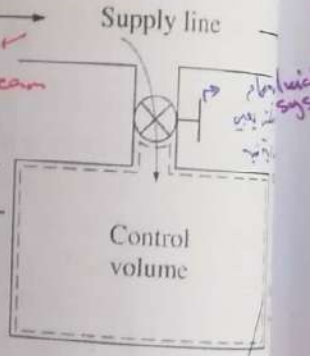
$$\dot{W}_{e,in} - \dot{Q}_{out} = \dot{m}c_p(T_2 - T_1)$$



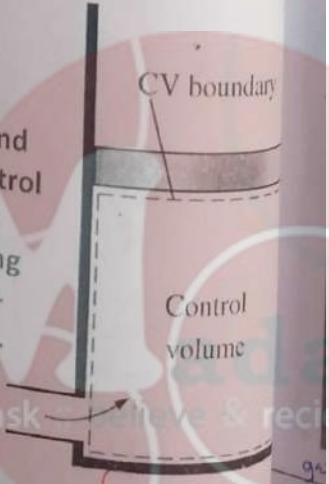
ENERGY ANALYSIS OF UNSTEADY-FLOW PROCESSES

- Many processes of interest, however, involve *changes* within the control volume with time.
- Such processes are called ***unsteady-flow,*** or ***transient-flow,*** processes.
- Most unsteady-flow processes can be represented reasonably well by the *uniform-flow process.*
- **Uniform-flow process:** The fluid flow at any inlet or exit is uniform and steady, and thus the fluid properties do not change with time or position over the cross section of an inlet or exit.
- If they do, they are averaged and treated as constants for the entire process.

Charging of a rigid tank from a supply line is an unsteady-flow process since it involves changes within the control volume.



The shape and size of a control volume may change during an unsteady-flow process.



CamScanner المسوحة ضوئيا بـ

Mass balance

$$\Delta m_{\text{system}} = m_{\text{final}} - m_{\text{initial}}$$

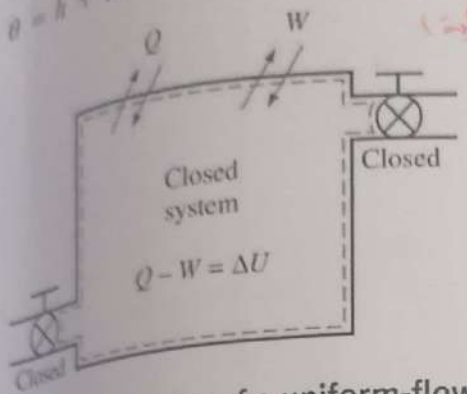
i = inlet, e = exit, 1 = initial state, and 2 = final state

Energy balance

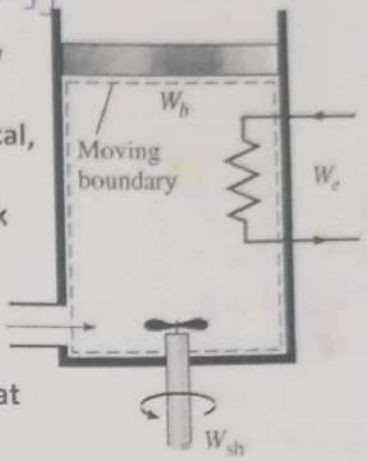
$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{\text{system}}}_{\text{Change in internal, kinetic, potential, etc., energies}}$$

$$\left(Q_{\text{in}} + W_{\text{in}} + \sum_{\text{in}} m\theta\right) - \left(Q_{\text{out}} + W_{\text{out}} + \sum_{\text{out}} m\theta\right) = (m_2 e_2 - m_1 e_1)_{\text{system}}$$

$$\theta = h + \text{ke} + \text{pe} \qquad e = u + \text{ke} + \text{pe}$$



The energy equation of a uniform-flow system reduces to that of a closed system when all the inlets and exits are closed.



A uniform-flow system may involve electrical, shaft, and boundary work all at once.

EXAMPLE 5–4 Deceleration of Air in a Diffuser

Air at 10°C and 80 kPa enters the diffuser of a jet engine steadily with a velocity of 200 m/s. The inlet area of the diffuser is 0.4 m². The air leaves the diffuser with a velocity that is very small compared with the inlet velocity. Determine (*a*) the mass flow rate of the air and (*b*) the temperature of the air leaving the diffuser.

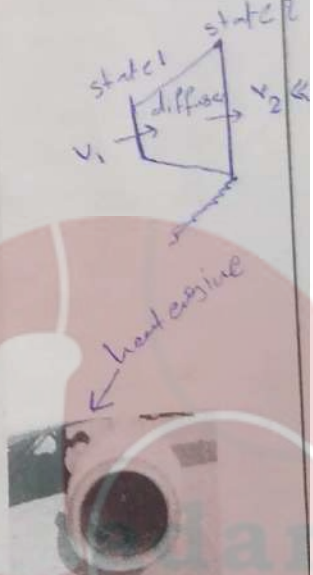
SOLUTION Air enters the diffuser of a jet engine steadily at a specified velocity. The mass flow rate of air and the temperature at the diffuser exit are to be determined.

Assumptions **1** This is a steady-flow process since there is no change with time at any point and thus $\Delta m_{\text{cv}} = 0$ and $\Delta E_{\text{cv}} = 0$. **2** Air is an ideal gas since it is at a high temperature and low pressure relative to its critical-point values. **3** The potential energy change is zero, $\Delta \text{pe} = 0$. **4** Heat transfer is negligible. **5** Kinetic energy at the diffuser exit is negligible. **6** There are no work interactions.

Analysis We take the *diffuser* as the system (Fig. 5–27). This is a *control volume* since mass crosses the system boundary during the process. We observe that there is only one inlet and one exit and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$.

(*a*) To determine the mass flow rate, we need to find the specific volume of the air first. This is determined from the ideal-gas relation at the inlet conditions:

$$v_1 = \frac{RT_1}{P_1} = \frac{(0.287 \text{ kPa·m}^3/\text{kg·K})(283 \text{ K})}{80 \text{ kPa}} = 1.015 \text{ m}^3/\text{kg}$$



CamScanner الممسوحة ضوئيا بـ

Then,

$$\dot{m} = \frac{1}{v_1} V_1 A_1 = \frac{1}{1.015\ \text{m}^3/\text{kg}} (200\ \text{m/s})(0.4\ \text{m}^2) = 78.8\ \text{kg/s}$$

Since the flow is steady, the mass flow rate through the entire diffuser remains constant at this value.

(*b*) Under stated assumptions and observations, the energy balance for this steady-flow system can be expressed in the rate form as

$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{\text{system}}/dt}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} = 0 \quad (\text{steady})$$

$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

$$\dot{m}\left(h_1 + \frac{V_1^2}{2}\right) = \dot{m}\left(h_2 + \frac{V_2^2}{2}\right) \quad (\text{since } \dot{Q} \cong 0,\ \dot{W} = 0, \text{ and } \Delta pe \cong 0)$$

$$h_2 = h_1 - \frac{V_2^2 - V_1^2}{2}$$

The exit velocity of a diffuser is usually small compared with the inlet velocity ($V_2 << V_1$); thus, the kinetic energy at the exit can be neglected. The enthalpy of air at the diffuser inlet is determined from the air table (Table A–17) to be

$$h_1 = h_{@\,283\,\text{K}} = 283.14\ \text{kJ/kg}$$

Substituting, we get

$$h_2 = 283.14\ \text{kJ/kg} - \frac{0 - (200\ \text{m/s})^2}{2}\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right)$$
$$= 303.14\ \text{kJ/kg}$$

From Table A–17, the temperature corresponding to this enthalpy value is

$$T_2 = 303\ \text{K}$$

EXAMPLE 5–6 Compressing Air by a Compressor

Air at 100 kPa and 280 K is compressed steadily to 600 kPa and 400 K. The mass flow rate of the air is 0.02 kg/s, and a heat loss of 16 kJ/kg occurs during the process. Assuming the changes in kinetic and potential energies are negligible, determine the necessary power input to the compressor.

SOLUTION Air is compressed steadily by a compressor to a specified temperature and pressure. The power input to the compressor is to be determined.

Assumptions **1** This is a steady-flow process since there is no change with time at any point and thus $\Delta m_{\text{CV}} = 0$ and $\Delta E_{\text{CV}} = 0$. **2** Air is an ideal gas since it is at a high temperature and low pressure relative to its critical-point values. **3** The kinetic and potential energy changes are zero, $\Delta ke = \Delta pe = 0$.

Analysis We take the *compressor* as the system (Fig. 5–30). This is a *control volume* since mass crosses the system boundary during the process. We observe that there is only one inlet and one exit and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. Also, heat is lost from the system and work is supplied to the system.

Under stated assumptions and observations, the energy balance for this steady-flow system can be expressed in the rate form as

$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{\text{system}}/dt}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} = 0 \quad (\text{steady})$$

CamScanner الممسوحة ضوئيا بـ

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{W}_{in} + \dot{m}h_1 = \dot{Q}_{out} + \dot{m}h_2 \quad (\text{since } \Delta ke = \Delta pe \cong 0)$$

$$\dot{W}_{in} = \dot{m}q_{out} + \dot{m}(h_2 - h_1)$$

The enthalpy of an ideal gas depends on temperature only, and the enthalpies of the air at the specified temperatures are determined from the air table (Table A–17) to be

$$h_1 = h_{@\,280\,K} = 280.13\ \text{kJ/kg}$$

$$h_2 = h_{@\,400\,K} = 400.98\ \text{kJ/kg}$$

Substituting, the power input to the compressor is determined to be

$$\dot{W}_{in} = (0.02\ \text{kg/s})(16\ \text{kJ/kg}) + (0.02\ \text{kg/s})(400.98 - 280.13)\ \text{kJ/kg}$$

$$= 2.74\ \text{kW}$$

Discussion Note that the mechanical energy input to the compressor manifests itself as a rise in enthalpy of air and heat loss from the compressor.

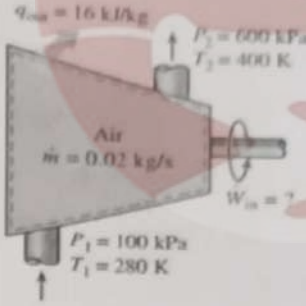


FIGURE 5–30
Schematic for Example 5–6.

EXAMPLE 5–7 Power Generation by a Steam Turbine

The power output of an adiabatic steam turbine is 5 MW, and the inlet and the exit conditions of the steam are as indicated in Fig. 5–31.

(a) Compare the magnitudes of Δh, Δke, and Δpe.
(b) Determine the work done per unit mass of the steam flowing through the turbine.
(c) Calculate the mass flow rate of the steam.

SOLUTION The inlet and exit conditions of a steam turbine and its power output are given. The changes in kinetic energy, potential energy, and enthalpy of steam, as well as the work done per unit mass and the mass flow rate of steam are to be determined.

Assumptions 1 This is a steady-flow process since there is no change with time at any point and thus $\Delta m_{CV} = 0$ and $\Delta E_{CV} = 0$. 2 The system is adiabatic and thus there is no heat transfer.

Analysis We take the *turbine* as the system. This is a *control volume* since mass crosses the system boundary during the process. We observe that there is only one inlet and one exit and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. Also, work is done by the system. The inlet and exit velocities and elevations are given, and thus the kinetic and potential energies are to be considered.

(a) At the inlet, steam is in a superheated vapor state, and its enthalpy is

$$\left.\begin{matrix} P_1 = 2\ \text{MPa} \\ T_1 = 400°\text{C} \end{matrix}\right\} \quad h_1 = 3248.4\ \text{kJ/kg} \quad \text{(Table A–6)}$$

At the turbine exit, we obviously have a saturated liquid–vapor mixture at 15-kPa pressure. The enthalpy at this state is

$$h_2 = h_f + x_2 h_{fg} = [225.94 + (0.9)(2372.3)]\ \text{kJ/kg} = 2361.01\ \text{kJ/kg}$$

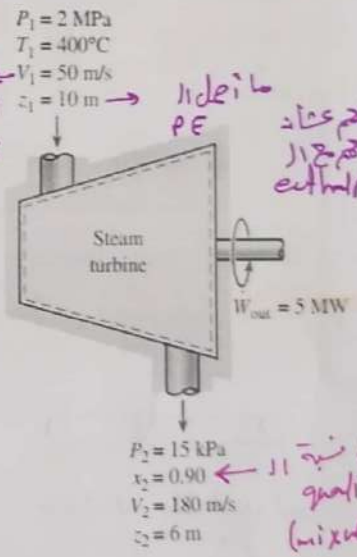


FIGURE 5–31
Schematic for Example 5–7.

Then

$$\Delta h = h_2 - h_1 = (2361.01 - 3248.4)\ \text{kJ/kg} = -887.39\ \text{kJ/kg}$$

$$\Delta ke = \frac{V_2^2 - V_1^2}{2} = \frac{(180\ \text{m/s})^2 - (50\ \text{m/s})^2}{2}\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = 14.95\ \text{kJ/kg}$$

$$\Delta pe = g(z_2 - z_1) = (9.81\ \text{m/s}^2)[(6 - 10)\ \text{m}]\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = -0.04\ \text{kJ/kg}$$

→ negligible

(b) The energy balance for this steady-flow system can be expressed in the rate form as

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt}_{\text{Rate of change in internal, kinetic, potential, etc. energies}} \overset{\text{0 (steady)}}{= 0}$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}\left(h_1 + \frac{V_1^2}{2} + gz_1\right) = \dot{W}_{out} + \dot{m}\left(h_2 + \frac{V_2^2}{2} + gz_2\right) \quad (\text{since } \dot{Q} = 0)$$

Dividing by the mass flow rate $\dot{m}$ and substituting, the work done by the turbine per unit mass of the steam is determined to be

$$w_{out} = -\left[(h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right] = -(\Delta h + \Delta ke + \Delta pe)$$

$$= -[-887.39 + 14.95 - 0.04]\ \text{kJ/kg} = 872.48\ \text{kJ/kg}$$

← قيمنا كل mass وإذا بدنا إياه per unit mass :

(c) The required mass flow rate for a 5-MW power output is

$$\dot{m} = \frac{\dot{W}_{out}}{w_{out}} = \frac{5000\ \text{kJ/s}}{872.48\ \text{kJ/kg}} = 5.73\ \text{kg/s}$$

هيك إذا بدنا نحدد الـ conditions كل مرحلة بالتفصيل وبنظمية

EXAMPLE 5–8 **Expansion of Refrigerant-134a in a Refrigerator**

Refrigerant-134a enters the capillary tube of a refrigerator as saturated liquid at 0.8 MPa and is throttled to a pressure of 0.12 MPa. Determine the quality of the refrigerant at the final state and the temperature drop during this process.

Throttling device (أنبوب رفيع)

saturated liquid

$u_1 = 94.79$, $P_1v_1 = 0.63$, $h_1 = 95.47$ — $u_2 = 88.74$, $P_2v_2 = (1.8)$, $h_2 = 95.47$

T(C) — v — v_f

واضح من الرسمة إنه الـ volume بزيد

SOLUTION Refrigerant-134a that enters a capillary tube as saturated liquid is throttled to a specified pressure. The exit quality of the refrigerant and the temperature drop are to be determined.

Assumptions 1 Heat transfer from the tube is negligible. 2 Kinetic energy change of the refrigerant is negligible.

Analysis A capillary tube is a simple flow-restricting device that is commonly used in refrigeration applications to cause a large pressure drop in the refrigerant. Flow through a capillary tube is a throttling process; thus, the enthalpy of the refrigerant remains constant (Fig. 5–34).



adjustable valve

$$\text{At inlet: } \left.\begin{matrix} P_1 = 0.8\ \text{MPa} \\ \text{sat. liquid} \end{matrix}\right\} \begin{matrix} T_1 = T_{\text{sat @ 0.8 MPa}} = 31.31°\text{C} \\ h_1 = h_{f\,@\,0.8\,\text{MPa}} = 95.48\ \text{kJ/kg} \end{matrix} \quad \text{(Table A–12)}$$

$$\text{At exit: } \begin{matrix} P_2 = 0.12\ \text{MPa} \\ (h_2 = h_1) \end{matrix} \longrightarrow \begin{matrix} h_f = 22.47\ \text{kJ/kg} \\ h_g = 236.99\ \text{kJ/kg} \end{matrix} \quad T_{sat} = -22.32°\text{C}$$

for Ref

Obviously $h_f < h_2 < h_g$; thus, the refrigerant exists as a saturated mixture at the exit state. The quality at this state is

$$x_2 = \frac{h_2 - h_f}{h_{fg}} = \frac{95.48 - 22.47}{236.99 - 22.47} = 0.340$$

→ h_f on 95 c

Since the exit state is a saturated mixture at 0.12 MPa, the exit temperature must be the saturation temperature at this pressure, which is −22.32°C. Then the temperature change for this process becomes

$$\text{drop in temp} \rightarrow \Delta T = T_2 - T_1 = (-22.32 - 31.31)°\text{C} = -53.63°\text{C}$$

Discussion Note that the temperature of the refrigerant drops by 53.63°C during this throttling process. Also note that 34.0 percent of the refrigerant vaporizes during this throttling process, and the energy needed to vaporize this refrigerant is absorbed from the refrigerant itself.

ماذا زاد الـ pv نقل الـ u
وإذا قل الـ pv زاد الـ u

pv زاد بسبب الـ u يعني إذا زاد الـ pv ← بقل الـ u وال throttling!

ask recieve

الممسوحة ضوئيا بـ CamScanner

Cooling of Refrigerant-134a by Water

EXAMPLE 5–10

Refrigerant-134a is to be cooled by water in a condenser. The refrigerant enters the condenser with a mass flow rate of 6 kg/min at 1 MPa and 70°C and leaves at 25°C. The cooling water enters at 300 kPa and 15°C and leaves at 25°C. Neglecting any pressure drops, determine (*a*) the mass flow rate of the cooling water required and (*b*) the heat transfer rate from the refrigerant to water.

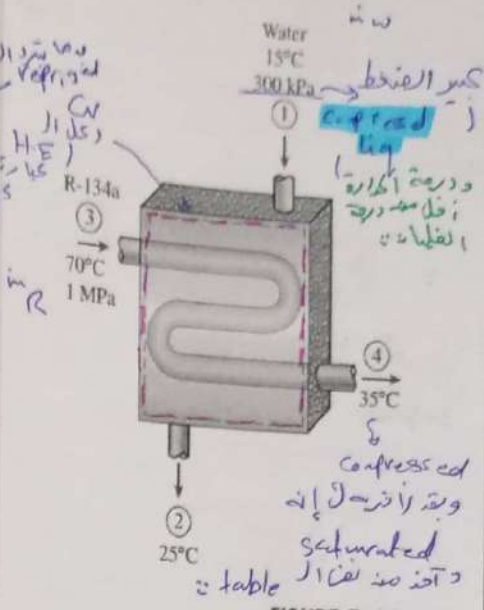


FIGURE 5–40
Schematic for Example 5–10.

SOLUTION Refrigerant-134a is cooled by water in a condenser. The mass flow rate of the cooling water and the rate of heat transfer from the refrigerant to the water are to be determined.

Assumptions 1 This is a steady-flow process since there is no change with time at any point and thus $\Delta m_{cv} = 0$ and $\Delta E_{cv} = 0$. 2 The kinetic and potential energies are negligible, $ke \cong pe \cong 0$. 3 Heat losses from the system are negligible and thus $\dot{Q} \cong 0$. 4 There is no work interaction.

Analysis We take the *entire heat exchanger* as the system (Fig. 5–40). This is a control volume since mass crosses the system boundary during the process. In general, there are several possibilities for selecting the control volume for multiple-stream steady-flow devices, and the proper choice depends on the situation at hand. We observe that there are two fluid streams (and thus two inlets and two exits) but no mixing.

(*a*) Under the stated assumptions and observations, the mass and energy balances for this steady-flow system can be expressed in the rate form as follows:

Mass balance:

$$\dot{m}_{in} = \dot{m}_{out}$$

for each fluid stream since there is no mixing. Thus,

$$\dot{m}_1 = \dot{m}_2 = \dot{m}_w$$

$$\dot{m}_3 = \dot{m}_4 = \dot{m}_R$$

Energy balance:

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} \overset{0 \text{ (steady)}}{} = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}_1 h_1 + \dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_4 h_4 \quad (\text{since } \dot{Q} \cong 0,\ \dot{W} = 0,\ ke \cong pe \cong 0)$$

Combining the mass and energy balances and rearranging give

$$\dot{m}_w(h_1 - h_2) = \dot{m}_R(h_4 - h_3)$$

Now we need to determine the enthalpies at all four states. Water exists as a compressed liquid at both the inlet and the exit since the temperatures at both locations are below the saturation temperature of water at 300 kPa (133.52°C). Approximating the compressed liquid as a saturated liquid at the given temperatures, we have

$$h_1 \cong h_{f@15°C} = 62.982 \text{ kJ/kg} \quad \text{(Table A–4)}$$

$$h_2 \cong h_{f@25°C} = 104.83 \text{ kJ/kg}$$

CamScanner الممسوحة ضوئيا بـ

The refrigerant enters the condenser as a superheated vapor and leaves as a compressed liquid at 35°C. From refrigerant-134a tables,

$$\left.\begin{matrix} P_3 = 1\ \text{MPa} \\ T_3 = 70°\text{C} \end{matrix}\right\} \quad h_3 = 303.87\ \text{kJ/kg} \quad \text{(Table A–13)}$$

for in. Ref → superheated

$$\left.\begin{matrix} P_4 = 1\ \text{MPa} \\ T_4 = 35°\text{C} \end{matrix}\right\} \quad h_4 \cong h_{f\,@\,35°\text{C}} = 100.88\ \text{kJ/kg} \quad \text{(Table A–11)}$$

for out. Ref → compressed)

Substituting, we find

$$\dot{m}_w(62.982 - 104.83)\ \text{kJ/kg} = (6\ \text{kg/min})[(100.88 - 303.87)\ \text{kJ/kg}]$$

$$\dot{m}_w = 29.1\ \text{kg/min}$$

(b) To determine the heat transfer from the refrigerant to the water, we have to choose a control volume whose boundary lies on the path of heat transfer. We can choose the volume occupied by either fluid as our control volume. For no particular reason, we choose the volume occupied by the water. All the assumptions stated earlier apply, except that the heat transfer is no longer zero. Then assuming heat to be transferred to water, the energy balance for this single-stream steady-flow system reduces to

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} \quad (\text{0 (steady)}) = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{Q}_{w,in} + \dot{m}_w h_1 = \dot{m}_w h_2$$

Rearranging and substituting,

$$\dot{Q}_{w,in} = \dot{m}_w(h_2 - h_1) = (29.1\ \text{kg/min})[(104.83 - 62.982)\ \text{kJ/kg}]$$

$$= 1218\ \text{kJ/min}$$

EXAMPLE 5–12 Charging of a Rigid Tank by Steam

A rigid, insulated tank that is initially evacuated is connected through a valve to a supply line that carries steam at 1 MPa and 300°C. Now the valve is opened, and steam is allowed to flow slowly into the tank until the pressure reaches 1 MPa, at which point the valve is closed. Determine the final temperature of the steam in the tank.

SOLUTION A valve connecting an initially evacuated tank to a steam line is opened, and steam flows in until the pressure inside rises to the line level. The final temperature in the tank is to be determined.

Assumptions **1** This process can be analyzed as a *uniform-flow process* since the properties of the steam entering the control volume remain constant during the entire process. **2** The kinetic and potential energies of the streams are negligible, ke ≅ pe ≅ 0. **3** The tank is stationary and thus its kinetic and potential energy changes are zero; that is, $\Delta KE = \Delta PE = 0$ and $\Delta E_{system} = \Delta U_{system}$. **4** There are no boundary, electrical, or shaft work interactions involved. **5** The tank is well insulated and thus there is no heat transfer.

Analysis We take the *tank* as the system (Fig. 5–50). This is a *control volume* since mass crosses the system boundary during the process. We observe that this is an unsteady-flow process since changes occur within the control volume. The control volume is initially evacuated and thus $m_1 = 0$ and $m_1 u_1 = 0$. Also, there is one inlet and no exits for mass flow.

Noting that microscopic energies of flowing and nonflowing fluids are represented by enthalpy h and internal energy u, respectively, the mass and energy balances for this uniform-flow system can be expres

CamScanner الممسوحة ضوئيا بـ

Inlet

Mass balance:

$$m_{in} - m_{out} = \Delta m_{system} \rightarrow m_i = m_2 - m_1 = m_2$$

Energy balance:

$$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic, potential, etc., energies}}$$

$$m_i h_i = m_2 u_2 \quad (\text{since } W = Q = 0,\ ke \cong pe \cong 0,\ m_1 = 0)$$

Combining the mass and energy balances gives

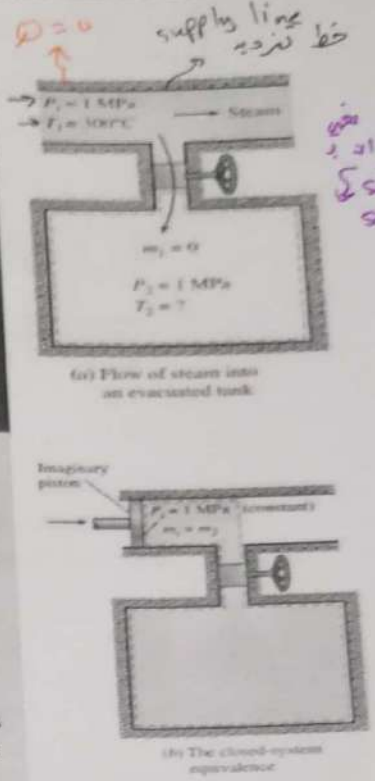
$$u_2 = h_i$$

That is, the final internal energy of the steam in the tank is equal to the enthalpy of the steam entering the tank. The enthalpy of the steam at the inlet state is

$$\left.\begin{matrix} P_i = 1\ \text{MPa} \\ T_i = 300°\text{C} \end{matrix}\right\} \quad h_i = 3051.6\ \text{kJ/kg} \quad \text{(Table A–6)}$$

which is equal to u_2. Since we now know two properties at the final state, it is fixed and the temperature at this state is determined from the same table to be

$$\left.\begin{matrix} P_2 = 1\ \text{MPa} \\ u_2 = 3051.6\ \text{kJ/kg} \end{matrix}\right\} \quad T_2 = 456.1°\text{C}$$



(a) Flow of steam into an evacuated tank

(b) The closed-system equivalence

33

E_2

$u_2 = h_i$ * إذا كانت الـ inlet أو $m_2 = h_i$



Chapter 6

THE SECOND LAW OF THERMODYNAMICS

Thermodynamics: An Engineering Approach
Yunus A. Cengel, Michael A. Boles, Mehmet Kanoglu
McGraw-Hill

$\frac{Q_H}{Q_L} < \frac{T_H}{T_H}$ (in Kelvin)

Dr. Ahmad M. AbuYaghi
October 2023

ال second law بتحكم في اتجاه الطاقة الحرارية

INTRODUCTION TO THE SECOND LAW

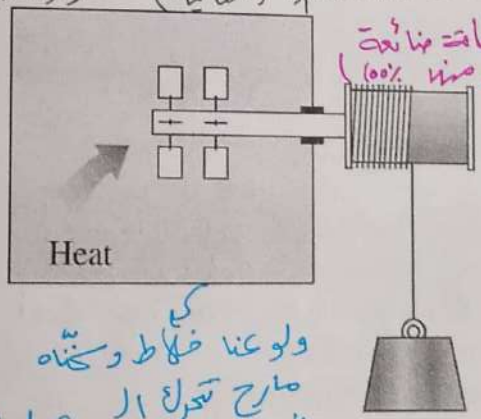
بحدد اتجاه انتقال الطاقة ← بتحكم في الطاقة من حيث الكمية والنوعية

ال direction (quality)

another process الطاقة spontaneous (تلقائية) من الحرارة العالية للأقل و من الأقل لا يحدث

A cup of hot coffee does not get hotter in a cooler room.





→ Transferring heat to a paddle wheel will not cause it to rotate.

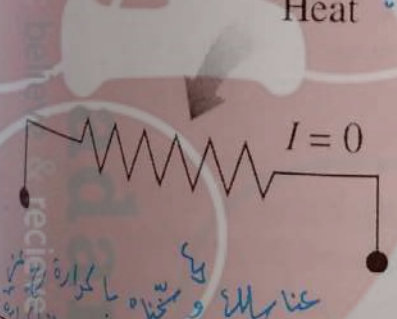
في تعريف طاقة ضائعة (مستحيل أستفيد منها 100%) ← dissipated energy

ولو عنا خلاط وسخناه صار تتحرك ال blades وما تحولت لشغل

طيب كيف صار حيل؟ زي السيارة الحرارة سببت انفجار وحركتها

طيب كيف صار حيل؟ ← نتيجة وجود ال cycles

وأكيد من كل الحرارة تحولت لشغل، في ضائعة



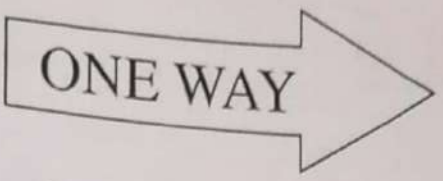
Transferring heat to a wire will not generate electricity.

These processes cannot occur even though they are not in violation of the first law.

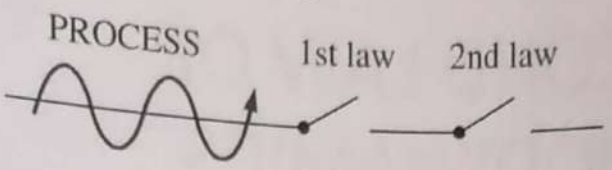
عنا هالخلاط وسخناه بالحرارة صار يتحرك! لازم يكون في شغل

أي برو سيس بتقدر تطبق عليه ال first law

CamScanner الممسوحة ضوئيا بـ



Processes occur in a certain direction, and not in the reverse direction.

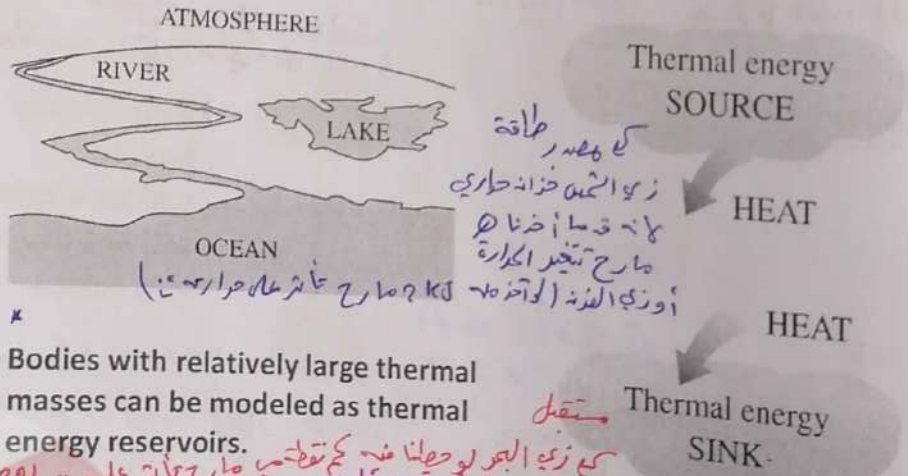


A process must satisfy both the first and second laws of thermodynamics to proceed.

MAJOR USES OF THE SECOND LAW

1) The second law may be used to identify the direction of processes.
2) The second law also asserts that energy has *quality* as well as quanti
The first law is concerned with the quantity of energy and the transformations of energy from one form to another with no regard to
quality. The second law provides the necessary means to determine t
quality as well as the degree of degradation of energy during a proces
3) The second law of thermodynamics is also used in determining the *theoretical limits* for the performance of commonly used engineering systems, such as heat engines and refrigerators, as well as predicting *degree of completion* of chemical reactions.

THERMAL ENERGY RESERVOIRS



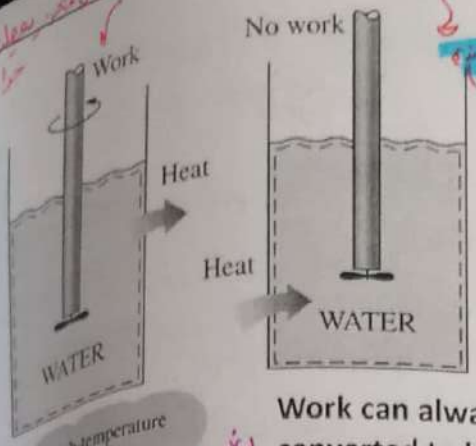
A source supp
energy in the
form of heat,
a sink absorbs

Bodies with relatively large thermal masses can be modeled as thermal energy reservoirs.

- A hypothetical body with a relatively large *thermal energy capacity* (mass specific heat) that can supply or absorb finite amounts of heat without undergoing any change in temperature is called a thermal energy reservoir, or just a reservoir.
- In practice, large bodies of water such as oceans, lakes, and rivers as wel as the atmospheric air can be modeled accurately as thermal energy reservoirs because of their large thermal energy storage capabilities or thermal masses.

CamScanner الممسوحة ضوئيا بـ

HEAT ENGINES

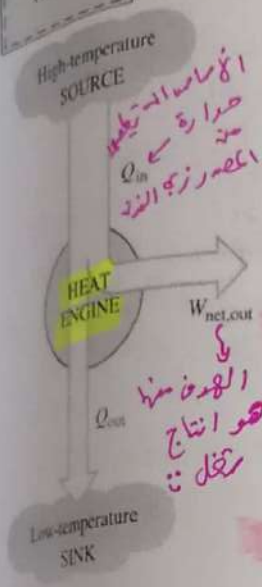


The devices that convert heat to work.

1) They receive heat from a high-temperature source (solar energy, oil furnace, nuclear reactor, etc.).
2) They convert part of this heat to work (usually in the form of a rotating shaft.)
3) They reject the remaining waste heat to a low-temperature sink (the atmosphere, rivers, etc.).
4) They operate on a cycle.

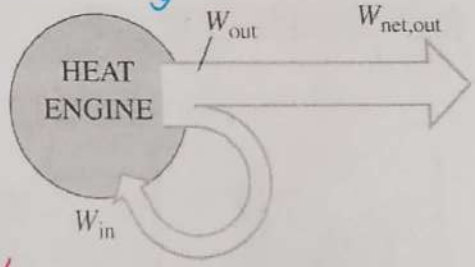
Heat engines and other cyclic devices usually involve a fluid to and from which heat is transferred while undergoing a cycle. This fluid is called the **working fluid**.

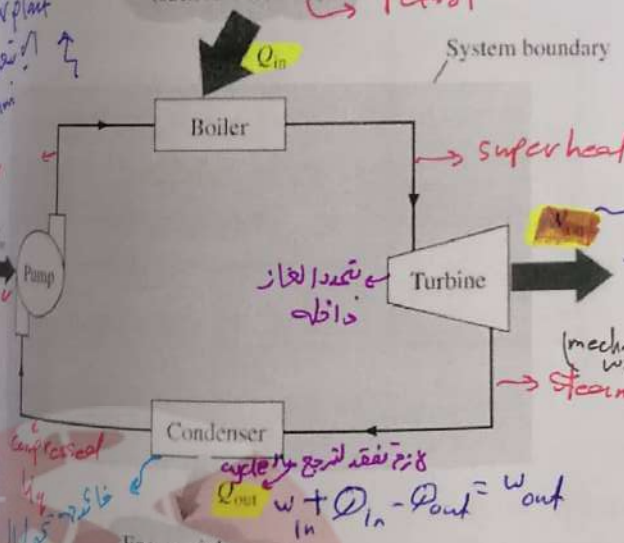
Work can always be converted to heat directly and completely, but the reverse is not true.



Part of the heat received by a heat engine is converted to work, while the rest is rejected to a sink.

A steam power plant





A portion of the work output of a heat engine is consumed internally to maintain continuous operation.

$$W_{net,out} = W_{out} - W_{in} \quad \text{(kJ)}$$

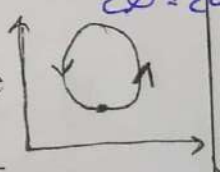
$$W_{net,out} = Q_{in} - Q_{out} \quad \text{(kJ)}$$

Q_{in} = amount of heat supplied to steam in boiler from a high-temperature source (furnace)

Q_{out} = amount of heat rejected from steam in condenser to a low-temperature sink (the atmosphere, a river, etc.)

W_{out} = amount of work delivered by steam as it expands in turbine

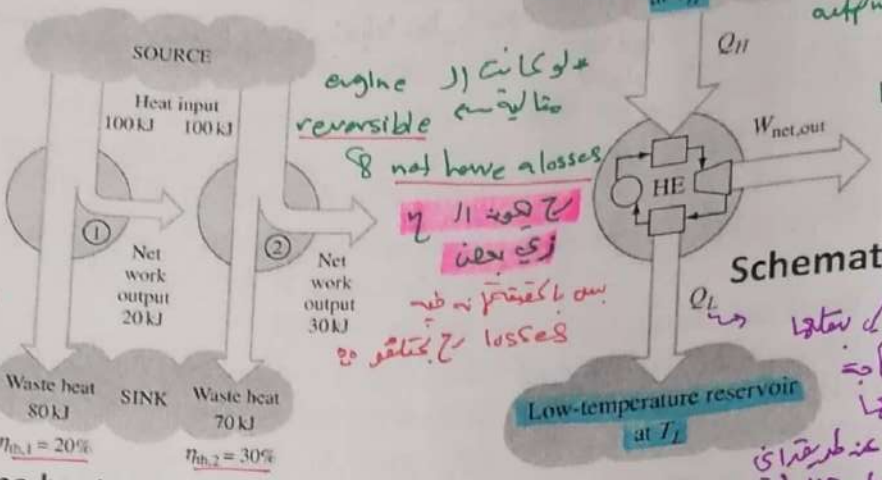
W_{in} = amount of work required to compress water to boiler pressure



$$\eta = \frac{W_{net,out}}{Q_{in}}$$ ← thermal efficiency

CamScanner الممسوحة ضوئيا بـ

Thermal efficiency



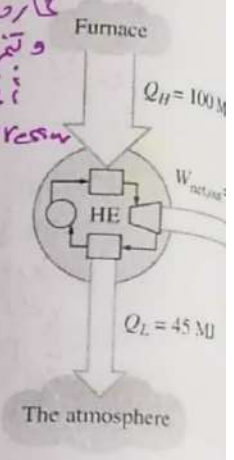
Some heat engines perform better than others (convert more of the heat they receive to work).

$$\text{Thermal efficiency} = \frac{\text{Net work output}}{\text{Total heat input}}$$

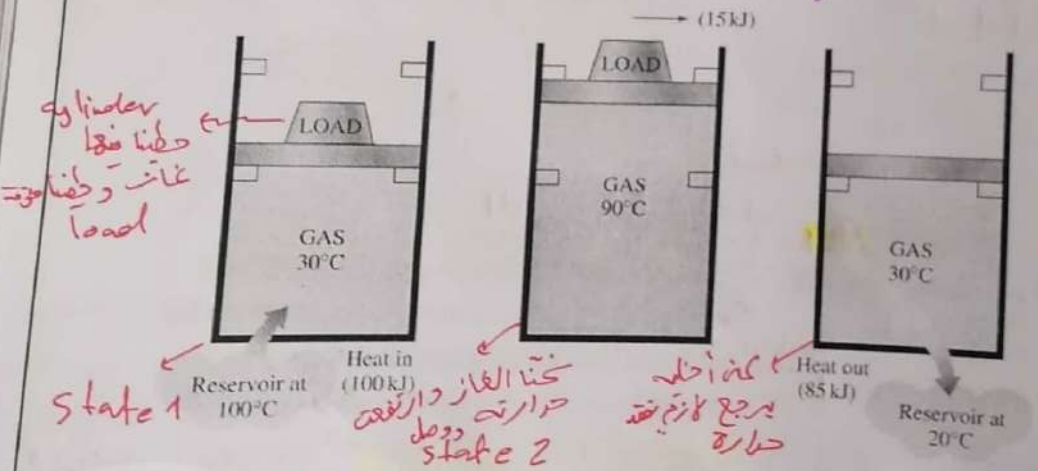
$$\eta_{th} = \frac{W_{net,out}}{Q_{in}} \qquad \eta_{th} = 1 - \frac{Q_{out}}{Q_{in}}$$

$$W_{net,out} = Q_{in} - Q_{out}$$

Even the most efficient heat engines reject almost one-half of the energy they receive as waste heat.



Can we save Q_{out}?



A heat-engine cycle cannot be completed without rejecting some heat to a low-temperature sink.

- Every heat engine must *waste* some energy by transferring it to a low-temperature reservoir in order to complete the cycle, even under idealized conditions.

- In a steam power pl... the condenser is the device where large quantities of waste ... is rejected to rivers, lakes, or the atmosphere.
- Can we not just take condenser out of the plant and save all th... waste energy?
- The answer is, unfortunately, a firm ... for the simple reason that without a heat rejection process in the condenser, the cycle cannot be completed.

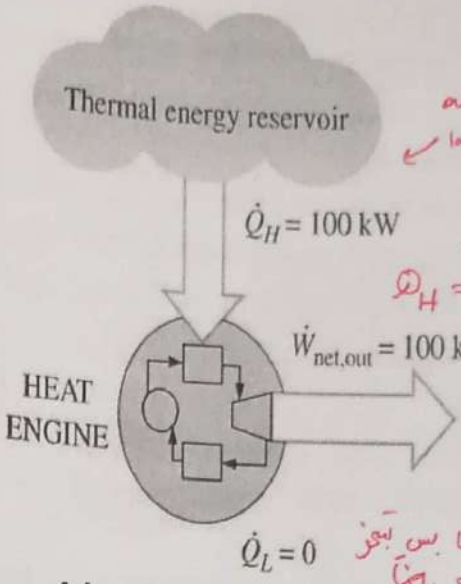
CamScanner الممسوحة ضوئيا بـ

The Second Law of Thermodynamics: Kelvin–Planck Statement

It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work.

- *No heat engine can have a thermal efficiency of 100 percent, or as for a power plant to operate, the working fluid must exchange heat with the environment as well as the furnace.*
- **The impossibility of having a 100% efficient heat engine is not due to friction or other dissipative effects.**

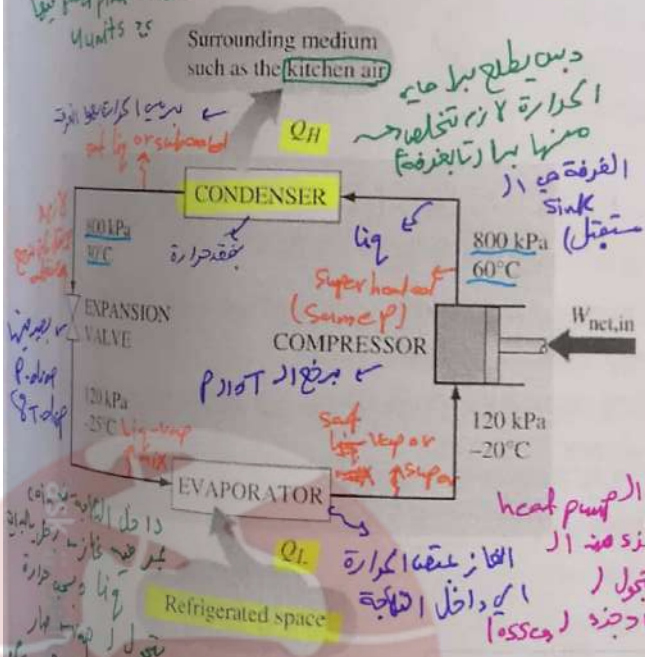
It is a limitation that applies to both the idealized and the actual heat engines.



A heat engine that violates the Kelvin–Planck statement of the second law.

REFRIGERATORS AND HEAT PUMPS

1) The transfer of heat from a low-temperature medium to a high-temperature one requires special devices called **refrigerators**.
2) Refrigerators, like heat engines, are cyclic devices.
3) The working fluid used in the refrigeration cycle is called a **refrigerant**.
4) The most frequently used refrigeration cycle is the *vapor-compression refrigeration cycle*.

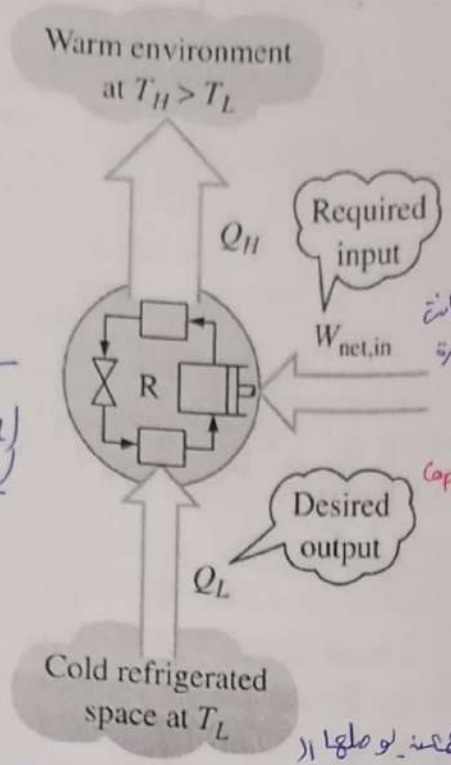


Basic components of a refrigeration system and typical operating conditions.

In a household refrigerator, the freezer compartment where heat is absorbed by the refrigerant serves as the evaporator, and the coils usually behind the refrigerator where heat is dissipated to the kitchen air serve as the condenser.

CamScanner الممسوحة ضوئيا بـ

Coefficient of Performance



The *efficiency* of a refrigerator is expressed in terms of the coefficient of performance (COP).

The objective of a refrigerator is to remove heat (Q_L) from the refrigerated space.

$$COP_R = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_L}{W_{net,in}}$$

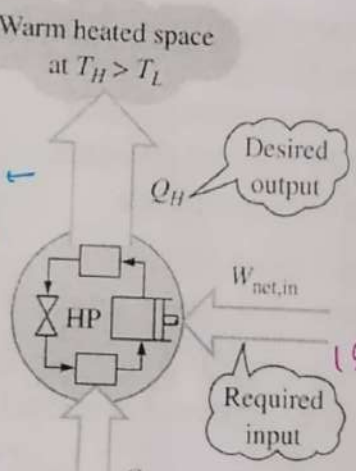
$$W_{net,in} = Q_H - Q_L \quad \text{(kJ)}$$

$$COP_R = \frac{Q_L}{Q_H - Q_L} = \frac{1}{Q_H/Q_L - 1}$$

Can the value of COP_R be greater than unity? Yes

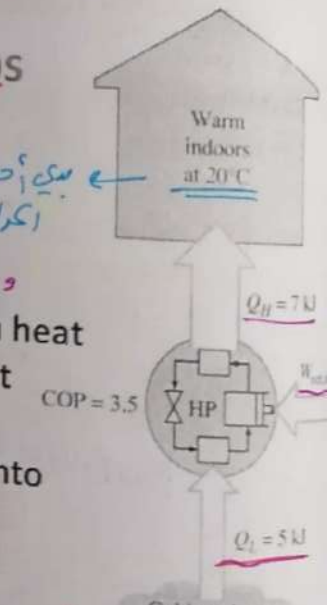
The objective of a refrigerator is to remove Q_L from the cooled space.

Heat Pumps



The objective of a heat pump is to supply heat Q_H into the warmer space.

The work supplied to a heat pump is used to extract energy from the cold outdoors and carry it into the warm indoors.



$$COP_{HP} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_H}{W_{net,in}}$$

$$COP_{HP} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - Q_L/Q_H}$$

$$COP_{HP} = COP_R + 1$$

for fixed values of Q_L and Q_H

Can the value of COP_{HP} be lower than unity?

What does $COP_{HP}=1$ represent?

CamScanner الممسوحة ضوئيا بـ

Heat Pumps

- Most heat pumps in operation today have a seasonally averaged COP of 2 to 3
- Most existing heat pumps use the cold outside air as the heat source in winter (*air-source* HP).
- In cold climates their efficiency drops considerably when temperatures are below the freezing point.
- In such cases, *geothermal* (*ground-source*) HP that use the ground as the heat source can be used.
- Such heat pumps are more expensive to install, but they are also more efficient.
- **Air conditioners** are basically refrigerators whose refrigerated space is a room or a building instead of the food compartment.
- The COP of a refrigerator decreases with decreasing refrigeration temperature.
- Therefore, it is not economical to refrigerate to a lower temperature than needed.

When installed backward, an air conditioner functions as a heat pump.

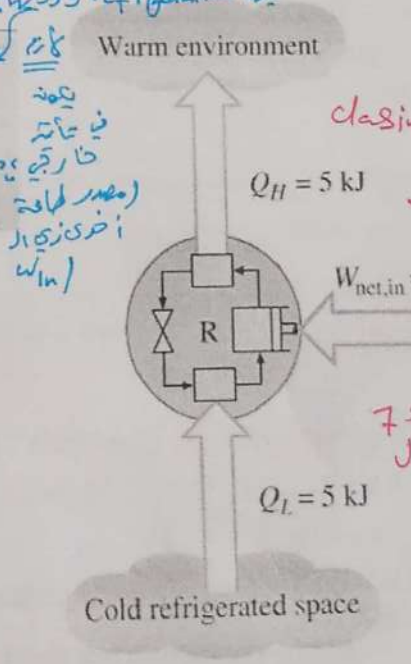
$$EER = 3.412\ COP_R$$

Energy efficiency rating (EER): The amount of heat removed from the cooled space in Btu's for 1 Wh (watthour) of electricity consumed.

The Second Law of Thermodynamics: Clasius Statement

It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower-temperature body to a higher-temperature body.

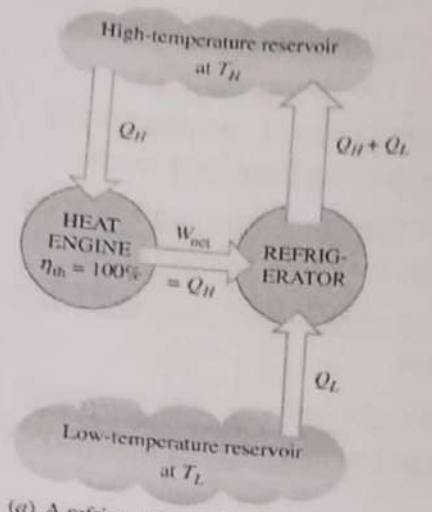
- *It states that a refrigerator cannot operate unless its compressor is driven by an external power source, such as an electric motor.*
- This way, the net effect on the surroundings involves the consumption of some energy in the form of work, in addition to the transfer of heat from a colder body to a warmer one.
- To date, no experiment has been conducted that contradicts the second law, and this should be taken as sufficient proof of its validity.



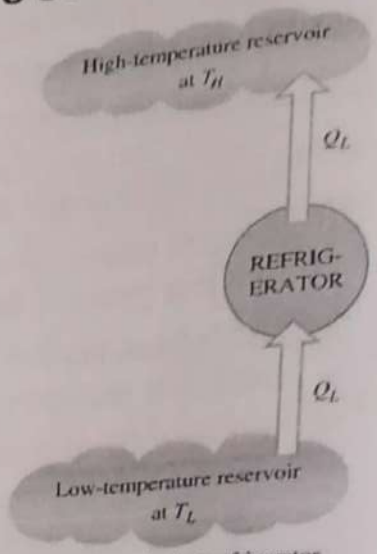
A refrigerator that violates the Clausius statement of the second law.

CamScanner الممسوحة ضوئيا بـ

Equivalence of the Two Statements



(a) A refrigerator that is powered by a 100 percent efficient heat engine



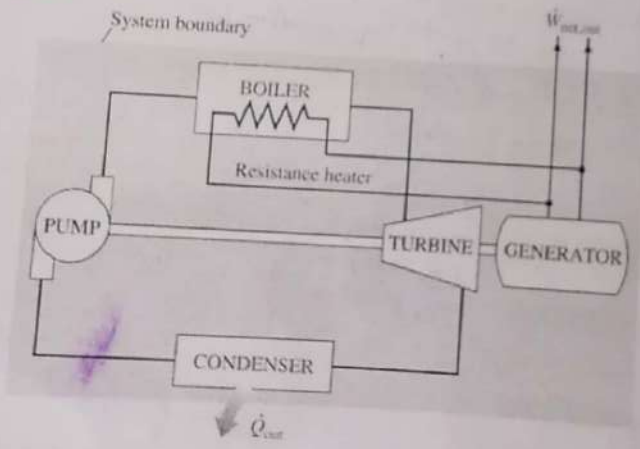
(b) The equivalent refrigerator

Proof that a violation of the Kelvin–Planck statement leads to the violation of the Clausius statement.

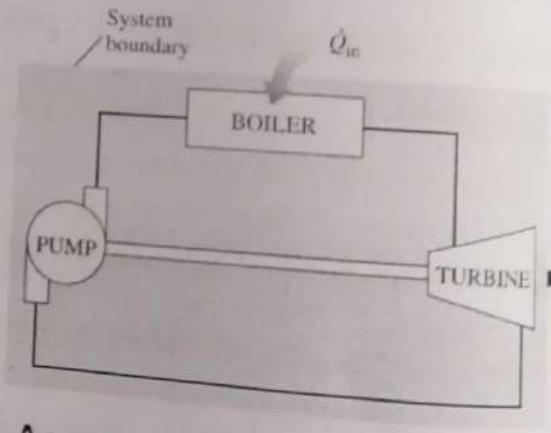
- The Kelvin–Planck and the Clausius statements are equivalent in their consequences, and either statement can be used as the expression of the second law of thermodynamics.
- Any device that violates the Kelvin–Planck statement also violates the Clausius statement, and vice versa.

reversible عكسية work الشغل

PERPETUAL-MOTION MACHINES (PPM)



A perpetual-motion machine that violates the first law (PMM1).



A perpetual-motion machine that violates the second law of thermodynamics (PMM2).

- Perpetual-motion machine: Any device that violates the first or the second
- A device that violates the first law (by *creating* energy) is called a PMM1.
- A device that violates the second law is called a PMM2.
- Despite numerous attempts, no perpetual-motion machine is known to have worked. ***If something sounds too good to be true, it probably is.***

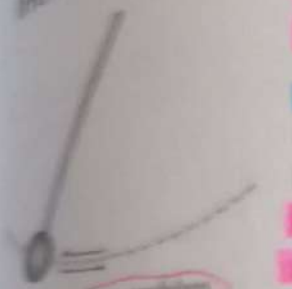
CamScanner الممسوحة ضوئيا بـ

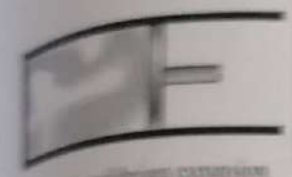
REVERSIBLE AND IRREVERSIBLE PROCESSES

Reversible process: A process that can be reversed without leaving any trace on the surroundings.

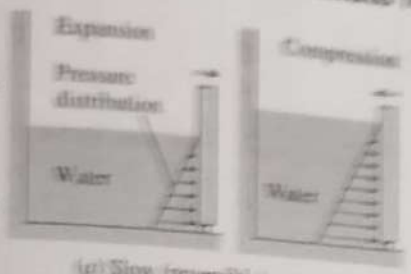
Irreversible process: A process that is not reversible (Will leave traces).

- All the processes occurring in nature are irreversible.
- Why are we interested in reversible processes? (1) they are easy to analyze and (2) they serve as idealized models (theoretical limits) to which actual processes can be compared.
- Some processes are more irreversible than others.
- We try to approximate reversible processes. Why?

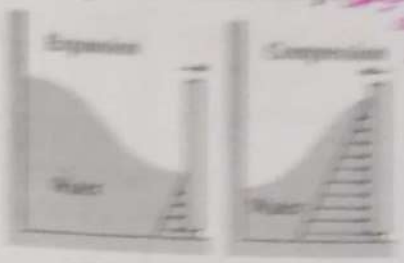




Two familiar reversible processes.

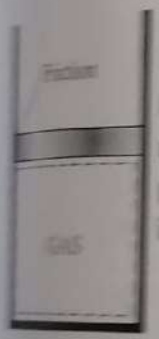


(a) Slow (reversible) process



(b) Fast (irreversible) process

Reversible processes deliver the most and consume the least work.



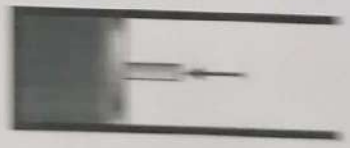
Friction renders a process irreversible.

- The factors that cause a process to be irreversible are called irreversibilities.
- They include friction, unrestrained expansion, mixing of two fluids, heat transfer across a finite temperature difference, electric resistance, inelastic deformation of solids, and chemical reactions.
- The presence of any of these effects renders a process irreversible.

Irreversibilities

(a) Heat transfer through a temperature difference is irreversible,

(b) The reverse process is impossible.



(a) Fast compression



(b) Fast expansion



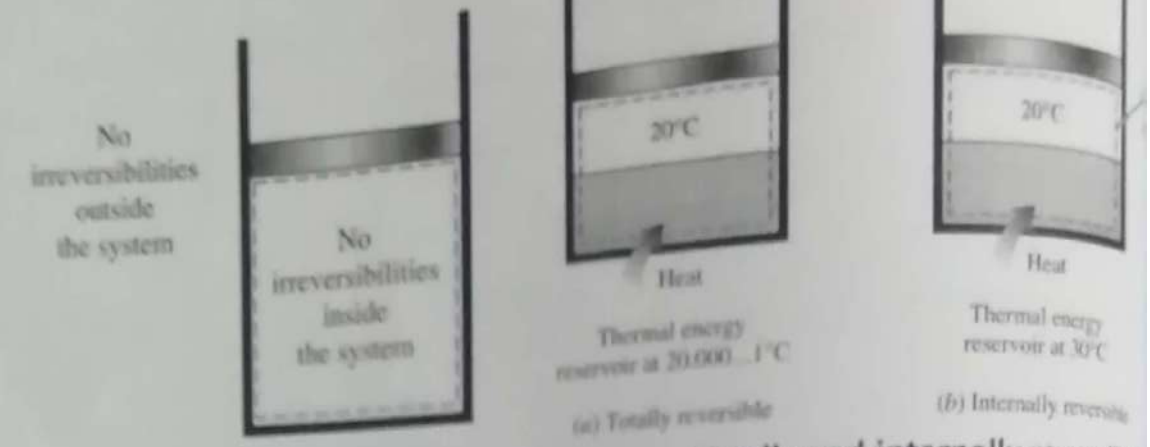
(c) Unrestrained expansion

Irreversible compression and expansion processes.

CamScanner الممسوحة ضوئيا بـ

Internally and Externally

- Internally reversible process: If no irreversibl... the system during the process.
- Externally reversible: If no irreversibilities occur outside the system boundar...
- Totally reversible process: It involves no irreversibilities within the system ... surroundings.
- A totally reversible process involves no heat transfer through a finite tempera... difference, no nonquasi-equilibrium changes, and no friction or other dissipa... effects.

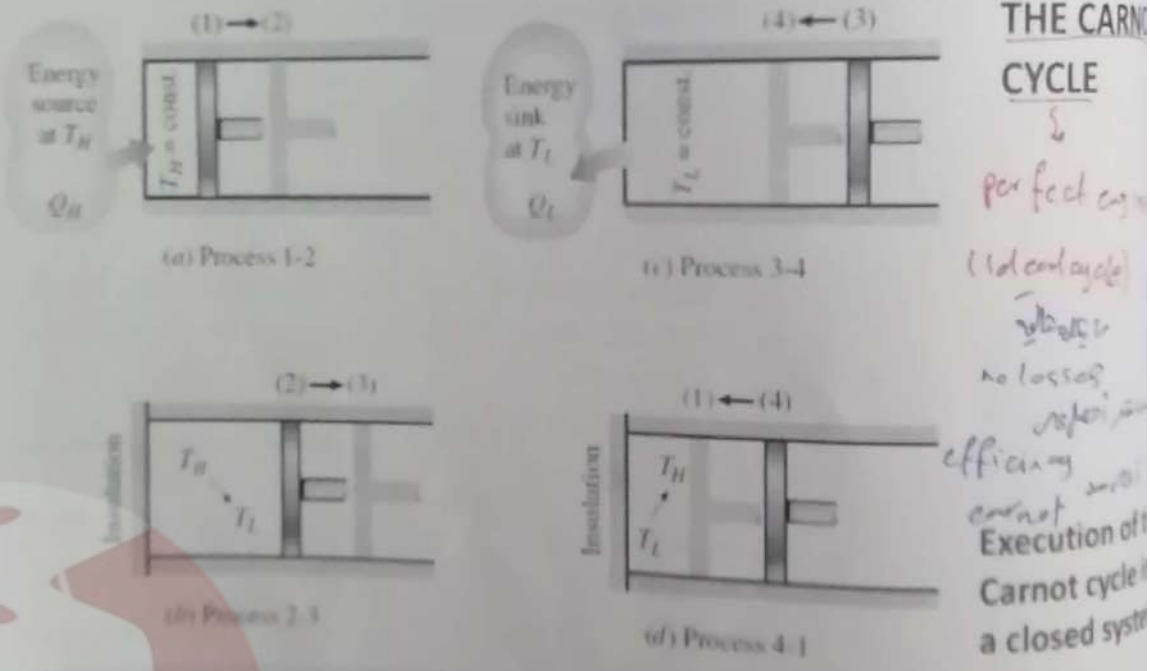


A reversible process involves no internal and external irreversibilities.

Totally and internally reversible heat transfer processes.

THE CARNOT CYCLE

perfect engine (ideal cycle) بدون خسائر no losses أعلى كفاءة efficiency ممكنة carnot



Execution of the Carnot cycle in a closed system

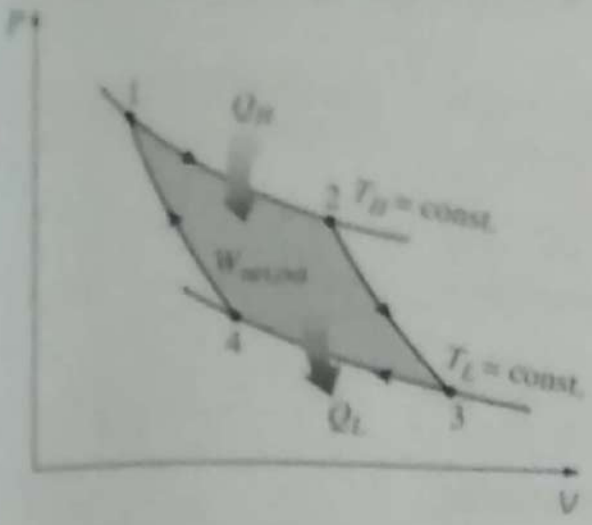
Reversible Isothermal Expansion (process 1-2, T_H = constant)

Reversible Adiabatic Expansion (process 2-3, temperature drops from T_H to

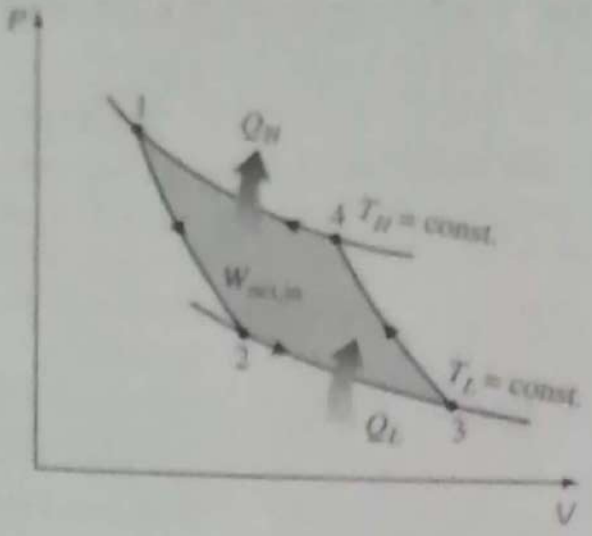
Reversible Isothermal Compression (process 3-4, T_L = constant)

Reversible Adiabatic Compression (process 4-1, temperature rises from T_L t

ask & recieve
الممسوحة ضوئيا بـ CamScanner



P-V diagram of the Carnot cycle.



P-V diagram of the reversed Carnot cycle.

The Reversed Carnot Cycle

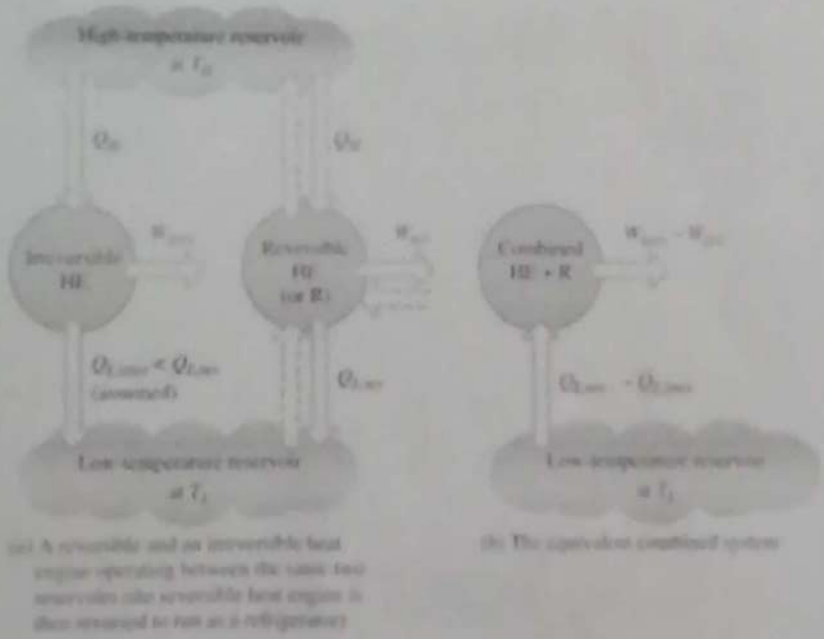
The Carnot heat-engine cycle is a totally reversible cycle.

Therefore, all the processes that comprise it can be *reversed*, in which case it becomes the **Carnot refrigeration cycle**.

THE CARNOT PRINCIPLES



The Carnot principles.



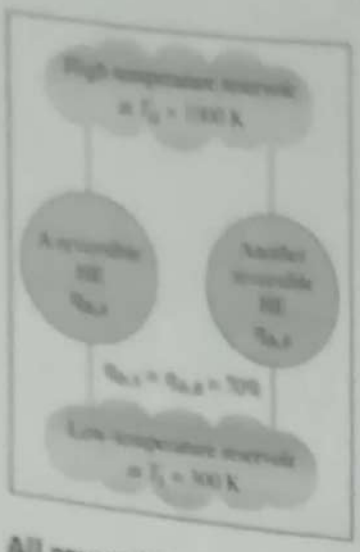
Proof of the first Carnot principle.

The efficiency of an irreversible heat engine is always less than the efficiency of a reversible one operating between the same two reservoirs.

The efficiencies of all reversible heat engines operating between the same two reservoirs are the same.

CamScanner الممسوحة ضوئيا بـ

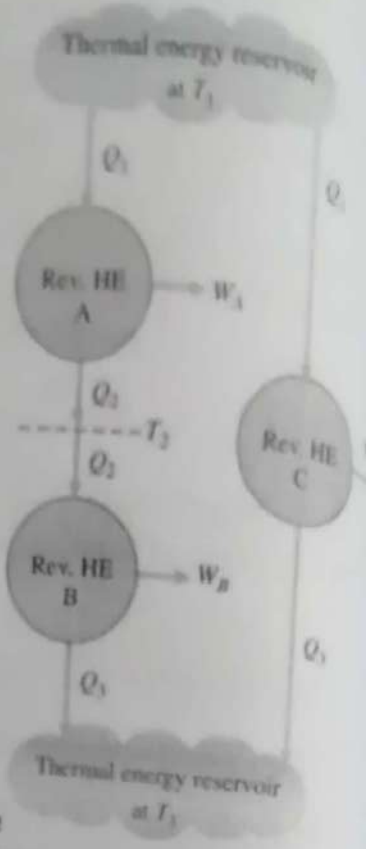
THE THERMODYNAMIC TEMPERATURE SCALE



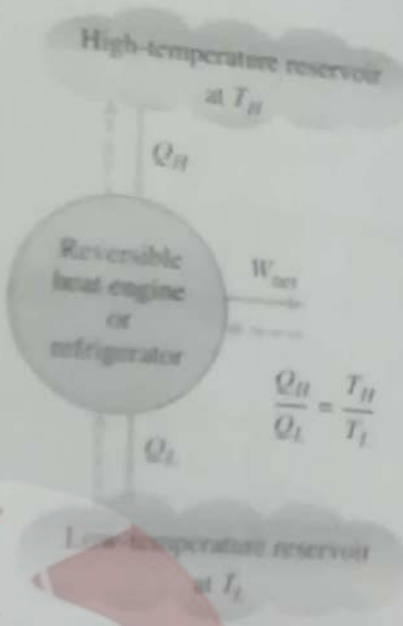
All reversible heat engines operating between the same two reservoirs have the same efficiency.

A temperature scale that is independent of the properties of the substances that are used to measure temperature is called a thermodynamic temperature scale.

Such a temperature scale offers great conveniences in thermodynamic calculations.

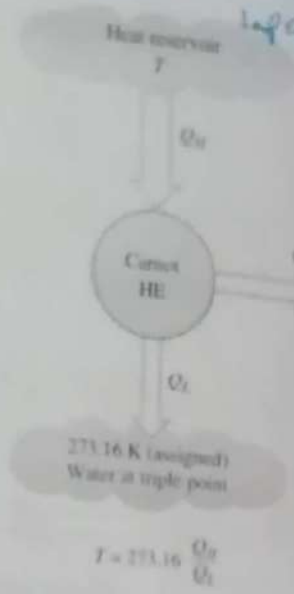


The arrangement of heat engines used to develop the thermodynamic temperature scale.



$$\frac{Q_H}{Q_L} = \frac{T_H}{T_L}$$

For reversible cycles, the heat transfer ratio Q_H/Q_L can be replaced by the absolute temperature ratio T_H/T_L.



A conceptual experimental setup to determine thermodynamic temperatures on the Kelvin scale by measuring heat transfers Q_H and Q_L.

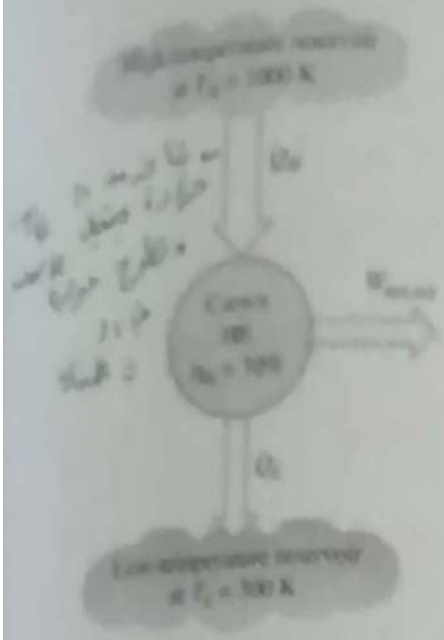
$$\left(\frac{Q_H}{Q_L}\right)_{rev} = \frac{T_H}{T_L}$$

This temperature scale is called the Kelvin scale, and the temperatures on this scale are called absolute temperatures.

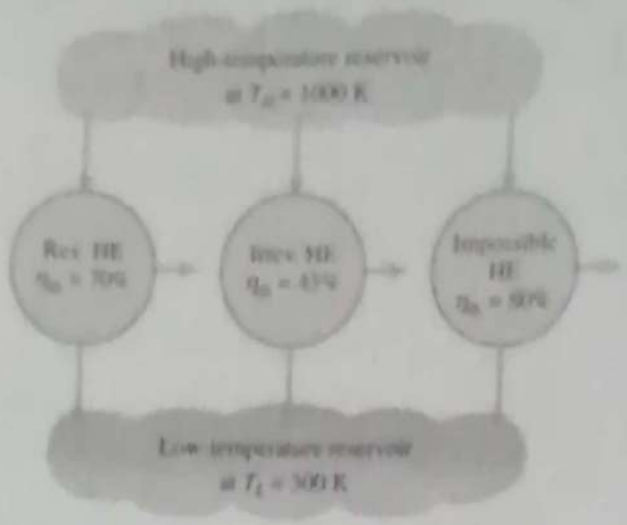
$$T(°C) = T(K) - 273.15$$

CamScanner الممسوحة ضوئيا بـ

THE CARNOT HEAT ENGINE



The Carnot heat engine is the most efficient of all heat engines operating between the same high- and low-temperature reservoirs.



No heat engine can have a higher efficiency than a reversible heat engine operating between the same high- and low-temperature reservoirs.

Any heat engine

$$\eta_{th} = 1 - \frac{Q_L}{Q_H}$$

Carnot heat engine

$$\eta_{th,rev} = 1 - \frac{T_L}{T_H}$$

$$\eta_{th} \begin{cases} < \eta_{th,rev} & \text{irreversible heat engine} \\ = \eta_{th,rev} & \text{reversible heat engine} \\ > \eta_{th,rev} & \text{impossible heat engine} \end{cases}$$

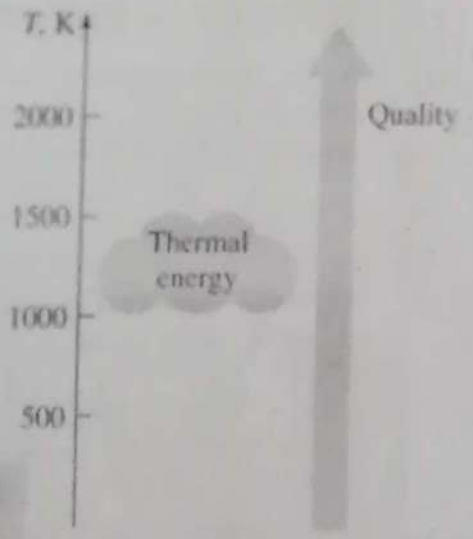
The Quality of Energy



T_H, K	η_{th}, %
925	67.2
800	62.1
700	56.7
500	39.4
350	13.4

$$\eta_{th,rev} = 1 - \frac{T_L}{T_H}$$

Can we use °C unit for temperature here?



The higher the temperature of the thermal energy, the higher its quality.

The fraction of heat that can be converted to work is a function of source temperature.

How do you increase the thermal efficiency of a Carnot heat engine? How about for actual heat engines?

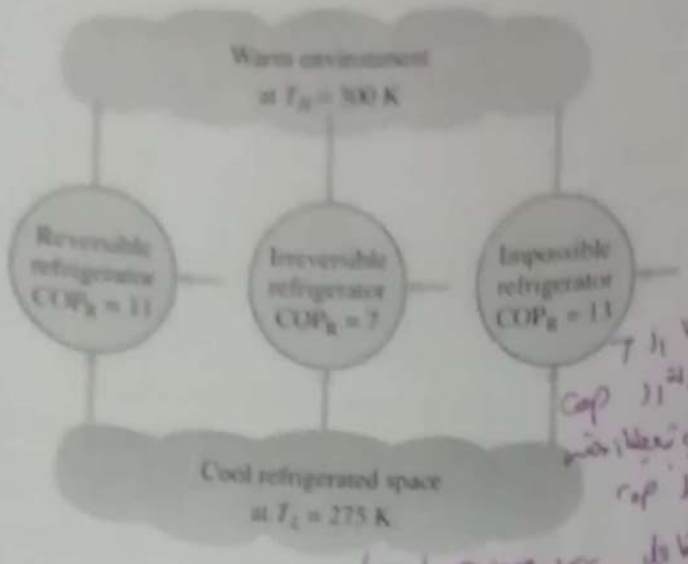
CamScanner الممسوحة ضوئيا بـ

THE CARNOT REFRIGERATOR AND HEAT PUMP

Any refrigerator or heat pump

$$COP_R = \frac{1}{Q_H/Q_L - 1}$$

$$COP_{HP} = \frac{1}{1 - Q_L/Q_H}$$



Carnot refrigerator or heat

$$COP_{HP,rev} = \frac{1}{1 - T_L/T_H}$$

$$COP_{R,rev} = \frac{1}{T_H/T_L - 1}$$

No refrigerator can have a higher COP than a reversible refrigerator operating between the same temperature limits.

How do you increase the COP of a Carnot refrigerator or heat pump? How about for actual ones?

EXAMPLE 6–1 Net Power Production of a Heat Engine

Heat is transferred to a heat engine from a furnace at a rate of 80 MW. If the rate of waste heat rejection to a nearby river is 50 MW, determine the net power output and the thermal efficiency for this heat engine.

SOLUTION The rates of heat transfer to and from a heat engine are given. The net power output and the thermal efficiency are to be determined.

Assumptions Heat losses through the pipes and other components are negligible.

Analysis A schematic of the heat engine is given in Fig. 6–16. The furnace serves as the high-temperature reservoir for this heat engine and the river as the low-temperature reservoir. The given quantities can be expressed as

$$\dot{Q}_H = 80 \text{ MW} \quad \text{and} \quad \dot{Q}_L = 50 \text{ MW}$$

The net power output of this heat engine is

$$\dot{W}_{net,out} = \dot{Q}_H - \dot{Q}_L = (80 - 50) \text{ MW} = 30 \text{ MW}$$

Then the thermal efficiency is easily determined to be

$$\eta_{th} = \frac{\dot{W}_{net,out}}{\dot{Q}_H} = \frac{30 \text{ MW}}{80 \text{ MW}} = 0.375 \text{ (or } 37.5\%\text{)}$$

Discussion Note that the heat engine converts 37.5 percent of the heat it receives to work.

الممسوحة ضوئيا بـ CamScanner

EXAMPLE 6–3 Heat Rejection by a Refrigerator

The food compartment of a refrigerator, shown in Fig. 6–23, is maintained at 4°C by removing heat from it at a rate of 360 kJ/min. If the required power input to the refrigerator is 2 kW, determine (a) the coefficient of performance of the refrigerator and (b) the rate of heat rejection to the room that houses the refrigerator.

SOLUTION The power consumption of a refrigerator is given. The COP and the rate of heat rejection are to be determined.

Assumptions Steady operating conditions exist.

Analysis (a) The coefficient of performance of the refrigerator is

$$\text{COP}_R = \frac{Q_L}{W_{\text{net,in}}} = \frac{360 \text{ kJ/min}}{2 \text{ kW}}\left(\frac{1 \text{ kW}}{60 \text{ kJ/min}}\right) = 3$$

That is, 3 kJ of heat is removed from the refrigerated space for each kJ of work supplied.

(b) The rate at which heat is rejected to the room that houses the refrigerator is determined from the conservation of energy relation for cyclic devices,

$$Q_H = Q_L + W_{\text{net,in}} = 360 \text{ kJ/min} + (2 \text{ kW})\left(\frac{60 \text{ kJ/min}}{1 \text{ kW}}\right) = 480 \text{ kJ/min}$$

Discussion Notice that both the energy removed from the refrigerated space as heat and the energy supplied to the refrigerator as electrical work eventually show up in the room air and become part of the internal energy of the air. This demonstrates that energy can change from one form to another, can move from one place to another, but is never destroyed during a process.

EXAMPLE 6–5 Analysis of a Carnot Heat Engine

A Carnot heat engine, shown in Fig. 6–47, receives 500 kJ of heat per cycle from a high-temperature source at 652°C and rejects heat to a low-temperature sink at 30°C. Determine (a) the thermal efficiency of this Carnot engine and (b) the amount of heat rejected to the sink per cycle.

SOLUTION The heat supplied to a Carnot heat engine is given. The thermal efficiency and the heat rejected are to be determined.

Analysis (a) The Carnot heat engine is a reversible heat engine, and so its efficiency can be determined from Eq. 6–18 to be

$$\eta_{th,rev} = 1 - \frac{T_L}{T_H} = 1 - \frac{(30 + 273) \text{ K}}{(652 + 273) \text{ K}} = 0.672$$

That is, this Carnot heat engine converts 67.2 percent of the heat it receives to work.

(b) The amount of heat rejected Q_L by this reversible heat engine is easily determined from Eq. 6–16 to be

$$Q_{L,rev} = \frac{T_L}{T_H} Q_{H,rev} = \frac{(30 + 273) \text{ K}}{(652 + 273) \text{ K}} (500 \text{ kJ}) = 164 \text{ kJ}$$

Discussion Note that this Carnot heat engine rejects to a low-temperature sink 164 kJ of the 500 kJ of heat it receives during each cycle.

adar ask & believe & recieve
CamScanner الممسوحة ضوئيا بـ

EXAMPLE 6-6 **A Carnot Refrigeration Cycle Operating in the Saturation Dome**

A Carnot refrigeration cycle is executed in a closed system in the saturated liquid–vapor mixture region using 0.8 kg of refrigerant-134a as the working fluid (Fig. 6–51). The maximum and the minimum temperatures in the cycle are 20 and −8°C, respectively. It is known that the refrigerant is saturated liquid at the end of the heat rejection process, and the net work input to the cycle is 15 kJ. Determine the fraction of the mass of the refrigerant that vaporizes during the heat addition process and the pressure at the end of the heat rejection process.

SOLUTION A Carnot refrigeration cycle is executed in a closed system. The mass fraction of the refrigerant that vaporizes during the heat addition process and the pressure at the end of the heat rejection process are to be determined.

Assumptions The refrigerator operates on the ideal Carnot cycle.

Analysis Knowing the high and low temperatures, the coefficient of performance of the cycle is

$$\text{COP}_R = \frac{1}{T_H/T_L - 1} = \frac{1}{(20 + 273\text{ K})/(-8 + 273\text{ K}) - 1} = 9.464$$

The amount of cooling is determined from the definition of the coefficient of performance to be

$$Q_L = \text{COP}_R \times W_{net} = (9.464)(15\text{ kJ}) = 142\text{ kJ}$$

The enthalpy of vaporization R-134a at −8°C is $h_{fg} = 204.59$ kJ/kg (Table A-11). Then the amount of refrigerant that vaporizes during heat absorption becomes

$$Q_L = m_{vap} h_{fg@-8°C} \rightarrow m_{vap} = \frac{142\text{ kJ}}{204.59\text{ kJ/kg}} = 0.694\text{ kg}$$

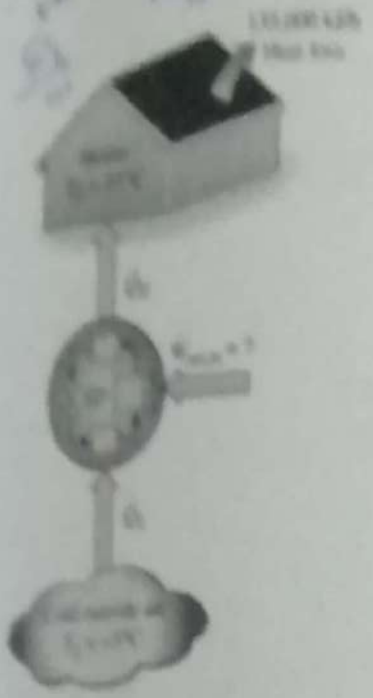
Therefore, the fraction of mass that vaporized during heat addition process to the refrigerant is

$$\text{Mass fraction} = \frac{m_{vap}}{m_{total}} = \frac{0.694\text{ kg}}{0.8\text{ kg}} = 0.868 \text{ or } 86.8\%$$

The pressure at the end of heat rejection process is simply the saturation pressure at heat rejection temperature,

$$P_4 = P_{sat@-8°C} = 272.1\text{ kPa}$$

Discussion Carnot cycle is an idealized refrigeration cycle, thus it cannot be achieved in practice. Practical refrigeration cycles are analyzed in Chap. 11.



EXAMPLE 6–7 **Heating a House by a Carnot Heat Pump**

A heat pump is to be used to heat a house during the winter, as shown in Fig. 6–62. The house is to be maintained at 21°C at all times. The house is estimated to be losing heat at a rate of 135,000 kJ/h when the outside temperature drops to −5°C. Determine the minimum power required to drive this heat pump.

SOLUTION A heat pump maintains a house at a certain temperature. The required minimum power input to the heat pump is to be determined.

Assumptions Steady operating conditions exist.

Analysis The heat pump must supply heat to the house at a rate of Q_H = 135,000 kJ/h = 37.5 kW. The power requirements are minimum when a reversible heat pump is used to do the job. The COP of a reversible heat pump operating between the house and the outside air is

$$\text{COP}_{\text{HP,rev}} = \frac{1}{1 - T_L/T_H} = \frac{1}{1 - (-5 + 273\ \text{K})/(21 + 273\ \text{K})} = 11.3$$

Then, the required power input to this reversible heat pump becomes

$$\dot{W}_{\text{net,in}} = \frac{\dot{Q}_H}{\text{COP}_{\text{HP}}} = \frac{37.5\ \text{kW}}{11.3} = 3.32\ \text{kW}$$

CamScanner الممسوحة ضوئيا بـ

CamScanner الممسوحة ضوئيا بـ

• ال 1st law بيقول ان الطاقة موجودة وبتتنقل من شكل لشكل او مكان لمكان

• ال 2nd law بيقول مع الطاقة انتقلت بتتحول dissipated energy :: disintegrated

وممكن تروح lost

← وانتقال الطاقة من الطبيعة بيأثر على quality of energy

← ال 2nd law بيقول كمان في spontaneous transfer ← وصار فيها losses و ...

In entropy generation (بتزيد دايما)

← عكس تغيرها ال S_u متغير extensive property

← زي ال energy بنعرفها انها ability to do work (تقريبا من كتير واضح)

← ال entropy فيها غموض أكتر :

Thermodynamics

Chapter 7

Concept & Calculations of ENTROPY

Thermodynamics: An Engineering Approach
Yunus A. Cengel, Michael A. Boles, Mehmet Kanoglu
McGraw-Hill

Dr. Ahmad M. AbuYaghi
October 2023

ENTROPY

Clausius inequality

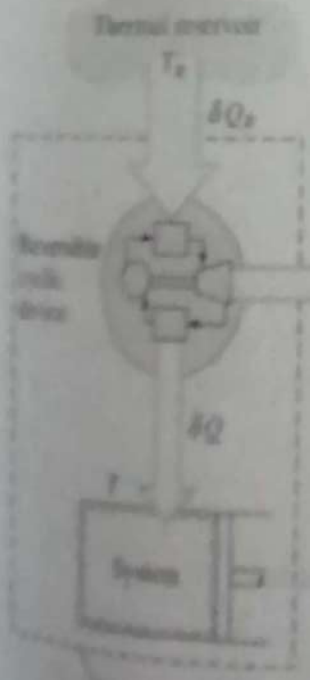
$$\oint \frac{\delta Q}{T} \le 0$$

$$\oint \left(\frac{\delta Q}{T}\right)_{\text{int rev}} = 0$$

$$dS = \left(\frac{\delta Q}{T}\right)_{\text{int rev}} \quad \text{(kJ/K)}$$

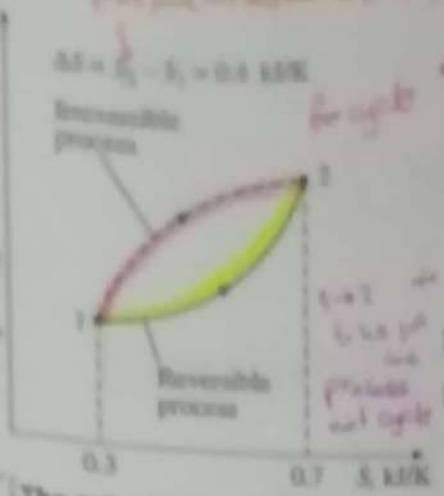
Formal definition of entropy

$$\Delta S = S_2 - S_1 = \int_1^2 \left(\frac{\delta Q}{T}\right)_{\text{int rev}}$$



The system considered in the development of the Clausius inequality

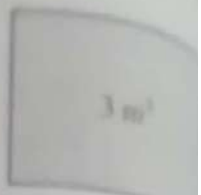
The equality in the Clausius inequality holds for totally or just internally reversible cycles and the inequality for the irreversible ones.



A quantity whose cyclic integral is zero (i.e., a property like volume)

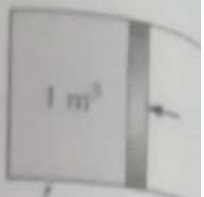
Entropy is an extensive property of a system.





The entropy change between two specified states is the same whether the process is reversible or irreversible.

The net change in volume (a property) during a cycle is always zero.

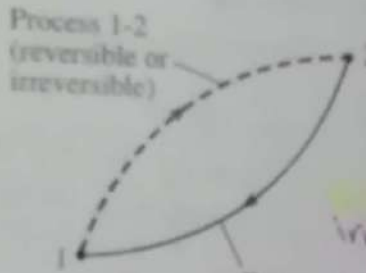


A Special Case: Internally Reversible Isothermal Heat Transfer Processes

$$\Delta S = \int_1^2 \left(\frac{\delta Q}{T}\right)_{\text{int rev}} = \int_1^2 \left(\frac{\delta Q}{T_0}\right)_{\text{int rev}} = \frac{1}{T_0}\int_1^2 (\delta Q)_{\text{int rev}}$$

This equation is particularly useful for determining the entropy changes of thermal energy reservoirs.

THE INCREASE OF ENTROPY PRINCIPLE



A cycle composed of a reversible and an irreversible process.

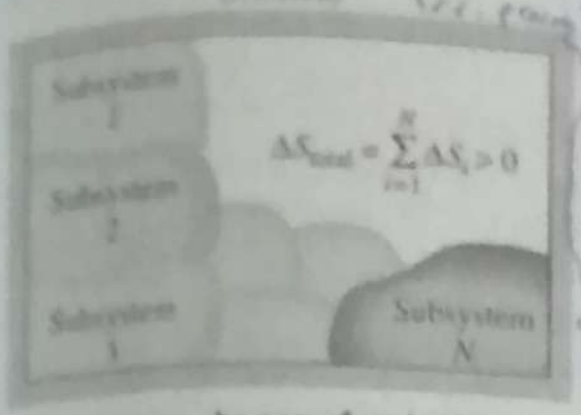
$$dS \geq \frac{\delta Q}{T}$$

The equality holds for an internally reversible process and the inequality for an irreversible process.

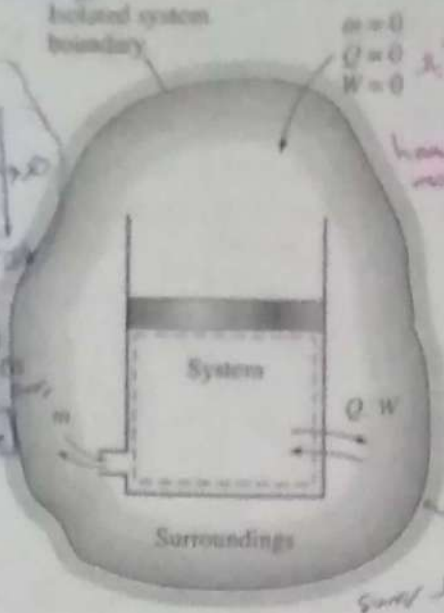
- Some entropy is generated or created during an irreversible process; this generation is due entirely to the presence of irreversibilities.
- The entropy generation S_{gen} is always a positive quantity or zero.

Can the entropy of a system during a process decrease?

الممسوحة ضوئيا بـ CamScanner



The entropy change of an isolated system is the sum of the entropy changes of its components and is never less than zero.



A system and its surroundings form an isolated system.

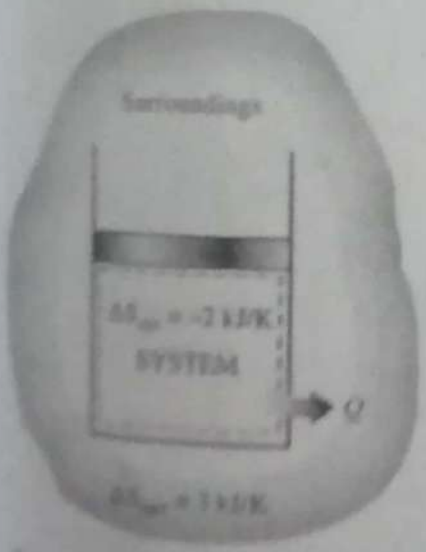
$$\Delta S_{isolated} \geq 0$$

$$S_{gen} = \Delta S_{total} = \Delta S_{sys} + \Delta S_{surr} \geq 0$$

$$S_{gen} \begin{cases} > 0 & \text{Irreversible process} \\ = 0 & \text{Reversible process} \\ < 0 & \text{Impossible process} \end{cases}$$

The increase of entropy principle

Some Remarks about Entropy



The entropy change of a system can be negative, but the entropy generation cannot.

1) Processes can occur in a *certain* direction only, not in *any* direction. A process must proceed in the direction that complies with the increase of entropy principle, that is, $S_{gen} \geq 0$. A process that violates this principle is impossible.

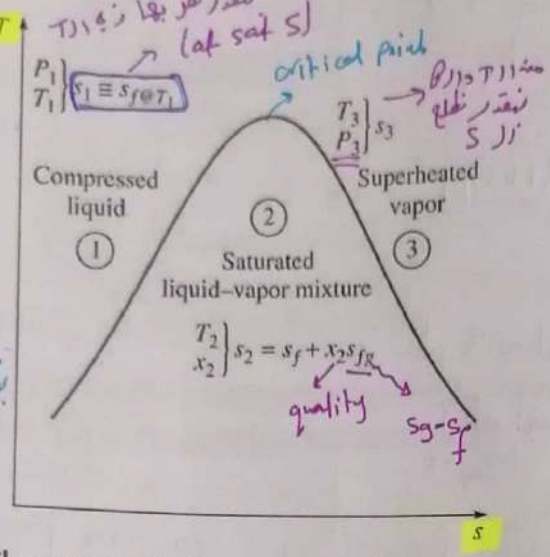
2) Entropy is a *nonconserved property*, and there is *no* such thing as the *conservation of entropy principle*. Entropy is conserved during the idealized reversible processes only and increases during *all* actual processes.

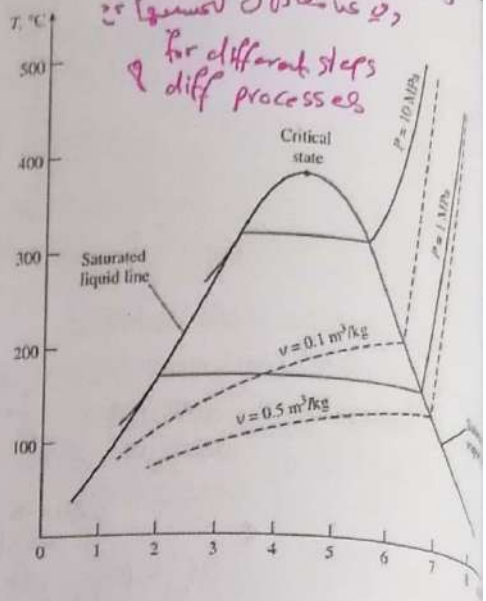
3) The performance of engineering systems is degraded by the presence of irreversibilities, and *entropy generation* is a measure of the magnitudes of the irreversibilities during that process. It is also used to establish criteria for the performance of engineering devices.

ask recieve
الممسوحة ضوئيا بـ CamScanner

ENTROPY CHANGE OF PURE SUBSTANCES

Entropy is a property, and thus the value of entropy of a system is fixed once the state of the system is fixed.





Schematic of the *T-s* diagram for wa

The entropy of a pure substance is determined from the tables (like other properties).

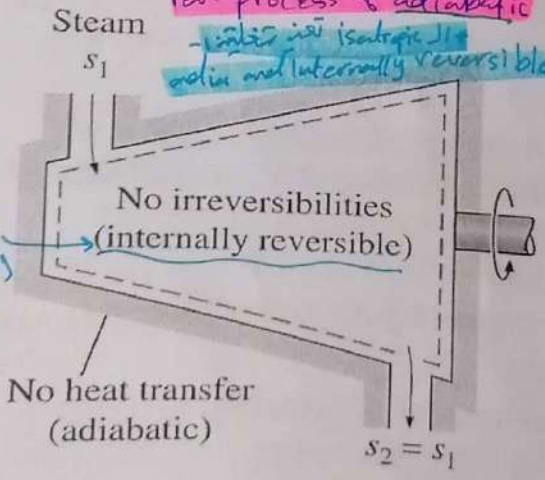
Entropy change:

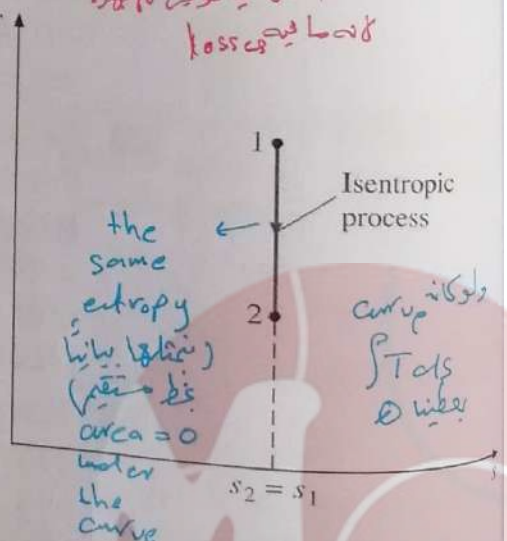
$$\Delta S = m\Delta s = m(s_2 - s_1) \quad (kJ$$

ISENTROPIC PROCESSES

❑ A process during which the entropy remains constant is called an **isentropic process**.

$$\Delta s = 0 \quad \text{or} \quad s_2 = s_1 \quad (kJ/kg$$



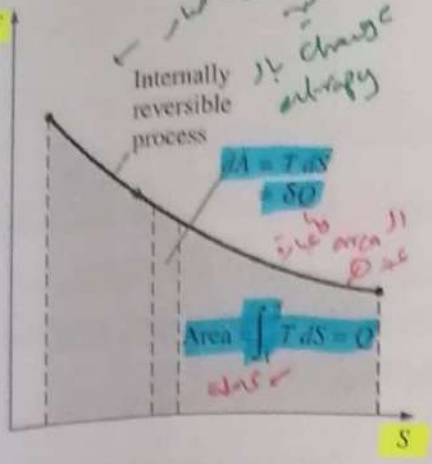


During an internally reversible, adiabatic (isentropic) process, the entropy remains constant.

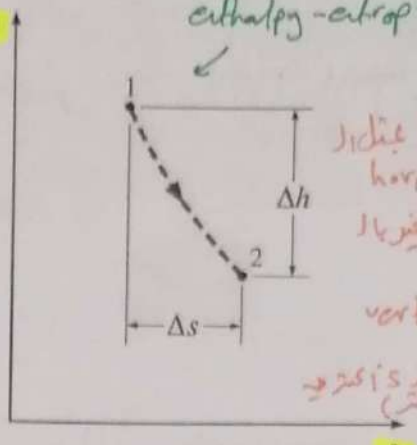
The isentropic process appears as a *vertical* line segment on a *T-s* diagra

CamScanner الممسوحة ضوئيا بـ

PROPERTY DIAGRAMS INVOLVING ENTROPY



On a *T-S* diagram, the area under the process curve represents the heat transfer for internally reversible processes.



$$\delta Q_{\text{int rev}} = T\,dS \qquad Q_{\text{int rev}} = \int_1^2 T\,dS$$

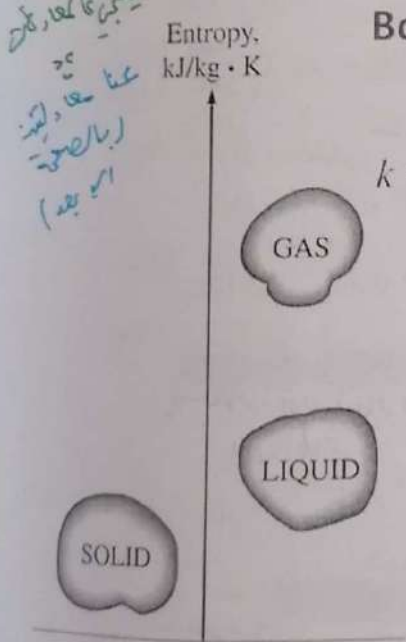
$$\delta q_{\text{int rev}} = T\,ds \qquad q_{\text{int rev}} = \int_1^2 T\,ds$$

$$Q_{\text{int rev}} = T_0\,\Delta S \qquad q_{\text{int rev}} = T_0\,\Delta s$$

For adiabatic steady-flow devices, the vertical distance Δh on an *h-s* diagram is a measure of work and the horizontal distance Δs is a measure of irreversibilities.

Mollier diagram: The *h-s* diagram

WHAT IS ENTROPY?

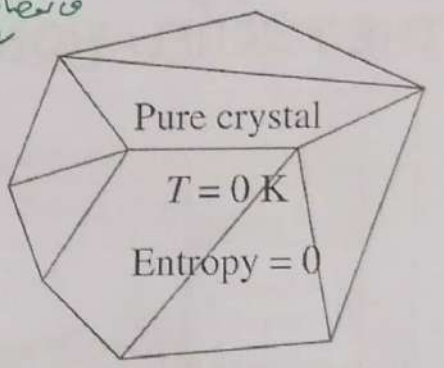


The level of molecular disorder (entropy) of a substance increases as it melts or evaporates.

Boltzmann relation:

$$S = k \ln p$$

$$k = 1.3806 \times 10^{-23}\ \text{J/K}$$

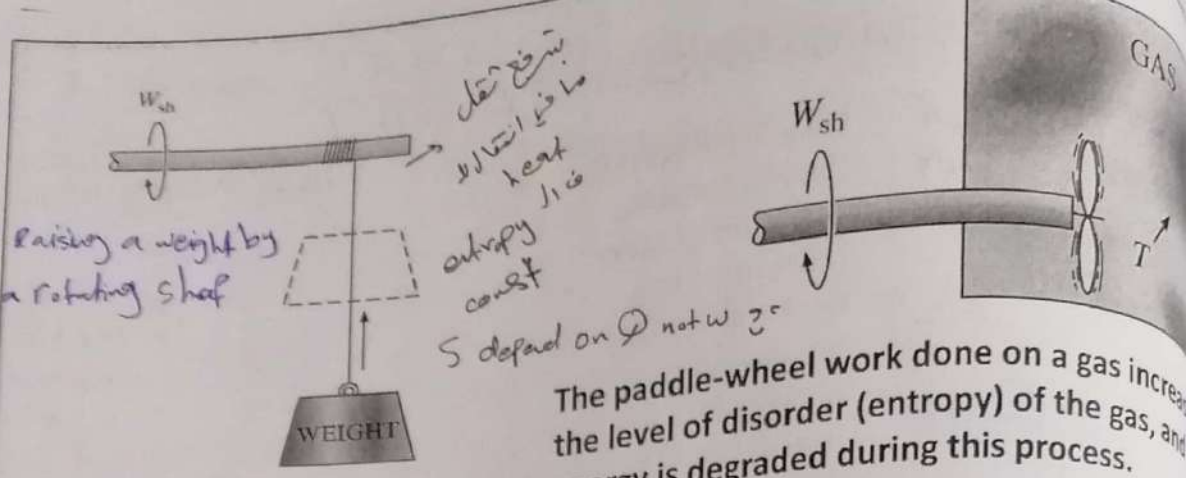


The third law of thermodynamics:
A pure crystalline substance at absolute zero temperature is in perfect order, and its entropy is zero.



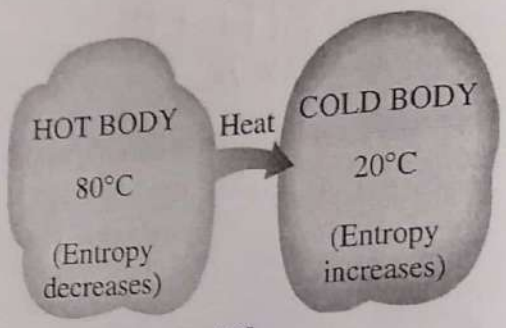
Disorganized energy does not create much useful effect, no matter how large it is.

CamScanner الممسوحة ضوئيا بـ



The paddle-wheel work done on a gas increa the level of disorder (entropy) of the gas, an energy is degraded during this process.

In the absence of friction, raising a weight by a rotating shaft does not create any disorder (entropy), and thus energy is not degraded during this process.



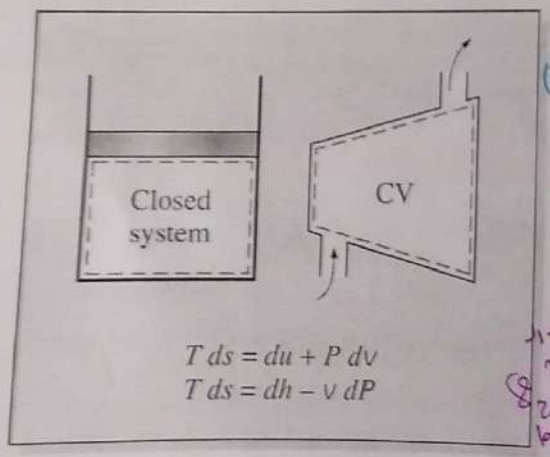
During a heat tran process, the net entropy increases. (The increase in th entropy of the cold body more than of the decrease in the entropy of the hot body.)

$H_{2(g)} + I_{2(g)} = 2\,HI_{(g)}$

$CaCO_{3(s)} \rightleftharpoons CaO_{(s)} + CO_{2(g)}$ ⇝ increase entropy

How entropy change during chemical rxns ?

THE *T ds* RELATIONS



$$\delta Q_{\text{int rev}} - \delta W_{\text{int rev,out}} = dU \quad \text{(1st law)}$$

$$\delta Q_{\text{int rev}} = T\,dS \quad \text{(2nd law)}$$

$$\delta W_{\text{int rev,out}} = P\,dV$$

$$T\,dS = dU + P\,dV \quad \text{(kJ)}$$

$$T\,ds = du + P\,dv \quad \text{(kJ/kg)}$$

First *T ds*, or *Gibbs* equation:

$$h = u + Pv$$

$$dh = du + P\,dv + v\,dP$$

$$T\,ds = du + P\,dv$$

$$T\,ds = dh - v\,dP$$

The *T ds* relations are valid for both reversible and irreversible processes and for both closed and open systems.

Second *T ds* equation:

$$ds = \frac{du}{T} + \frac{P\,dv}{T}$$

$$ds = \frac{dh}{T} - \frac{v\,dP}{T}$$

Differential chang entropy in terms o other properties

الممسوحة ضوئيا بـ CamScanner

ENTROPY CHANGE OF LIQUIDS AND SOLIDS

$$ds = \frac{du}{T} + \frac{P\,dv}{T}$$

Liquids and solids can be approximated as *incompressible substances* since their specific volumes remain nearly constant during a process.

Since $dv \equiv 0$ for liquids and solids

$$ds = \frac{du}{T} = \frac{c\,dT}{T}$$

since $c_p = c_v = c$ and $du = c\,dT$

Liquids, solids:
$$s_2 - s_1 = \int_1^2 c(T)\frac{dT}{T} \cong c_{avg}\ln\frac{T_2}{T_1} \quad (kJ/kg\cdot K)$$

For and isentropic process of an incompressible substance:

Isentropic:
$$s_2 - s_1 = c_{avg}\ln\frac{T_2}{T_1} = 0 \rightarrow T_2 = T_1$$

THE ENTROPY CHANGE OF IDEAL GASES

From the first *T ds* relation

$$ds = \frac{du}{T} + \frac{P\,dv}{T}$$

$$du = c_v\,dT$$

$$P = RT/v$$

$$ds = c_v\frac{dT}{T} + R\frac{dv}{v}$$

$$s_2 - s_1 = \int_1^2 c_v(T)\frac{dT}{T} + R\ln\frac{v_2}{v_1}$$

$$s_2 - s_1 = \int_1^2 c_p(T)\frac{dT}{T} - R\ln\frac{P_2}{P_1}$$

From the second *T ds* relation

$$ds = \frac{dh}{T} - \frac{v\,dP}{T}$$

$$dh = c_p\,dT$$

$$v = RT/P$$

$$Pv = RT$$
$$du = C_v\,dT$$
$$dh = C_p\,dT$$

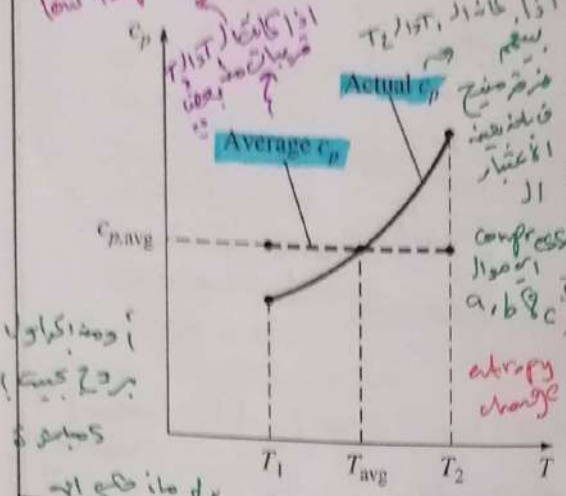
CamScanner

Constant Specific Heats (Approximate Analysis)

$$s_2 - s_1 = \int_1^2 c_v(T)\frac{dT}{T} + R\ln\frac{v_2}{v_1} \longrightarrow s_2 - s_1 = c_{v,avg}\ln\frac{T_2}{T_1} + R\ln\frac{v_2}{v_1}$$

$$s_2 - s_1 = \int_1^2 c_p(T)\frac{dT}{T} - R\ln\frac{P_2}{P_1} \longrightarrow s_2 - s_1 = c_{p,avg}\ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1}$$

(kJ/kg·K)



Entropy change of an ideal gas on a unit–mole basis:

$$\bar{s}_2 - \bar{s}_1 = \bar{c}_{v,avg}\ln\frac{T_2}{T_1} + R_u\ln\frac{v_2}{v_1} \quad (\text{kJ/kmol})$$

$$\bar{s}_2 - \bar{s}_1 = \bar{c}_{p,avg}\ln\frac{T_2}{T_1} - R_u\ln\frac{P_2}{P_1} \quad (\text{kJ/kmol})$$

Under the constant-specific-heat assumption, the specific heat is assumed to be constant at some average value.

Variable Specific Heats (Exact Analysis)

We choose absolute zero as the reference temperature and define a function s° as

$$s^\circ = \int_0^T c_p(T)\frac{dT}{T}$$

$$\int_1^2 c_p(T)\frac{dT}{T} = s_2^\circ - s_1^\circ$$

T, K	s°, kJ/kg·K
.	.
.	.
.	.
300	1.70203
310	1.73498
320	1.76690
.	.
.	.
.	.

(Table A-17)

On a unit–mass basis:

$$s_2 - s_1 = s_2^\circ - s_1^\circ - R\ln\frac{P_2}{P_1} \quad (\text{kJ/kg}\cdot\text{K})$$

On a unit–mole basis:

$$\bar{s}_2 - \bar{s}_1 = \bar{s}_2^\circ - \bar{s}_1^\circ - R_u\ln\frac{P_2}{P_1} \quad (\text{kJ/kmol}\cdot\text{K})$$

The entropy of an ideal gas depends on both T and P. The function s° represents only the temperature-dependent part of entropy.

CamScanner الممسوحة ضوئيا بـ

Isentropic Processes of Ideal Gases

Constant Specific Heats (Approximate Analysis)

$$s_2 - s_1 = c_{v,avg} \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1}$$

Setting this eq. equal to zero, we get:

$$\ln \frac{T_2}{T_1} = -\frac{R}{c_v} \ln \frac{v_2}{v_1} \qquad \ln \frac{T_2}{T_1} = \ln \left(\frac{v_1}{v_2}\right)^{R/c_v}$$

$$R = c_p - c_v \quad k = c_p/c_v$$

and thus $R/c_v = k - 1$

$$\left(\frac{T_2}{T_1}\right)_{s=\text{const.}} = \left(\frac{v_1}{v_2}\right)^{k-1}$$

$$\left(\frac{T_2}{T_1}\right)_{s=\text{const.}} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k}$$

$$\left(\frac{P_2}{P_1}\right)_{s=\text{const.}} = \left(\frac{v_1}{v_2}\right)^{k}$$

The isentropic relations of ideal gases are valid for the isentropic processes of ideal gases only.

$$Tv^{k-1} = \text{constant}$$

$$TP^{(1-k)/k} = \text{constant}$$

$$Pv^k = \text{constant}$$

$P_1 v_1^k = P_2 v_2^k$ ← ratio of heat capacity ($k = c_p/c_v$)

$k \approx 1.4$ for ideal gas

Isentropic Processes of Ideal Gases

Variable Specific Heats (Exact Analysis)

$$0 = s_2^\circ - s_1^\circ - R \ln \frac{P_2}{P_1} \longrightarrow s_2^\circ = s_1^\circ + R \ln \frac{P_2}{P_1}$$

$\Delta s = \Delta s^\circ - R \ln \frac{P_2}{P_1}$

Process: isentropic
Given: P_1, T_1, and P_2
Find: T_2

T	P_r
T_2 ← read	$P_{r2} = \frac{P_2}{P_1} P_{r1}$
T_1 ← read	P_{r1}

Relative Pressure and Relative Specific Volume

$$\frac{P_2}{P_1} = \exp \frac{s_2^\circ - s_1^\circ}{R}$$

$$\frac{P_2}{P_1} = \frac{\exp(s_2^\circ/R)}{\exp(s_1^\circ/R)}$$

$\exp(s^\circ/R)$ is the relative pressure P_r.

The use of P_r data for calculating the final temperature during an isentropic process.

$$\left(\frac{P_2}{P_1}\right)_{s=\text{const.}} = \frac{P_{r2}}{P_{r1}}$$

(reduced P)

$$\frac{P_1 v_1}{T_1} = \frac{P_2 v_2}{T_2} \rightarrow \frac{v_2}{v_1} = \frac{T_2}{T_1}\frac{P_1}{P_2} = \frac{T_2}{T_1}\frac{P_{r1}}{P_{r2}} = \frac{T_2/P_{r2}}{T_1/P_{r1}}$$

$$\left(\frac{v_2}{v_1}\right)_{s=\text{const.}} = \frac{v_{r2}}{v_{r1}}$$

T/P_r is the relative specific volume v_r.

Process: isentropic
Given: v_1, T_1, and v_2
Find: T_2

T	v_r
T_2 ← read	$v_{r2} = \frac{v_2}{v_1} v_{r1}$
T_1 ← read	v_{r1}

The use of v_r data for calculating the final temperature during an isentropic process

ask : believe & recieve
CamScanner الممسوحة ضوئيا بـ

REVERSIBLE STEADY-FLOW WORK

$$\delta q_{rev} - \delta w_{rev} = dh + dke + dpe$$

$$\delta q_{rev} = T\,ds \quad \text{(Eq. 7–16)}$$
$$T\,ds = dh - v\,dP \quad \text{(Eq. 7–24)}$$

$$\delta q_{rev} = dh - v\,dP$$

$$-\delta w_{rev} = v\,dP + dke + dpe$$

$$w_{rev} = -\int_1^2 v\,dP - \Delta ke - \Delta pe$$

When kinetic and potential energies are negligible

$$w_{rev} = -\int_1^2 v\,dP$$

$$w_{rev,in} = \int_1^2 v\,dP + \Delta ke + \Delta pe$$

$$w_{rev} = -v(P_2 - P_1) - \Delta ke - \Delta pe$$

For the steady flow of a liquid through a device that involves no work interactions (such as a pipe section), the work term is zero (Bernoulli equation):

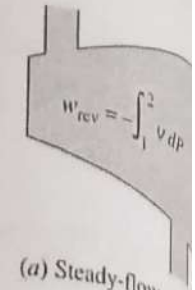
$$v(P_2 - P_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) = 0$$

$$w_{rev} = -\int_1^2 v\,dP$$

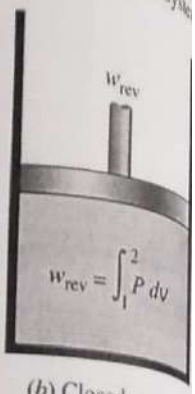
$$w = -\int_1^2 v\,dP$$

$$W = -\int_1^2 V\,dP$$

The larger the specific volume, the greater the work produced (or consumed) by a steady-flow device.



(a) Steady-flow system



(b) Closed system

Reversible work relations for steady flow and closed systems.

Proof that Steady-Flow Devices Deliver the Most and Consume the Least Work when the Process Is Reversible:

Taking heat input and work output positive:

$$\delta q_{act} - \delta w_{act} = dh + dke + dpe \quad \text{Actual}$$

$$\delta q_{rev} - \delta w_{rev} = dh + dke + dpe \quad \text{Reversible}$$

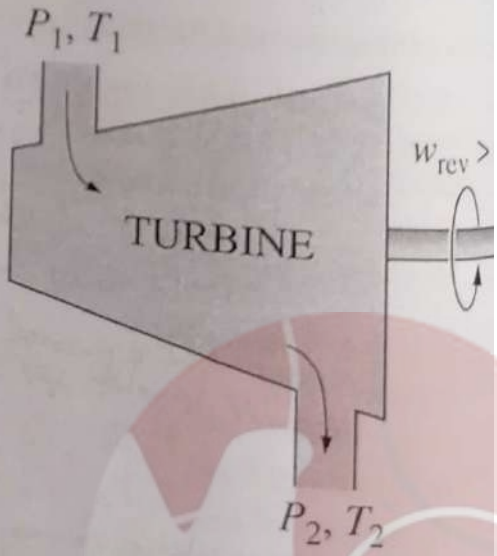
$$\delta q_{act} - \delta w_{act} = \delta q_{rev} - \delta w_{rev}$$
$$\delta w_{rev} - \delta w_{act} = \delta q_{rev} - \delta q_{act}$$

$$\delta q_{rev} = T\,ds \qquad ds \geq \frac{\delta q_{act}}{T}$$

$$\frac{\delta w_{rev} - \delta w_{act}}{T} = ds - \frac{\delta q_{act}}{T} \geq 0$$

$$\partial w_{rev} \geq \partial w_{act}$$

$$w_{rev} \geq w_{act}$$



Work-producing devices such as turbines deliver more work, and work-consuming devices such as pumps and compressors require less work when they operate reversibly.

A reversible turbine delivers m work than an irreversible one i both operate between the same end states.

الممسوحة ضوئيا بـ CamScanner

MINIMIZING THE COMPRESSOR WORK

$$w_{in,in} = \int_1^2 v\,dP$$

When kinetic and potential energies are negligible

Isentropic (Pv^k = constant):

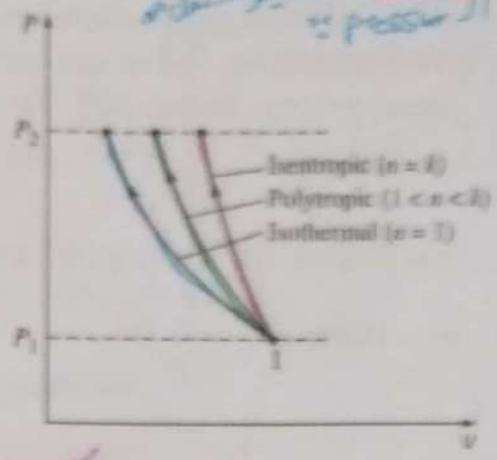
$$w_{comp,in} = \frac{kR(T_2 - T_1)}{k-1} = \frac{kRT_1}{k-1}\left[\left(\frac{P_2}{P_1}\right)^{(k-1)/k} - 1\right]$$

Polytropic (Pv^n = constant):

$$w_{comp,in} = \frac{nR(T_2 - T_1)}{n-1} = \frac{nRT_1}{n-1}\left[\left(\frac{P_2}{P_1}\right)^{(n-1)/n} - 1\right]$$

Isothermal (Pv = constant):

$$w_{comp,in} = RT \ln \frac{P_2}{P_1}$$

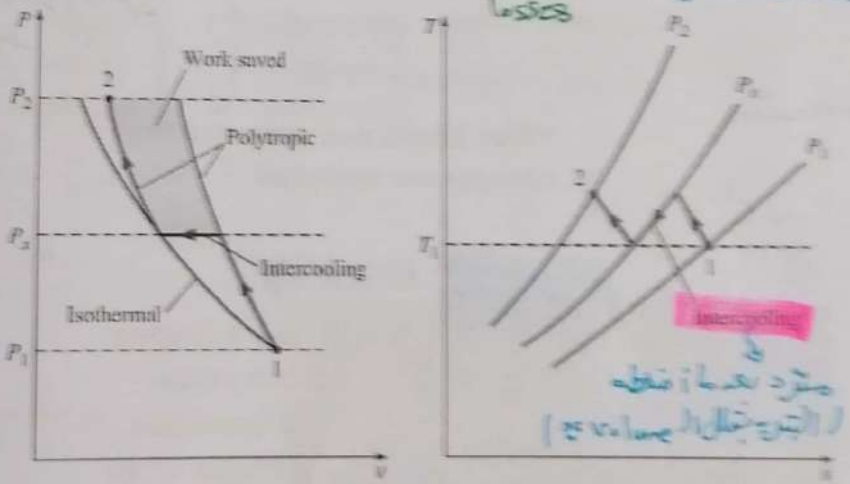


P-v diagrams of isentropic, polytropic, and isothermal compression processes between the same pressure limits.

The adiabatic compression (Pv^k = constant) requires the maximum work, and the isothermal compression (T = constant) requires the minimum. Why?

Multistage Compression with Intercooling

The gas is compressed in stages and cooled between each stage by passing it through a heat exchanger called an *intercooler*.



P-v and *T-s* diagrams for a two-stage steady-flow compression process.

$$W_{comp,in} = W_{comp\ I,in} + W_{comp\ II,in}$$

$$= \frac{nRT_1}{n-1}\left[\left(\frac{P_x}{P_1}\right)^{(n-1)/n} - 1\right] + \frac{nRT_1}{n-1}\left[\left(\frac{P_2}{P_x}\right)^{(n-1)/n} - 1\right]$$

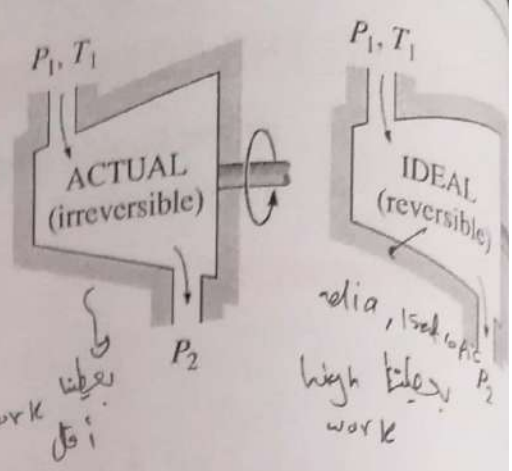
$$P_x = (P_1 P_2)^{1/2} \quad \text{or} \quad \frac{P_x}{P_1} = \frac{P_2}{P_x}$$

To minimize compression work during two-stage compression, the pressure ratio across each stage of the compressor must be the same.

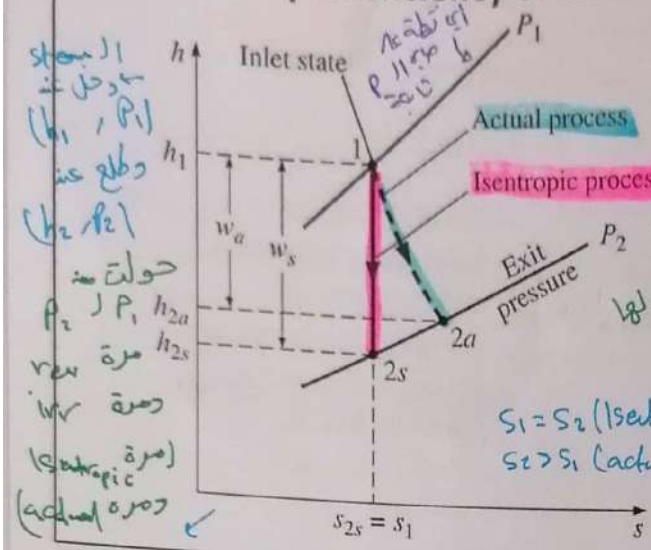
الممسوحة ضوئيا بـ CamScanner

ISENTROPIC EFFICIENCIES OF STEADY-FLOW DEVICES

The isentropic process involves no irreversibilities and serves as the ideal process for adiabatic devices.



Isentropic Efficiency of Turbines



The *h-s* diagram for the actual and isentropic processes of an adiabatic turbine.

$$\eta_T = \frac{\text{Actual turbine work}}{\text{Isentropic turbine work}} = \frac{w_a}{w_s}$$

$$\eta_T \cong \frac{h_1 - h_{2a}}{h_1 - h_{2s}}$$

Isentropic Efficiencies of Compressors and Pumps

$$\eta_C = \frac{\text{Isentropic compressor work}}{\text{Actual compressor work}} = \frac{w_s}{w_a}$$

$$\eta_C \cong \frac{h_{2s} - h_1}{h_{2a} - h_1}$$

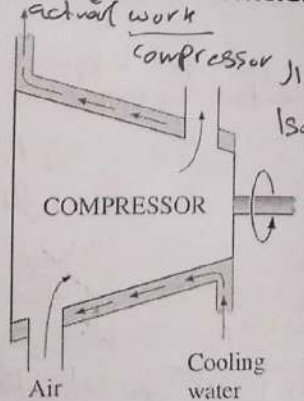
When kinetic and potential energies are negligible

$$\eta_P = \frac{w_s}{w_a} = \frac{v(P_2 - P_1)}{h_{2a} - h_1}$$

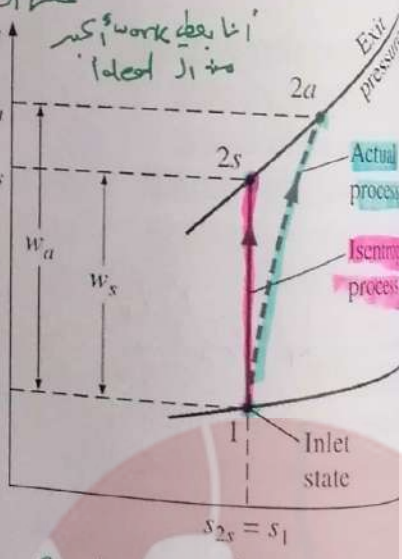
For a pump

$$\eta_C = \frac{w_t}{w_a}$$

Isothermal efficiency



Compressors are sometimes intentionally cooled to minimize the work input.



The *h-s* diagram of the actual and isentropic processes of an adiabatic compressor.

Can you use isentropic efficiency for non-adiabatic compressor?

Can you use isothermal efficiency for adiabatic compressor?

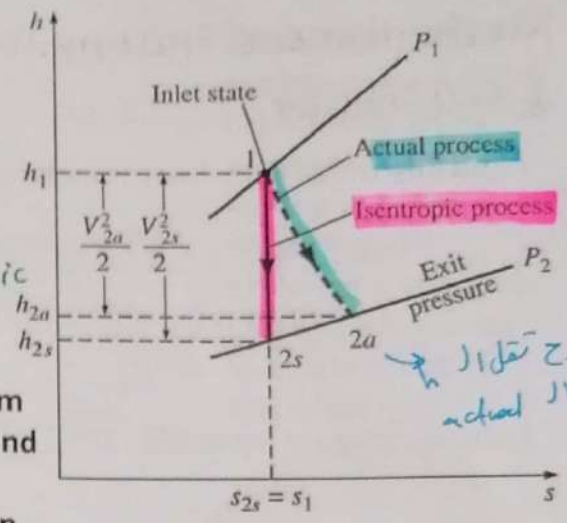
CamScanner الممسوحة ضوئيا بـ

Isentropic Efficiency of Nozzles

$$\eta_N = \frac{\text{Actual KE at nozzle exit}}{\text{Isentropic KE at nozzle exit}} = \frac{V_{2a}^2}{V_{2s}^2}$$

- If the inlet velocity of the fluid is small relative to the exit velocity, the energy balance is:

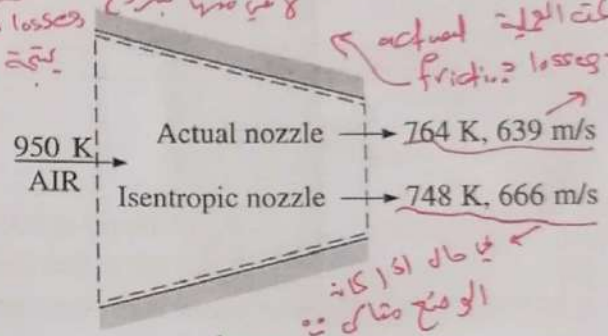
$$h_1 = h_{2a} + \frac{V_{2a}^2}{2}$$



The *h-s* diagram of the actual and isentropic processes of an adiabatic nozzle.

Then,

$$\eta_N \cong \frac{(h_1 - h_{2a})}{(h_1 - h_{2s})}$$



A substance leaves actual nozzles at a higher temperature (thus a lower velocity) as a result of friction.

ENTROPY BALANCE

$$\begin{pmatrix}\text{Total}\\ \text{entropy}\\ \text{entering}\end{pmatrix} - \begin{pmatrix}\text{Total}\\ \text{entropy}\\ \text{leaving}\end{pmatrix} + \begin{pmatrix}\text{Total}\\ \text{entropy}\\ \text{generated}\end{pmatrix} = \begin{pmatrix}\text{Change in the}\\ \text{total entropy}\\ \text{of the system}\end{pmatrix}$$

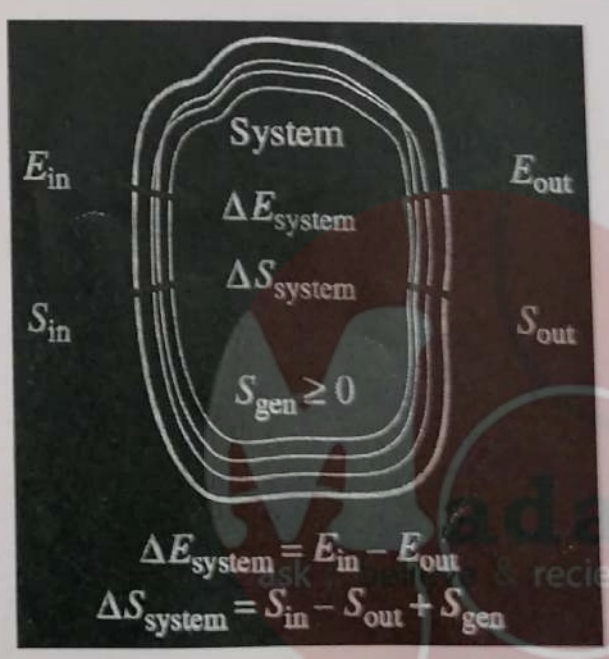
$$S_{in} - S_{out} + S_{gen} = \Delta S_{system}$$

Entropy Change of a System, ΔS_{system}

$$\Delta S_{system} = S_{final} - S_{initial} = S_2 - S_1$$

When the properties of the system are not uniform

$$S_{system} = \int s\,\delta m = \int_V s\rho\,dV$$



Energy and entropy balances for a system.

CamScanner الممسوحة ضوئيا بـ

Mechanisms of Entropy Transfer, S_{in} and S_{out}

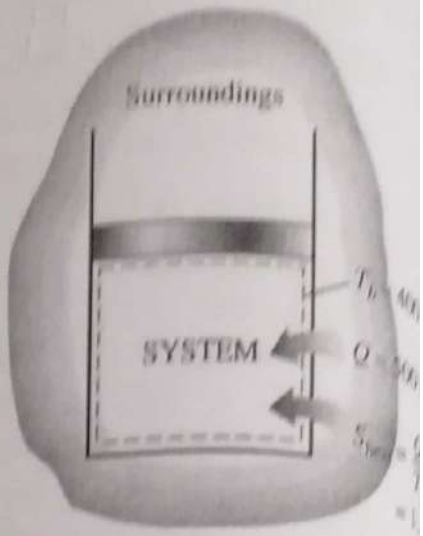
1 Heat Transfer

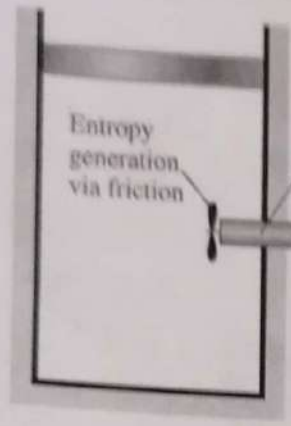
Entropy transfer by heat transfer:

$$S_{heat} = \frac{Q}{T} \qquad (T = \text{constant})$$

$$S_{heat} = \int_1^2 \frac{\delta Q}{T} = \sum \frac{Q_k}{T_k}$$

Entropy transfer by work: $S_{work} = 0$





Heat transfer is always accompanie
entropy transfer in the amount of
where T is the boundary temperat

No entropy accompanies work as it crosses the system boundary. But entropy may be generated within the syste work is dissipated into a less useful form of energy.

Mechanisms of Entropy Transfer, S_{in} and S_{out}

2 Mass Flow

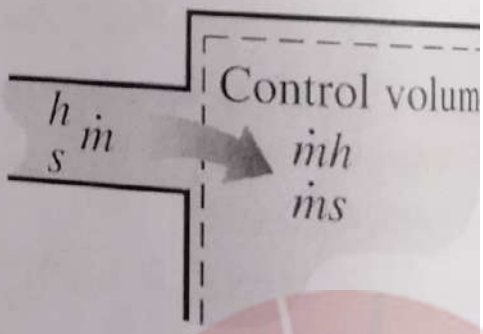
Entropy transfer by mass:

$$S_{mass} = ms$$

When the properties of the mass change during the process:

$$\dot{S}_{mass} = \int_{A_c} s\rho V_n \, dA_c$$

$$S_{mass} = \int s \, \delta m = \int_{\Delta t} \dot{S}_{mass} \, dt$$



Mass contains entropy as w
as energy, and thus mass flo
into or out of system is
always accompanied by
energy and entropy transfer

ask & believe & recieve
الممسوحة ضوئيا بـ CamScanner

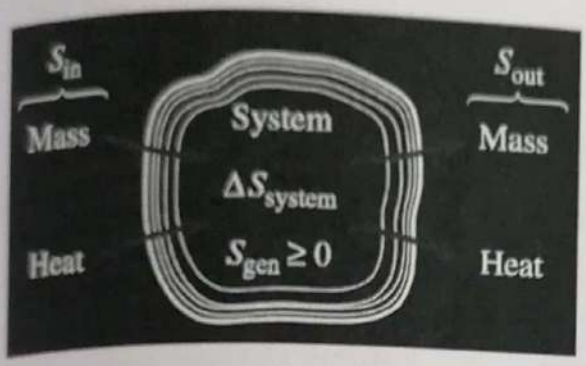
Entropy Generation, S_{gen}

$$\underbrace{S_{in} - S_{out}}_{\text{Net entropy transfer by heat and mass}} + \underbrace{S_{gen}}_{\text{Entropy generation}} = \underbrace{\Delta S_{system}}_{\text{Change in entropy}} \quad \text{(kJ/K)}$$

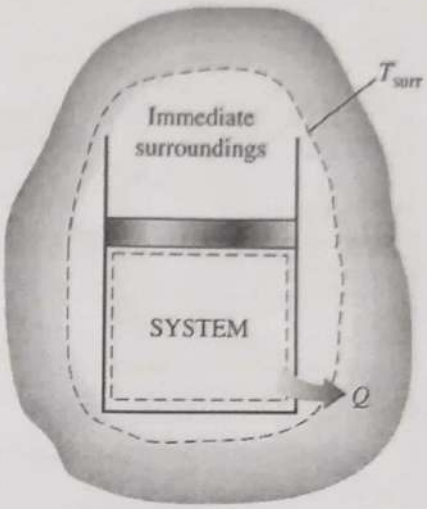
$$\underbrace{\dot{S}_{in} - \dot{S}_{out}}_{\text{Rate of net entropy transfer by heat and mass}} + \underbrace{\dot{S}_{gen}}_{\text{Rate of entropy generation}} = \underbrace{dS_{system}/dt}_{\text{Rate of change in entropy}} \quad \text{(kW/K)}$$

$$(s_{in} - s_{out}) + s_{gen} = \Delta s_{system} \quad \text{(kJ/kg · K)}$$

Entropy generation outside system boundaries can be accounted for by writing an entropy balance on an extended system that includes the system and its immediate surroundings.



Mechanisms of entropy transfer for a general system.



Closed Systems

Closed system: $$\sum \frac{Q_k}{T_k} + S_{gen} = \Delta S_{system} = S_2 - S_1 \quad \text{(kJ/K)}$$

The entropy change of a closed system during a process is equal to the sum of the net entropy transferred through the system boundary by heat transfer and the entropy generated within the system boundaries.

Adiabatic closed system: $$S_{gen} = \Delta S_{adiabatic\ system}$$

System + Surroundings: $$S_{gen} = \sum \Delta S = \Delta S_{system} + \Delta S_{surroundings}$$

$$\Delta S_{system} = m(s_2 - s_1)$$

$$\Delta S_{surr} = Q_{surr}/T_{surr}$$

adar
ask & believe & recieve
CamScanner الممسوحة ضوئيا بـ

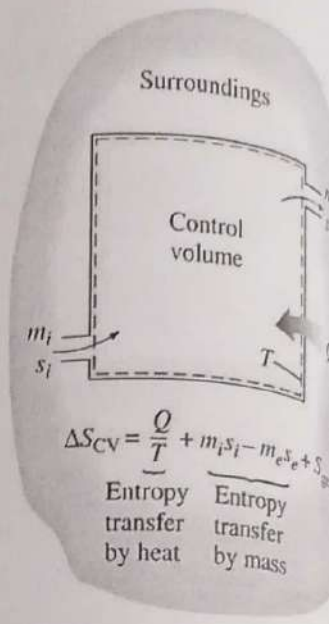
$$\sum \frac{Q_k}{T_k} + \sum m_i s_i - \sum m_e s_e + S_{gen} = (S_2 - S_1)_{CV} \quad \text{(kJ/K)}$$

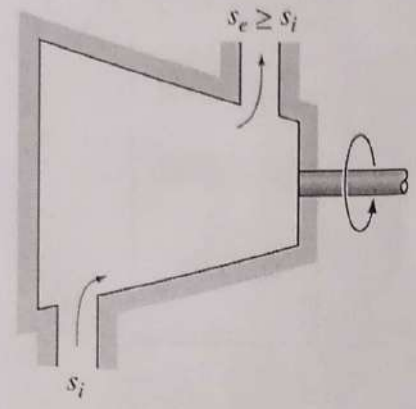
$$\sum \frac{\dot{Q}_k}{T_k} + \sum \dot{m}_i s_i - \sum \dot{m}_e s_e + \dot{S}_{gen} = dS_{CV}/dt \quad \text{(kW/K)}$$

Steady-flow: $$\dot{S}_{gen} = \sum \dot{m}_e s_e - \sum \dot{m}_i s_i - \sum \frac{\dot{Q}_k}{T_k}$$

Steady-flow, single-stream: $$\dot{S}_{gen} = \dot{m}(s_e - s_i) - \sum \frac{\dot{Q}_k}{T_k}$$

Steady-flow, single-stream, adiabatic: $$\dot{S}_{gen} = \dot{m}(s_e - s_i)$$





The entropy of a substance always increases (or remains constant in the case of a reversible process) as it flows through a single-stream, adiabatic, steady-flow device.

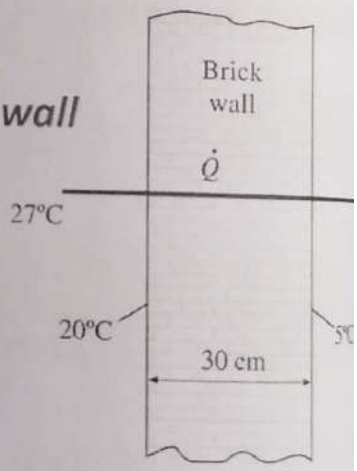
The entropy of a control volume changes as a result of mass flow as well as heat transfer.

EXAMPLES

Entropy balance for heat transfer through a wall

$$\underbrace{\dot{S}_{in} - \dot{S}_{out}}_{\substack{\text{Rate of net entropy}\\ \text{transfer by heat}\\ \text{and mass}}} + \underbrace{\dot{S}_{gen}}_{\substack{\text{Rate of entropy}\\ \text{generation}}} = \underbrace{\overbrace{dS_{system}/dt}^{0\ \text{(steady)}}}_{\substack{\text{Rate of change}\\ \text{in entropy}}}$$

$$\left(\frac{\dot{Q}}{T}\right)_{in} - \left(\frac{\dot{Q}}{T}\right)_{out} + \dot{S}_{gen} = 0$$

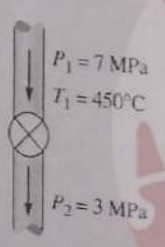


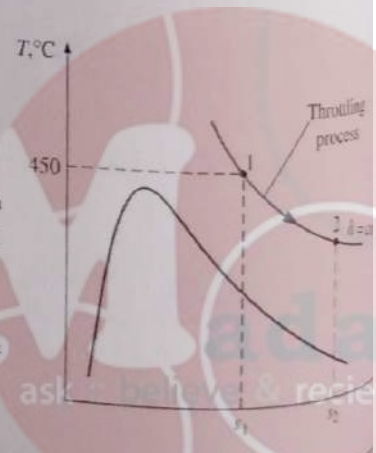
Entropy balance for a throttling process

$$\underbrace{\dot{S}_{in} - \dot{S}_{out}}_{\substack{\text{Rate of net entropy}\\ \text{transfer by heat}\\ \text{and mass}}} + \underbrace{\dot{S}_{gen}}_{\substack{\text{Rate of entropy}\\ \text{generation}}} = \underbrace{\overbrace{dS_{system}/dt}^{0\ \text{(steady)}}}_{\substack{\text{Rate of change}\\ \text{in entropy}}}$$

$$\dot{m}s_1 - \dot{m}s_2 + \dot{S}_{gen} = 0$$

$$\dot{S}_{gen} = \dot{m}(s_2 - s_1)$$



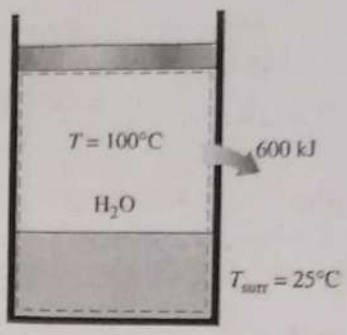


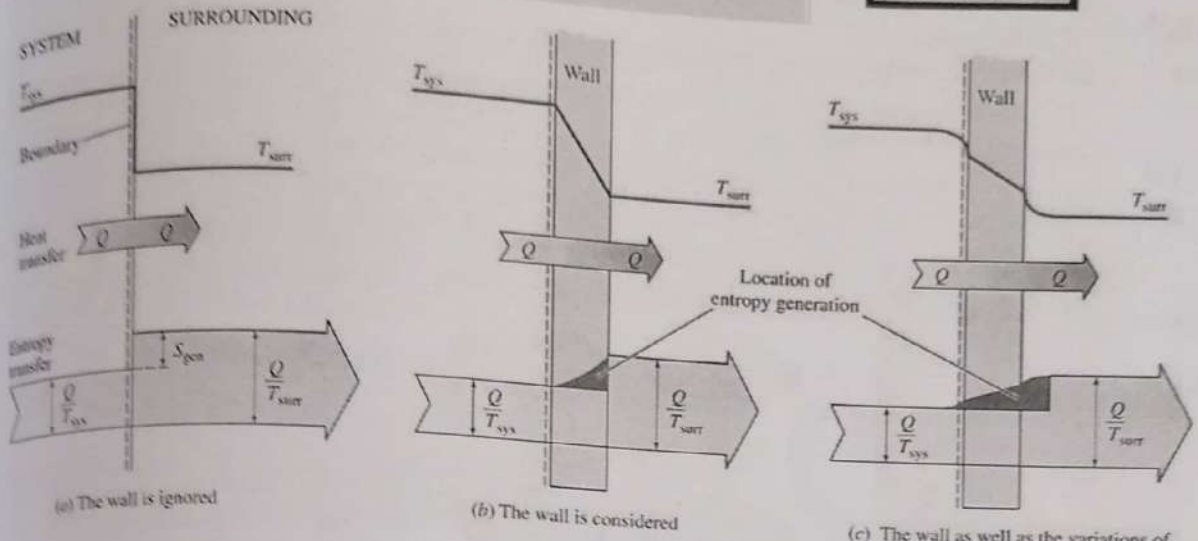
CamScanner الممسوحة ضوئيا بـ

Entropy generation associated with a heat transfer process

$$\underbrace{S_{in} - S_{out}}_{\text{Net entropy transfer by heat and mass}} + \underbrace{S_{gen}}_{\text{Entropy generation}} = \underbrace{\Delta S_{system}}_{\text{Change in entropy}}$$

$$-\frac{Q_{out}}{T_b} + S_{gen} = \Delta S_{sysem}$$





(a) The wall is ignored

(b) The wall is considered

(c) The wall as well as the variations of temperature in the system and the surroundings are considered

Graphical representation of entropy generation during a heat transfer process through a finite temperature difference.

33

EXAMPLE 7–1 Entropy Change during an Isothermal Process

تبخير حرارة ثابتة ← T const

A piston–cylinder device contains a liquid–vapor mixture of water at 300 K. During a constant-pressure process, 750 kJ of heat is transferred to the water. As a result, part of the liquid in the cylinder vaporizes. Determine the entropy change of the water during this process.

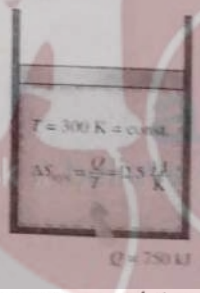
SOLUTION Heat is transferred to a liquid–vapor mixture of water in a piston–cylinder device at constant pressure. The entropy change of water is to be determined.

Assumptions No irreversibilities occur within the system boundaries during the process.

Analysis We take the *entire water* (liquid + vapor) in the cylinder as the system (Fig. 7–4). This is a *closed system* since no mass crosses the system boundary during the process. We note that the temperature of the system remains constant at 300 K during this process since the temperature of a pure substance remains constant at the saturation value during a phase-change process at constant pressure.

The system undergoes an internally reversible, isothermal process, and thus its entropy change can be determined directly from Eq. 7–6 to be

$$\Delta S_{sys,isothermal} = \frac{Q}{T_{sys}} = \frac{750\ \text{kJ}}{300\ \text{K}} = 2.5\ \text{kJ/K}$$



CamScanner الممسوحة ضوئيا بـ

EXAMPLE 7–2 Entropy Generation during Heat Transfer Processes

A heat source at 800 K loses 2000 kJ of heat to a sink at (*a*) 500 K and (*b*) 750 K. Determine which heat transfer process is more irreversible.

SOLUTION Heat is transferred from a heat source to two heat sinks at different temperatures. The heat transfer process that is more irreversible is to be determined.

Analysis A sketch of the reservoirs is shown in Fig. 7–9. Both cases involve heat transfer through a finite temperature difference, and therefore both are irreversible. The magnitude of the irreversibility associated with each process can be determined by calculating the total entropy change for each case. The total entropy change for a heat transfer process involving two reservoirs (a source and a sink) is the sum of the entropy changes of each reservoir since the two reservoirs form an adiabatic system.

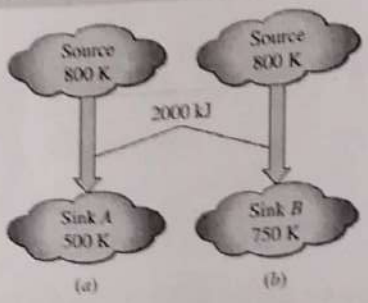


FIGURE 7–9
Schematic for Example 7–2.

The entropy change for each reservoir can be determined from Eq. 7–6 since each reservoir undergoes an internally reversible, isothermal process.

(*a*) For the heat transfer process to a sink at 500 K:

$$\Delta S_{source} = \frac{Q_{source}}{T_{source}} = \frac{-2000\ \text{kJ}}{800\ \text{K}} = -2.5\ \text{kJ/K}$$

$$\Delta S_{sink} = \frac{Q_{sink}}{T_{sink}} = \frac{2000\ \text{kJ}}{500\ \text{K}} = +4.0\ \text{kJ/K}$$

and

$$S_{gen} = \Delta S_{total} = \Delta S_{source} + \Delta S_{sink} = (-2.5 + 4.0)\ \text{kJ/K} = \boxed{1.5\ \text{kJ/K}}$$

Therefore, 1.5 kJ/K of entropy is generated during this process. Noting that both reservoirs have undergone internally reversible processes, the entire entropy generation took place in the partition.

(*b*) Repeating the calculations in part (*a*) for a sink temperature of 750 K, we obtain

$$\Delta S_{source} = -2.5\ \text{kJ/k}$$

$$\Delta S_{sink} = +2.7\ \text{kJ/K}$$

and

$$S_{gen} = \Delta S_{total} = (-2.5 + 2.7)\ \text{kJ/K} = \boxed{0.2\ \text{kJ/K}}$$

The total entropy change for the process in part (*b*) is smaller, and therefore it is less irreversible. This is expected since the process in (*b*) involves a smaller temperature difference and thus a smaller irreversibility.

CamScanner الممسوحة ضوئيا بـ

مثال لنعالج هذا بجدول

EXAMPLE 7–3 Entropy Change of a Substance in a Tank

A rigid tank contains 5 kg of refrigerant-134a initially at 20°C and 140 kPa. The refrigerant is now cooled while being stirred until its pressure drops to 100 kPa. Determine the entropy change of the refrigerant during this process.

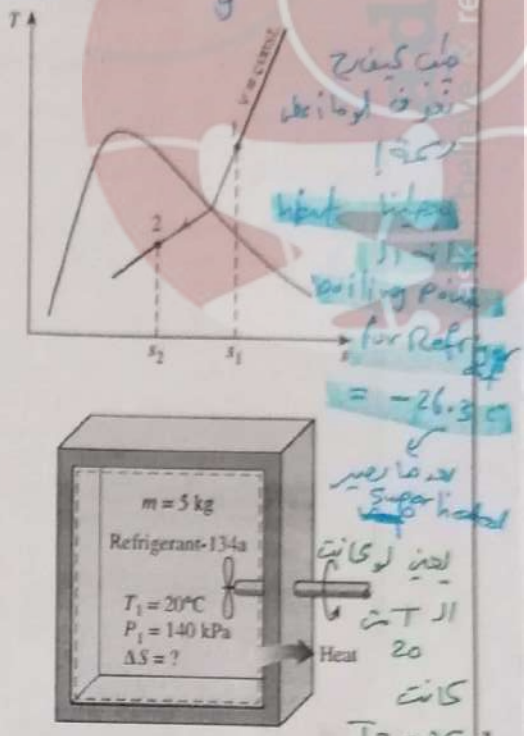
SOLUTION The refrigerant in a rigid tank is cooled while being stirred. The entropy change of the refrigerant is to be determined.

Assumptions The volume of the tank is constant and thus $v_2 = v_1$.

Analysis We take the refrigerant in the tank as the system (Fig. 7–12). This is a *closed system* since no mass crosses the system boundary during the process. We note that the change in entropy of a substance during a process is simply the difference between the entropy values at the final and initial states. The initial state of the refrigerant is completely specified.

Recognizing that the specific volume remains constant during this process, the properties of the refrigerant at both states are

State 1:	$P_1 = 140$ kPa, $T_1 = 20°C$	$s_1 = 1.0625$ kJ/kg·K, $v_1 = 0.16544$ m³/kg
State 2:	$P_2 = 100$ kPa, $(v_2 = v_1)$	$v_f = 0.0007258$ m³/kg, $v_g = 0.19255$ m³/kg



The refrigerant is a saturated liquid–vapor mixture at the final state since $v_f < v_2 < v_g$ at 100 kPa pressure. Therefore, we need to determine the quality first:

$$x_2 = \frac{v_2 - v_f}{v_{fg}} = \frac{0.16544 - 0.0007258}{0.19255 - 0.0007258} = 0.859$$

Thus,

$$s_2 = s_f + x_2 s_{fg} = 0.07182 + (0.859)(0.88008) = 0.8278 \text{ kJ/kg·K}$$

Then, the entropy change of the refrigerant during this process is

$$\Delta S = m(s_2 - s_1) = (5 \text{ kg})(0.8278 - 1.0625) \text{ kJ/kg·K}$$

$$= -1.173 \text{ kJ/K}$$

Discussion The negative sign indicates that the entropy of the system is decreasing during this process. This is not a violation of the second law, however, since it is the *entropy generation* S_{gen} that cannot be negative.

EXAMPLE 7–5 Isentropic Expansion of Steam in a Turbine

Steam enters an adiabatic turbine at 5 MPa and 450°C and leaves at a pressure of 1.4 MPa. Determine the work output of the turbine per unit mass of steam if the process is reversible.

SOLUTION Steam is expanded in an adiabatic turbine to a specified pressure in a reversible manner. The work output of the turbine is to be determined.

Assumptions 1 This is a steady-flow process since there is no change with time at any point and thus $\Delta m_{CV} = 0$, $\Delta E_{CV} = 0$, and $\Delta S_{CV} = 0$. 2 The process is reversible. 3 Kinetic and potential energies are negligible. 4 The turbine is adiabatic and thus there is no heat transfer.

Analysis We take the turbine as the system (Fig. 7–15). This is a control volume since mass crosses the system boundary during the process. We note that there is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$.

The power output of the turbine is determined from the rate form of the energy balance.

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{\frac{dE_{system}/dt}{\text{Rate of change in internal, kinetic, potential, etc., energies}}}_{(0 \text{ steady})} = 0$$



$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}h_1 = \dot{W}_{out} + \dot{m}h_2 \quad (\text{since } \dot{Q} = 0,\ \text{ke} \cong \text{pe} \cong 0)$$

$$\dot{W}_{out} = \dot{m}(h_1 - h_2)$$

The inlet state is completely specified since two properties are given. But only one property (pressure) is given at the final state, and we need one more property to fix it. The second property comes from the observation that the process is reversible and adiabatic, and thus isentropic. Therefore, $s_2 = s_1$, and

State 1: $P_1 = 5$ MPa, $T_1 = 450°C$ → $h_1 = 3317.2$ kJ/kg, $s_1 = 6.8210$ kJ/kg·K

State 2: $P_2 = 1.4$ MPa, $s_2 = s_1$ → $h_2 = 2967.4$ kJ/kg

Then, the work output of the turbine per unit mass of the steam becomes

$$w_{out} = h_1 - h_2 = 3317.2 - 2967.4 = \boxed{349.8 \text{ kJ/kg}}$$

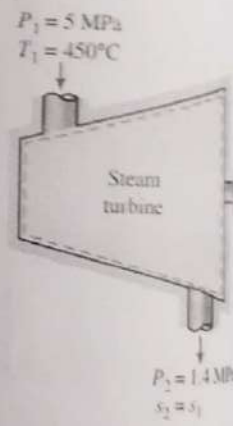


FIGURE
Schematic and T-s diagr
Exam

EXAMPLE 7–6 **The *T-S* Diagram of the Carnot Cycle**

Show the Carnot cycle on a *T-S* diagram and indicate the areas that represent the heat supplied Q_H, heat rejected Q_L, and the net work output $W_{net,out}$ on this diagram.

SOLUTION The Carnot cycle is to be shown on a *T-S* diagram, and the areas that represent Q_H, Q_L, and $W_{net,out}$ are to be indicated.

Analysis Recall that the Carnot cycle is made up of two reversible isothermal (T = constant) processes and two isentropic (s = constant) processes. These four processes form a rectangle on a *T-S* diagram, as shown in Fig. 7–19.

On a *T-S* diagram, the area under the process curve represents the heat transfer for that process. Thus the area $A12B$ represents Q_H, the area $A43B$ represents Q_L, and the difference between these two (the area in color) represents the net work since

$$W_{net,out} = Q_H - Q_L$$

Therefore, the area enclosed by the path of a cycle (area 1234) on a *T-S* diagram represents the net work. Recall that the area enclosed by the path of a cycle also represents the net work on a *P-V* diagram.

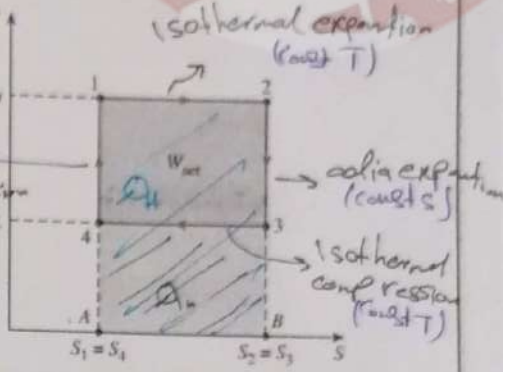


FIGURE 7–19
The *T-S* diagram of a Carnot cycle (Example 7–6).

EXAMPLE 7–7 **Effect of Density of a Liquid on Entropy**

Liquid methane is commonly used in various cryogenic applications. The critical temperature of methane is 191 K (or −82°C), and thus methane must be maintained below 191 K to keep it in liquid phase. The properties of liquid methane at various temperatures and pressures are given in Table 7–1. Determine the entropy change of liquid methane as it undergoes a process from 110 K and 1 MPa to 120 K and 5 MPa (*a*) using tabulated properties and (*b*) approximating liquid methane as an incompressible substance. What is the error involved in the latter case?

SOLUTION Liquid methane undergoes a process between two specified states. The entropy change of methane is to be determined by using actual data and by assuming methane to be incompressible.

Analysis (*a*) We consider a unit mass of liquid methane (Fig. 7–28). The properties of the methane at the initial and final states are

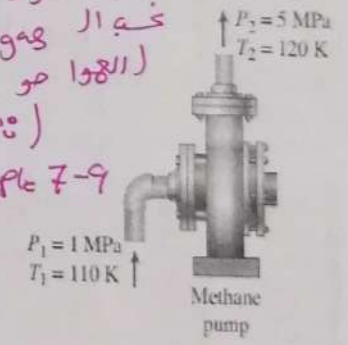


FIGURE 7–28
Schematic for Example 7–7.

TABLE 7–1

Properties of liquid methane

Temp., T, K	Pressure, P, MPa	Density, ρ, kg/m³	Enthalpy, h, kJ/kg	Entropy, s, kJ/kg·K	Specific heat, c_p, kJ/kg·K
110	0.5	425.3	208.3	4.878	3.476
	1.0	425.8	209.0	4.875	3.471
	2.0	426.6	210.5	4.867	3.460
	5.0	429.1	215.0	4.844	3.432
120	0.5	410.4	243.4	5.185	3.551
	1.0	411.0	244.1	5.180	3.543
	2.0	412.0	245.4	5.171	3.528
	5.0	415.2	249.6	5.145	3.486

CamScanner الممسوحة ضوئيا بـ

State 1: $P_1 = 1\ \text{MPa}$, $T_1 = 110\ \text{K}$ $\Rightarrow$ $s_1 = 4.875\ \text{kJ/kg·K}$, $c_{p1} = 3.471\ \text{kJ/kg·K}$

State 2: $P_2 = 5\ \text{MPa}$, $T_2 = 120\ \text{K}$ $\Rightarrow$ $s_2 = 5.145\ \text{kJ/kg·K}$, $c_{p2} = 3.486\ \text{kJ/kg·K}$

Therefore,

$$\Delta s = s_2 - s_1 = 5.145 - 4.875 = 0.270\ \text{kJ/kg·K}$$

(*b*) Approximating liquid methane as an incompressible substance, its entropy change is determined to be

$$\Delta s = c_{avg} \ln \frac{T_2}{T_1} = (3.4785\ \text{kJ/kg·K}) \ln \frac{120\ \text{K}}{110\ \text{K}} = 0.303\ \text{kJ/kg·K}$$

since

$$c_{avg} = \frac{c_{p1} + c_{p2}}{2} = \frac{3.471 + 3.486}{2} = 3.4785\ \text{kJ/kg·K}$$

Therefore, the error involved in approximating liquid methane as an incompressible substance is

$$\text{Error} = \frac{|\Delta s_{actual} - \Delta s_{ideal}|}{\Delta s_{actual}} = \frac{|0.270 - 0.303|}{0.270} = 0.122\ (\text{or } 12.2\%)$$

EXAMPLE 7–9 Entropy Change of an Ideal Gas

Air is compressed from an initial state of 100 kPa and 17°C to a final state of 600 kPa and 57°C. Determine the entropy change of air during this compression process by using (*a*) property values from the air table and (*b*) average specific heats.

SOLUTION Air is compressed between two specified states. The entropy change of air is to be determined by using tabulated property values and also by using average specific heats.

Assumptions Air is an ideal gas since it is at a high temperature and low pressure relative to its critical-point values. Therefore, entropy change relations developed under the ideal-gas assumption are applicable.

Analysis A sketch of the system and the *T*-*s* diagram for the process are given in Fig. 7–33. We note that both the initial and the final states of air are completely specified.

(*a*) The properties of air are given in the air table (Table A–17). Reading s° values at given temperatures and substituting, we find

$$s_2 - s_1 = s_2^\circ - s_1^\circ - R \ln \frac{P_2}{P_1}$$

$$= [1.79783 - 1.66802)\ \text{kJ/kg·K}] - (0.287\ \text{kJ/kg·K}) \ln \frac{600\ \text{kPa}}{100\ \text{kPa}}$$

$$= -0.3844\ \text{kJ/kg·K}$$

(*b*) The entropy change of air during this process can also be determined approximately from Eq. 7–34 by using a c_p value at the average temperature of 37°C (Table A–2*b*) and treating it as a constant:

$$s_2 - s_1 = c_{p,avg} \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$$

$$= (1.006\ \text{kJ/kg·K}) \ln \frac{330\ \text{K}}{290\ \text{K}} - (0.287\ \text{kJ/kg·K}) \ln \frac{600\ \text{kPa}}{100\ \text{kPa}}$$

$$= -0.3842\ \text{kJ/kg·K}$$

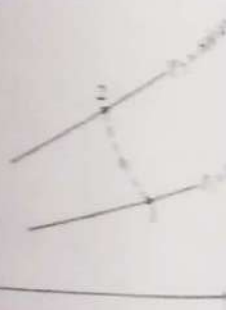


FIGURE
Schematic and *T*-*s* diagr
Exampl

EXAMPLE 7–10 **Isentropic Compression of Air in a Car Engine**

Air is compressed in a car engine from 22°C and 95 kPa in a reversible and adiabatic manner. If the compression ratio V_1/V_2 of this engine is 8, determine the final temperature of the air.

SOLUTION Air is compressed in a car engine isentropically. For a given compression ratio, the final air temperature is to be determined.

Assumptions At specified conditions, air can be treated as an ideal gas. Therefore, the isentropic relations for ideal gases are applicable.

Analysis A sketch of the system and the T-s diagram for the process are given in Fig. 7–37.

This process is easily recognized as being isentropic since it is both reversible and adiabatic. The final temperature for this isentropic process can be determined from Eq. 7–50 with the help of relative specific volume data (Table A–17), as illustrated in Fig. 7–38.

For closed systems: $$\frac{V_2}{V_1} = \frac{v_2}{v_1}$$

At $T_1 = 295$ K: $$v_{r1} = 647.9$$

From Eq. 7–50: $$v_{r2} = v_{r1}\left(\frac{V_2}{V_1}\right) = (647.9)\left(\frac{1}{8}\right) = 80.99 \rightarrow T_2 = 662.7 \text{ K}$$

Therefore, the temperature of air will increase by 367.7°C during this process.

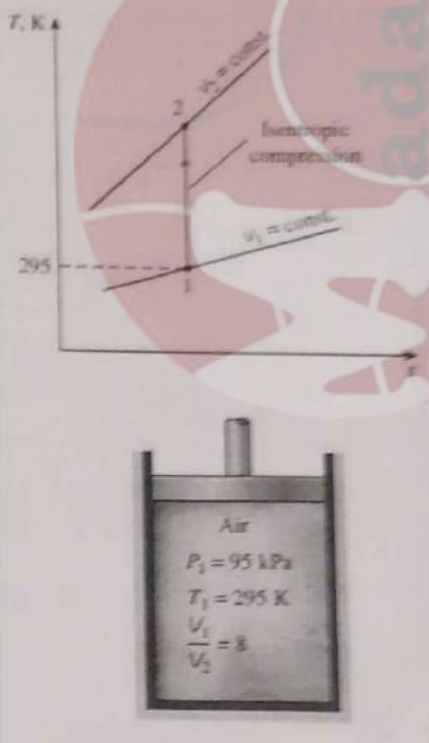


FIGURE 7–37
Schematic and T-s diagram for Example 7–10.

ALTERNATIVE SOLUTION The final temperature could also be determined from Eq. 7–42 by assuming constant specific heats for air:

$$\left(\frac{T_2}{T_1}\right)_{s=\text{const.}} = \left(\frac{V_1}{V_2}\right)^{k-1}$$

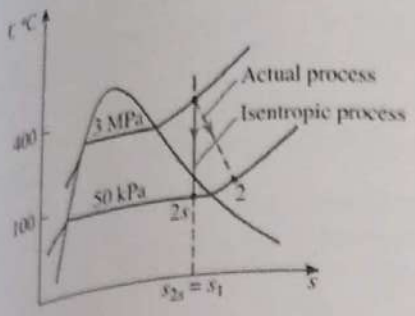
The specific heat ratio k also varies with temperature, and we need to use the value of k corresponding to the average temperature. However, the final temperature is not given, and so we cannot determine the average temperature in advance. For such cases, calculations can be started with a k value at the initial or the anticipated average temperature. This value could be refined later, if necessary, and the calculations can be repeated. We know that the temperature of the air will rise considerably during this adiabatic compression process, so we *guess* the average temperature to be about 450 K. The k value at this anticipated average temperature is determined from Table A–2*b* to be 1.391. Then, the final temperature of air becomes

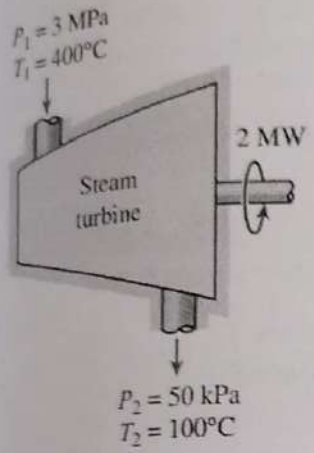
$$T_2 = (295 \text{ K})(8)^{1.391-1} = 665.2 \text{ K}$$

CamScanner الممسوحة ضوئيا بـ

EXAMPLE 7–14 **Isentropic Efficiency of a Steam Turbine**

Steam enters an adiabatic turbine steadily at 3 MPa and 400°C and leaves at 50 kPa and 100°C. If the power output of the turbine is 2 MW, determine (*a*) the isentropic efficiency of the turbine and (*b*) the mass flow rate of the steam flowing through the turbine.





SOLUTION Steam flows steadily in a turbine between inlet and exit states. For a specified power output, the isentropic efficiency and the mass flow rate are to be determined.

Assumptions 1 Steady operating conditions exist. 2 The changes in kinetic and potential energies are negligible.

Analysis A sketch of the system and the *T*-*s* diagram of the process are given in Fig. 7–49.

(*a*) The enthalpies at various states are

State 1: $P_1 = 3$ MPA, $T_1 = 400°C$ → $h_1 = 3231.7$ kJ/kg, $s_1 = 6.9235$ kJ/kg·K (Table A–6)

State 2a: $P_{2a} = 50$ kPa, $T_{2a} = 100°C$ → $h_{2a} = 2682.4$ kJ/kg (Table A–6)

The exit enthalpy of the steam for the isentropic process h_{2s} is determined from the requirement that the entropy of the steam remain constant ($s_{2s} = s_1$):

State 2s: $P_{2s} = 50$ kPa, $(s_{2s} = s_1)$ → $s_f = 1.0912$ kJ/kg·K, $s_g = 7.5931$ kJ/kg·K (Table A–5)

Obviously, at the end of the isentropic process steam exists as a saturated mixture since $s_f < s_{2s} < s_g$. Thus, we need to find the quality at state 2s first:

$$x_{2s} = \frac{s_{2s} - s_f}{s_{fg}} = \frac{6.9235 - 1.0912}{6.5019} = 0.897$$

and

$$h_{2s} = h_f + x_{2s}h_{fg} = 340.54 + 0.897(2304.7) = 2407.9 \text{ kJ/kg}$$

By substituting these enthalpy values into Eq. 7–61, the isentropic efficiency of this turbine is determined to be

$$\eta_T \cong \frac{h_1 - h_{2a}}{h_1 - h_{2s}} = \frac{3231.7 - 2682.4}{3231.7 - 2407.9} = 0.667 \text{ (or } 66.7\%)$$

(*b*) The mass flow rate of steam through this turbine is determined from the energy balance for steady-flow systems:

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}h_1 = \dot{W}_{a,out} + \dot{m}h_{2a}$$

$$\dot{W}_{a,out} = \dot{m}(h_1 - h_{2a})$$

$$\left(1000 \text{ kJ/s}\right) = \dot{m}(3231.7 - 2682.4) \text{ kJ/kg}$$

CamScanner الممسوحة ضوئيا بـ

EXAMPLE 7–12 Compressing a Substance in the Liquid versus Gas Phases

Determine the compressor work input required to compress steam isentropically from 100 kPa to 1 MPa, assuming that the steam exists as (*a*) saturated liquid and (*b*) saturated vapor at the inlet state.

SOLUTION Steam is to be compressed from a given pressure to a specified pressure isentropically. The work input is to be determined for the cases of steam being a saturated liquid and saturated vapor at the inlet.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible. **3** The process is given to be isentropic.

Analysis We take first the turbine and then the pump as the *system*. Both are *control volumes* since mass crosses the boundary. Sketches of the pump and the turbine together with the *T-s* diagram are given in Fig. 7–42.

(*a*) In this case, steam is a saturated liquid initially, and its specific volume is

$$v_1 = v_{f\,@\,100\,\text{kPa}} = 0.001043\ \text{m}^3/\text{kg} \quad \text{(Table A–5)}$$

which remains essentially constant during the process. Thus,

$$w_{\text{rev,in}} = \int_1^2 v\,dP \cong v_1(P_2 - P_1)$$
$$= (0.001043\ \text{m}^3/\text{kg})[(1000 - 100)\ \text{kPa}]\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right)$$
$$= 0.94\ \text{kJ/kg}$$

(*b*) This time, steam is a saturated vapor initially and remains a vapor during the entire compression process. Since the specific volume of a gas changes considerably during a compression process, we need to know how v varies

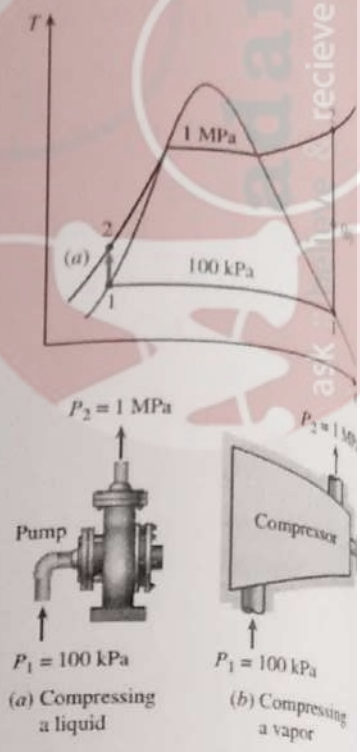


FIGURE 7–
Schematic and *T-s* diagram
Example 7–

with P to perform the integration in Eq. 7–53. This relation, in general, is not readily available. But for an isentropic process, it is easily obtained from the second $T\,ds$ relation by setting $ds = 0$:

$$\left.\begin{aligned} T\,ds &= dh - v\,dP \quad \text{(Eq. 7-24)} \\ ds &= 0 \quad \text{(isentropic process)} \end{aligned}\right\} \quad v\,dP = dh$$

Thus,

$$w_{\text{rev,in}} = \int_1^2 v\,dP = \int_1^2 dh = h_2 - h_1$$

This result could also be obtained from the energy balance relation for an isentropic steady-flow process. Next we determine the enthalpies:

$$\textit{State 1:} \quad \left.\begin{aligned} P_1 &= 100\ \text{kPa} \\ \text{(sat. vapor)} \end{aligned}\right\} \quad \begin{aligned} h_1 &= 2675.0\ \text{kJ/kg} \\ s_1 &= 7.3589\ \text{kJ/kg}\cdot\text{K} \end{aligned} \quad \text{(Table A–5)}$$

$$\textit{State 2:} \quad \left.\begin{aligned} P_2 &= 1\ \text{MPa} \\ s_2 &= s_1 \end{aligned}\right\} \quad h_2 = 3194.5\ \text{kJ/kg} \quad \text{(Table A–6)}$$

Thus,

$$w_{\text{rev,in}} = (3194.5 - 2675.0)\ \text{kJ/kg} = 519.5\ \text{kJ/kg}$$

Discussion Note that compressing steam in the vapor form would require over 500 times more work than compressing it in the liquid form between the same pressure limits.

CamScanner الممسوحة ضوئيا بـ

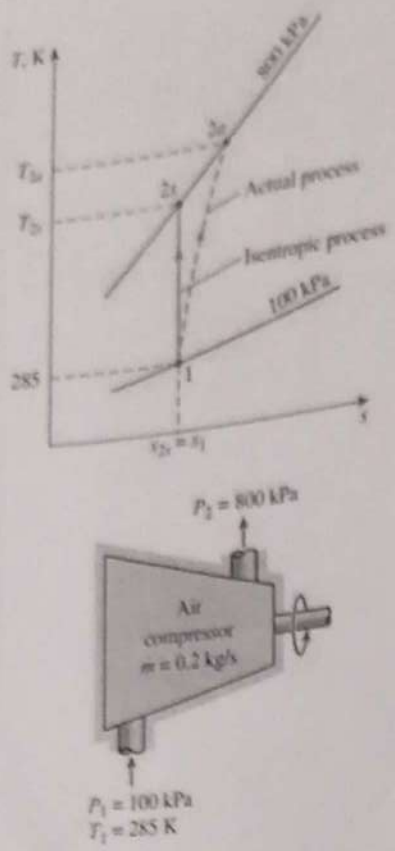


FIGURE 7–52
Schematic and *T-s* diagram for Example 7–15.

EXAMPLE 7–15 Effect of Efficiency on Compressor Power

Air is compressed by an adiabatic compressor from 100 kPa and [illegible] pressure of 800 kPa at a steady rate of 0.2 kg/s. If the isentropic [illegible] of the compressor is 80 percent, determine (*a*) the exit temperature and (*b*) the required power input to the compressor.

SOLUTION Air is compressed to a specified pressure at a specified [illegible] a given isentropic efficiency, the exit temperature and the power [illegible] be determined.

Assumptions 1 Steady operating conditions exist. 2 Air is an [illegible] 3 The changes in kinetic and potential energies are negligible.

Analysis A sketch of the system and the *T-s* diagram of the [illegible] given in Fig. 7–52.

(*a*) We know only one property (pressure) at the exit state, and we know one more to fix the state and thus determine the exit temperature property that can be determined with minimal effort in this case is the isentropic efficiency of the compressor is given. At the compressor

$$T_1 = 285 \text{ K} \rightarrow h_1 = 285.14 \text{ kJ/kg} \quad \text{(Table A–17)}$$
$$(P_{r1} = 1.1584)$$

The enthalpy of the air at the end of the isentropic compression [illegible] determined by using one of the isentropic relations of ideal gases,

$$P_{r2} = P_{r1}\left(\frac{P_2}{P_1}\right) = 1.1584\left(\frac{800 \text{ kPa}}{100 \text{ kPa}}\right) = 9.2672$$

and

$$P_{r2} = 9.2672 \rightarrow h_{2s} = 517.05 \text{ kJ/kg}$$

Substituting the known quantities into the isentropic efficiency relation, we have

$$\eta_C \cong \frac{h_{2s} - h_1}{h_{2a} - h_1} \rightarrow 0.80 = \frac{(517.05 - 285.14) \text{ kJ/kg}}{(h_{2a} - 285.14) \text{ kJ/kg}}$$

Thus,

$$h_{2a} = 575.03 \text{ kJ/kg} \rightarrow T_{2a} = \mathbf{569.5 \text{ K}}$$

(*b*) The required power input to the compressor is determined from the energy balance for steady-flow devices,

$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$
$$\dot{m}h_1 + \dot{W}_{a,\text{in}} = \dot{m}h_{2a}$$
$$\dot{W}_{a,\text{in}} = \dot{m}(h_{2a} - h_1)$$
$$= (0.2 \text{ kg/s})[(575.03 - 285.14) \text{ kJ/kg}]$$
$$= \mathbf{58.0 \text{ kW}}$$

Discussion Notice that in determining the power input to the compressor, we used h_{2a} instead of h_{2s} since h_{2a} is the actual enthalpy of the air as it exits the compressor. The quantity h_{2s} is a hypothetical enthalpy value that the air would have if the process were isentropic.

CamScanner الممسوحة ضوئيا بـ

Chapter 9

GAS POWER CYCLES



power ← cycle هنا انتاج الـ

$\dot{W}$ = work

$\dot{W}$ (KJ/s)

Thermodynamics: An Engineering Approach
Yunus A. Cengel, Michael A. Boles, Mehmet Kanoglu
McGraw-Hill

Dr. Ahmad M. AbuYaghi
October 2023

أهم الأنظمة التي سنستخدمها هنا لانتاج (شغل، زيادة انتاج الكهربا
(power cycle) وتستخدم غازات الـ stream لتوليد طاقة كهربائية وزيادة انتاج الأجهزة

BASIC CONSIDERATIONS IN THE ANALYSIS OF POWER CYCLES

Thermal efficiency of heat engines

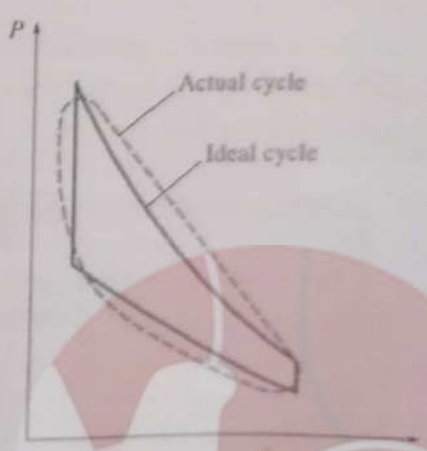
3 cycles هنا gas power cycle الـ

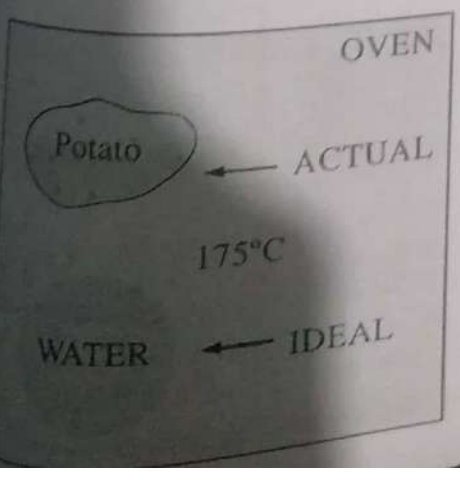
Most power-producing devices operate on cycles.

Ideal cycle: A cycle that resembles the actual cycle closely but is made up totally of internally reversible processes is called an.

$$\eta_{th} = \frac{W_{net}}{Q_{in}} \quad \text{or} \quad \eta_{th} = \frac{\dot{W}_{net}}{\dot{q}_{in}}$$

Reversible cycles such as Carnot cycle have the highest thermal efficiency of all heat engines operating between the same temperature levels. Unlike ideal cycles, they are totally reversible, and unsuitable as a realistic model.





Modeling is a powerful engineering tool that provides great insight and simplicity at the expense of some loss in accuracy.

The analysis of many complex processes can be reduced to a manageable level by utilizing some idealizations.

CamScanner الممسوحة ضوئيا بـ

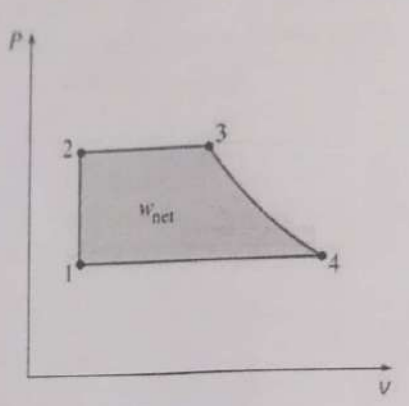
- On a *T-s* diagram, the ratio of the area enclosed by the cyclic curve to the area under the heat-addition process curve represents the thermal efficiency of the cycle.
- Any modification that increases the ratio of these two areas will also increase the thermal efficiency of the cycle.

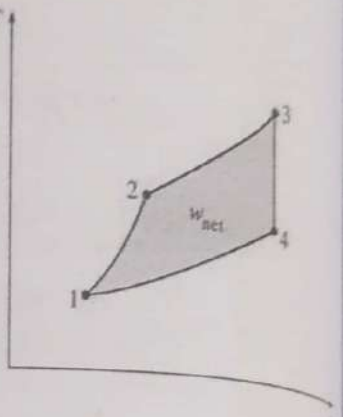
Care should be exercised in the interpretation of the results from ideal cycles.

The idealizations and simplifications in the analysis of power cycles:

1. The cycle does not involve any friction. Therefore, the working fluid does not experience any pressure drop as it flows in pipes or devices such as heat exchangers.
2. All expansion and compression processes take place in a *quasi-equilibrium* manner.
3. The pipes connecting the various components of a system are well insulated, and *heat transfer* through them is negligible.

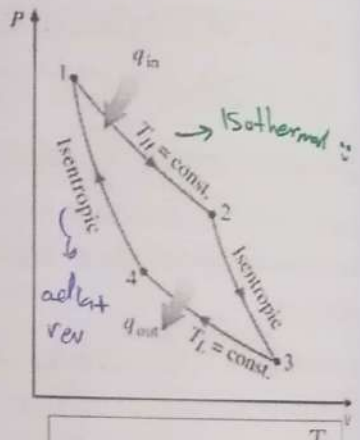
On both *P-v* and *T-s* diagrams, the area enclosed by the process curve represents the net work of the cycle.



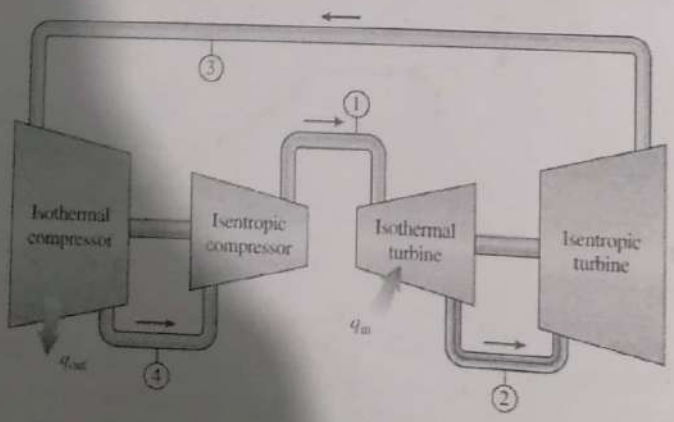


CARNOT CYCLE AND ITS VALUE IN ENG.

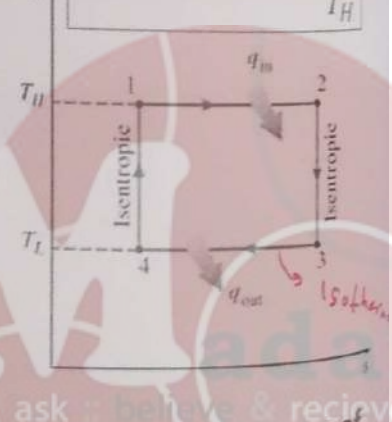
- The Carnot cycle is composed of four totally reversible processes: isothermal heat addition, isentropic expansion, isothermal heat rejection, and isentropic compression.
- ***For both ideal and actual cycles:*** *Thermal efficiency increases with an increase in the average temperature at which heat is supplied to the system or with a decrease in the average temperature at which heat is rejected from the system.*



$$\eta_{th,Carnot} = 1 - \frac{T_L}{T_H}$$



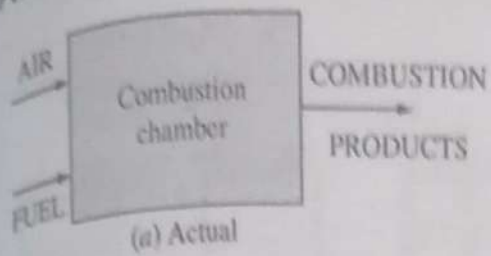
A steady-flow Carnot engine.



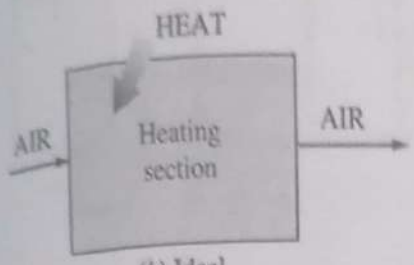
P-v and *T-s* diagrams of a Carnot cycle.

ask & believe & recive
CamScanner الممسوحة ضوئيا بـ

AIR-STANDARD ASSUMPTIONS



(a) Actual



(b) Ideal

The combustion process is replaced by a heat-addition process in ideal cycles.

Air-standard assumptions:

1. The working fluid is air, which continuously circulates in a closed loop and always behaves as an ideal gas.
2. All the processes that make up the cycle are internally reversible.
3. The combustion process is replaced by a heat-addition process from an external source.
4. The exhaust process is replaced by a heat-rejection process that restores the working fluid to its initial state.

Cold-air-standard assumptions: When the working fluid is considered to be air with constant specific heats at room temperature (25°C).

Air-standard cycle: A cycle for which the air-standard assumptions are applicable.

AN OVERVIEW OF RECIPROCATING ENGINES

Compression ratio

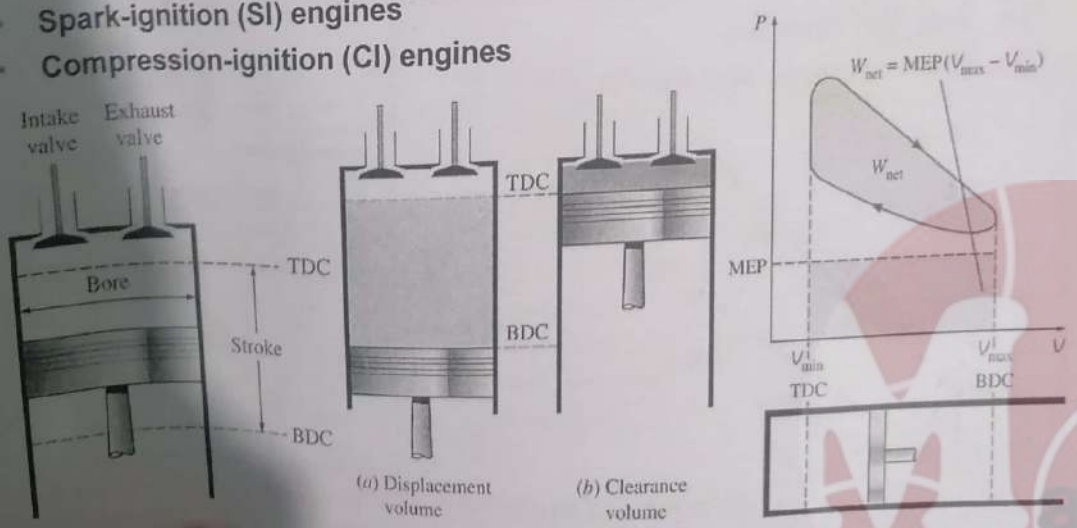
$$r = \frac{V_{max}}{V_{min}} = \frac{V_{BDC}}{V_{TDC}}$$

W_{net} = MEP × Piston area × Stroke = MEP × Displacement volume

Mean effective pressure

$$MEP = \frac{W_{net}}{V_{max} - V_{min}} = \frac{W_{net}}{V_{max} - V_{min}} \quad \text{(kPa)}$$

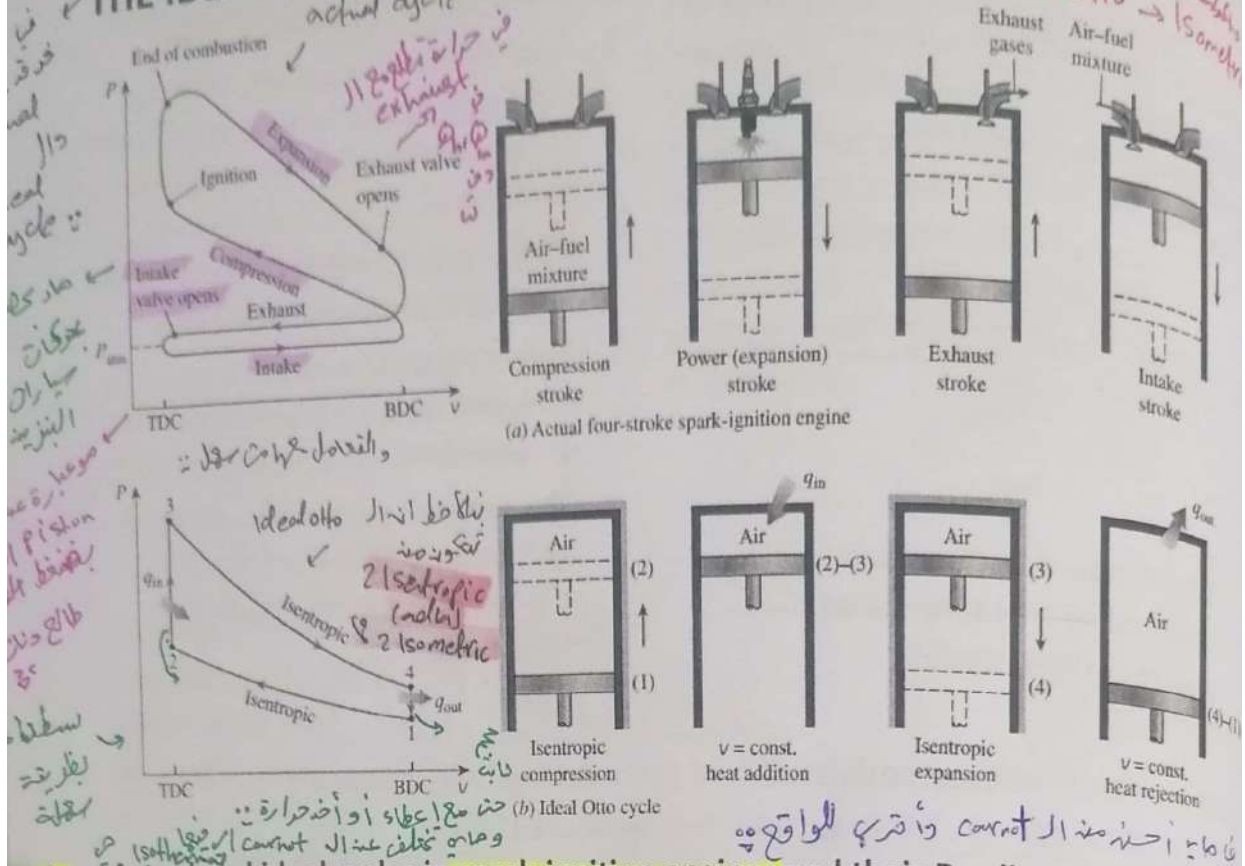
- **Spark-ignition (SI) engines**
- **Compression-ignition (CI) engines**



Nomencla[illegible] for reciprocating engines.

Qadar ask & believe & recieve
CamScanner الممسوحة ضوئيا بـ

OTTO CYCLE:
THE IDEAL CYCLE FOR SPARK-IGNITION (SI) ENGINES



Actual and ideal cycles in spark-ignition engines and their *P-v* diagrams.

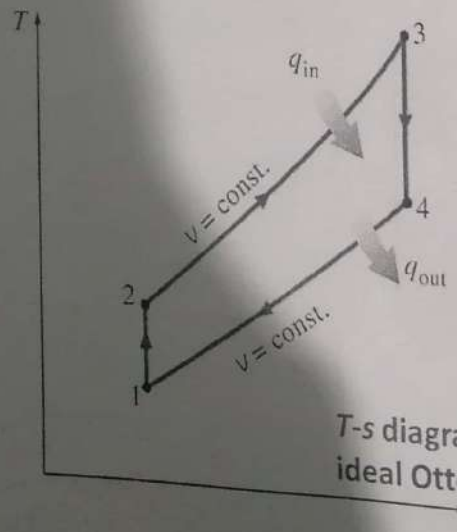
Four-stroke cycle

1 cycle = 4 stroke = 2 revolution

Two-stroke cycle

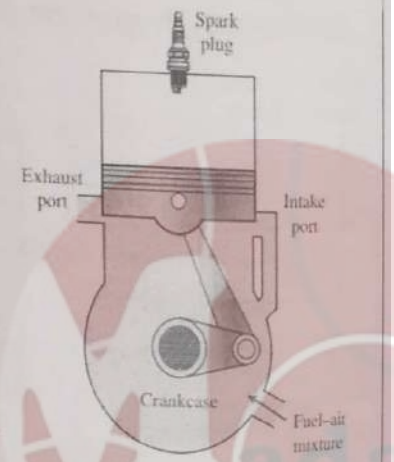
1 cycle = 2 stroke = 1 revolution

1-2 Isentropic compression
2-3 Constant-volume heat addition
3-4 Isentropic expansion
4-1 Constant-volume heat rejection



T-s diagram of the ideal Otto cycle.

The two-stroke engines are generally less efficient than their four-stroke counterparts, but they are relatively simple and inexpensive, and they have high power-to-weight and power-to-volume ratios.



Schematic of a two-stroke reciprocating engine.

CamScanner الممسوحة ضوئيا بـ

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_{exit} - h_{inlet}$$

$$q_{in} = u_3 - u_2 = c_v(T_3 - T_2)$$

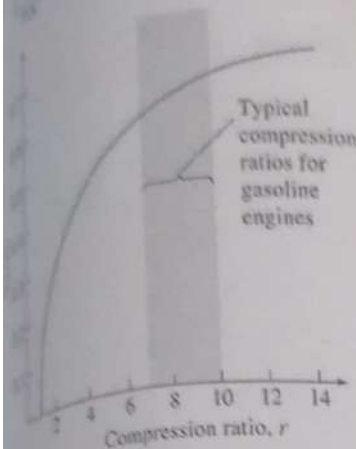
$$q_{out} = u_4 - u_1 = c_v(T_4 - T_1)$$

$$\eta_{th,Otto} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_4 - T_1}{T_3 - T_2} = 1 - \frac{T_1(T_4/T_1 - 1)}{T_2(T_3/T_2 - 1)}$$

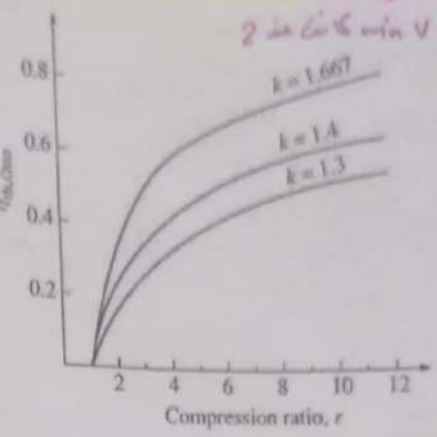
$$\frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{k-1} = \left(\frac{v_3}{v_4}\right)^{k-1} = \frac{T_4}{T_3}$$

$$r = \frac{V_{max}}{V_{min}} = \frac{V_1}{V_2} = \frac{v_1}{v_2}$$

$$\eta_{th,Otto} = 1 - \frac{1}{r^{k-1}}$$



In SI engines, the compression ratio is limited by autoignition or engine knock.

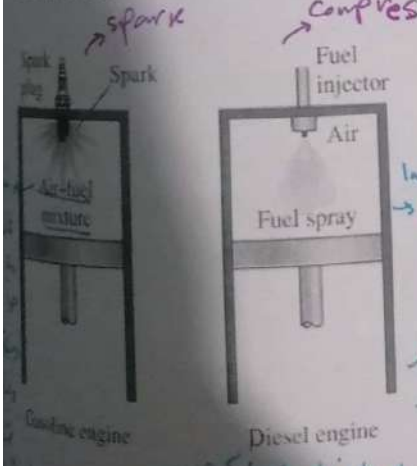


The thermal efficiency of the Otto cycle increases with the specific heat ratio k of the working fluid.

Thermal efficiency of the ideal Otto cycle as a function of compression ratio (k = 1.4).

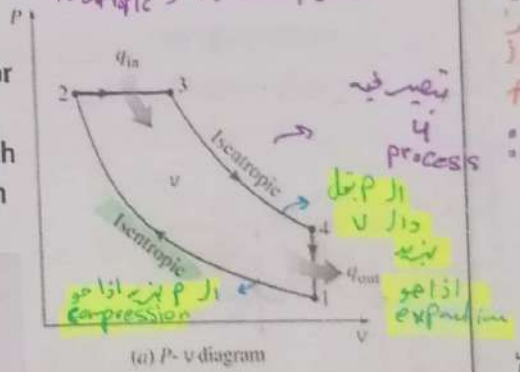
DIESEL CYCLE: THE IDEAL CYCLE FOR COMPRESSION-IGNITION ENGINES

- In diesel engines, only air is compressed during the compression stroke, eliminating the possibility of autoignition (engine knock).
- Therefore, diesel engines can be designed to operate at much higher compression ratios than SI engines, typically between 12 and 24.

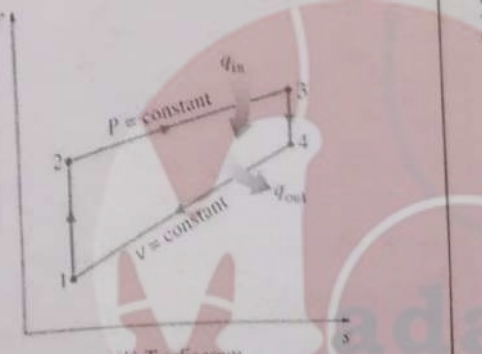


- 1-2 isentropic compression
- 2-3 constant-volume heat addition
- 3-4 isentropic expansion
- 4-1 constant-volume heat rejection.

In diesel engines, the spark plug is replaced by a fuel injector, and only air is compressed during the compression process.



(a) P-v diagram



(b) T-s diagram

CamScanner الممسوحة ضوئيا بـ

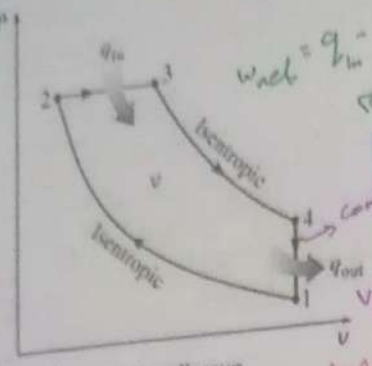
$$q_{in} - w_{b,out} = u_3 - u_2 \rightarrow q_{in} = P_2(v_3 - v_2) + (u_3 - u_2)$$
$$= h_3 - h_2 = c_p(T_3 - T_2)$$

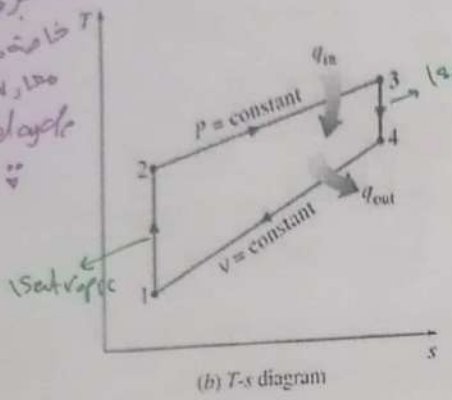
$$-q_{out} = u_1 - u_4 \rightarrow q_{out} = u_4 - u_1 = c_v(T_4 - T_1)$$

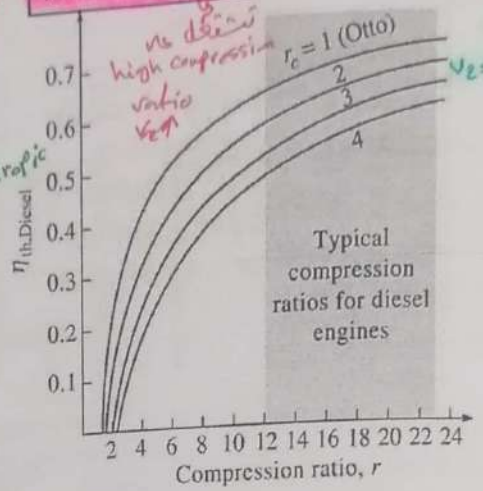
$$\eta_{th,Diesel} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_4 - T_1}{k(T_3 - T_2)} = 1 - \frac{T_1(T_4/T_1 - 1)}{kT_2(T_3/T_2 - 1)}$$

$$r_c = \frac{V_3}{V_2} = \frac{v_3}{v_2} \quad \text{Cutoff ratio}$$

$$\eta_{th,Diesel} = 1 - \frac{1}{r^{k-1}}\left[\frac{r_c^k - 1}{k(r_c - 1)}\right]$$



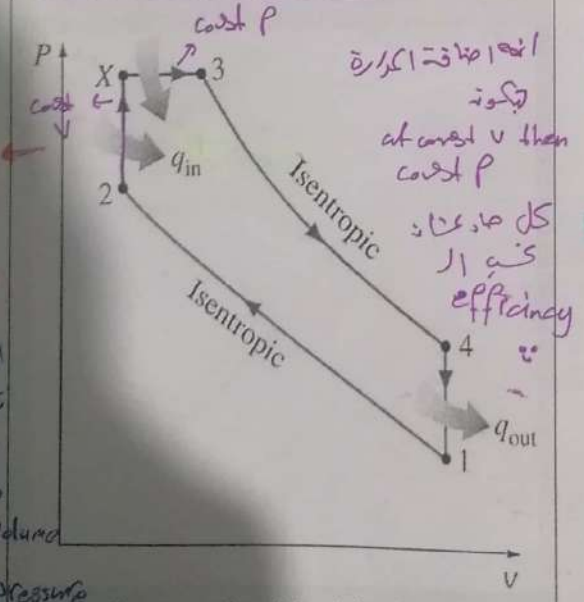




for the same compression ratio

Thermal efficiency of the ideal Diesel cycle as a function of compression and cutoff ratios (k=1.4).

Dual cycle: A more realistic ideal cycle model for modern, high-speed compression ignition engine.



P-v diagram of an ideal dual cycle

QUESTIONS

1) Diesel engines operate at higher air-fuel ratios than gasoline engines. Why?
2) Despite higher power to weight ratios, two-stroke engines are not used in automobiles. Why?
3) The stationary diesel engines are among the most efficient power producing devices (about 50%). Why?
4) What is a turbocharger? Why are they mostly used in diesel engines compared to gasoline engines.

CamScanner الممسوحة ضوئيا بـ

THE IDEAL CYCLE FOR GAS-TURBINE ENGINES

The combustion process is replaced by a constant-pressure heat-addition process from an external source, and the exhaust process is replaced by a constant-pressure heat-rejection process to the ambient air.

1-2 Isentropic compression (in a compressor)
2-3 Constant-pressure heat addition
3-4 Isentropic expansion (in a turbine)
4-1 Constant-pressure heat rejection

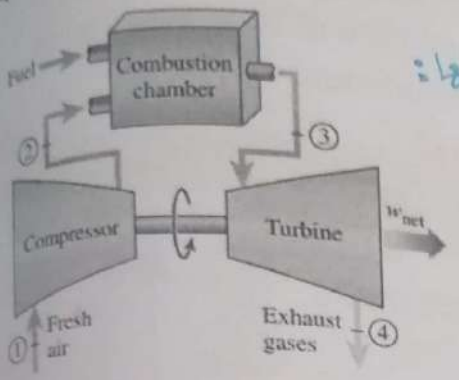


FIGURE 9–29
An open-cycle gas-turbine engine.

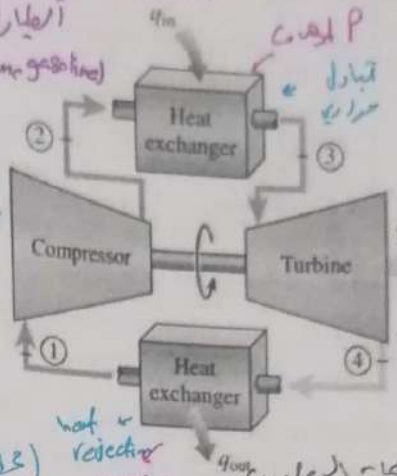
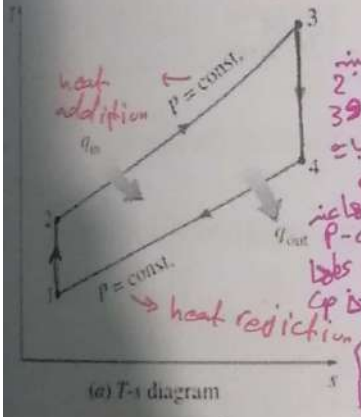


FIGURE 9–30
A closed-cycle gas-turbine engine.

An open-cycle gas-turbine engine. A closed-cycle gas-turbine engine.



(a) T-s diagram

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_{exit} - h_{inlet}$$

$$q_{in} = h_3 - h_2 = c_p(T_3 - T_2)$$

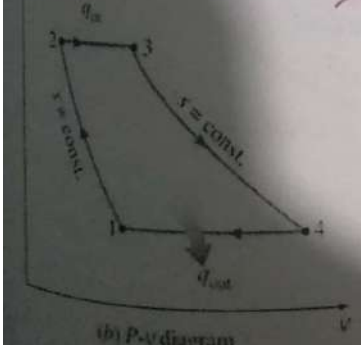
$$q_{out} = h_4 - h_1 = c_p(T_4 - T_1)$$

$$\eta_{th,Brayton} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{c_p(T_4 - T_1)}{c_p(T_3 - T_2)} = 1 - \frac{T_1(T_4/T_1 - 1)}{T_2(T_3/T_2 - 1)}$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k} = \left(\frac{P_3}{P_4}\right)^{(k-1)/k} = \frac{T_3}{T_4}$$

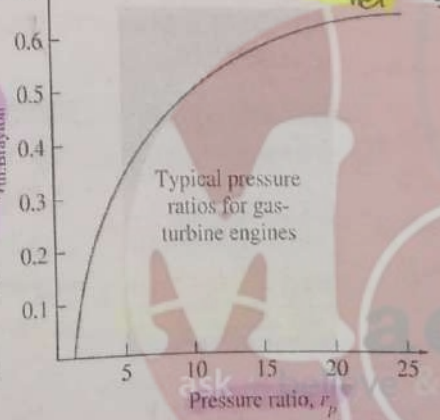
$$r_p = \frac{P_2}{P_1}$$ Pressure ratio

$$\eta_{th,Brayton} = 1 - \frac{1}{r_p^{(k-1)/k}}$$



(b) P-v diagram

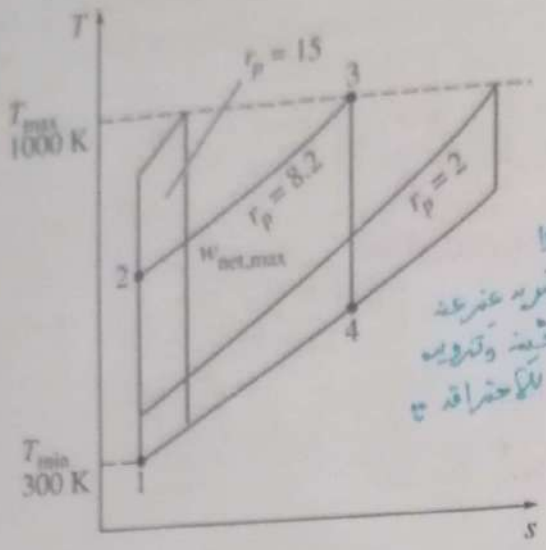
T-s and P-v diagrams for the ideal Brayton cycle.



Thermal efficiency of the ideal Brayton cycle as a function of the pressure ratio.

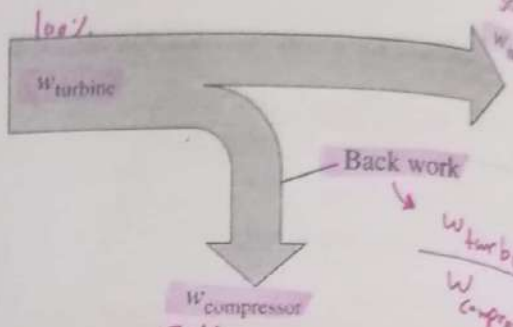
CamScanner الممسوحة ضوئيا بـ

- The two major application areas of gas-turbine engines are *aircraft propulsion* and *electric power generation*.



For fixed values of T_{min} and T_{max}, the net work of the Brayton cycle first increases with the pressure ratio, then reaches a maximum at $r_p = (T_{max}/T_{min})^{k/[2(k-1)]}$, and finally decreases.

- The highest temperature in the cycle is limited by the maximum temperature that the turbine blades can withstand. This also limits the pressure ratios that can be used in the cycle.
- The air in gas turbines supplies the necessary oxidant for the combustion of the fuel, and it serves as a coolant to keep the temperature of various components within safe limits. An air-fuel ratio of 50 or above is not uncommon.



The fraction of the turbine work used to drive the compressor is called the back work ratio.

Development of Gas Turbines

1. Increasing the turbine inlet (or firing) temperatures
2. Increasing the efficiencies of turbomachinery components (turbines, compressors):
3. Adding modifications to the basic cycle (intercooling, regeneration or recuperation, and reheating).

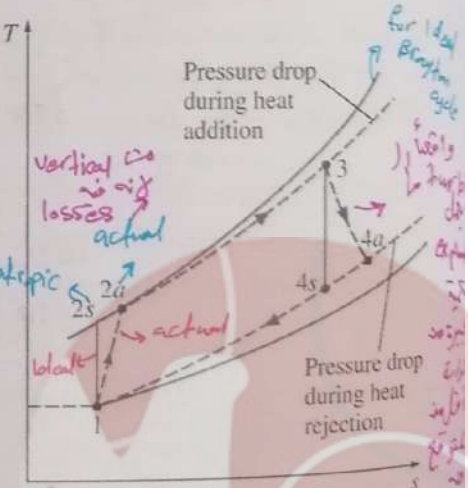
Deviation of Actual Gas-Turbine Cycles from Idealized Ones

Reasons: **Irreversibilities in turbine and compressors, pressure drops, heat losses**

Isentropic efficiencies of the compressor and turbine

$$\eta_C = \frac{w_s}{w_a} \cong \frac{h_{2s} - h_1}{h_{2a} - h_1}$$

$$\eta_T = \frac{w_a}{w_s} \cong \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$



The deviation of an actual gas-turbine cycle from the ideal Brayton cycle as a result of irreversibilities.

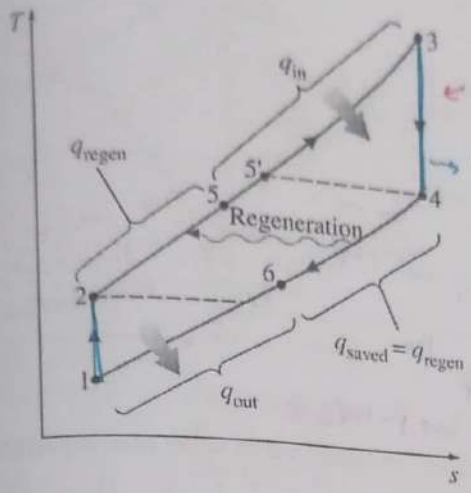
الممسوحة ضوئيا بـ CamScanner

THE BRAYTON CYCLE WITH REGENERATION-1

In gas-turbine engines, the temperature of the exhaust gas leaving the turbine is often considerably higher than the temperature of the air leaving the compressor.

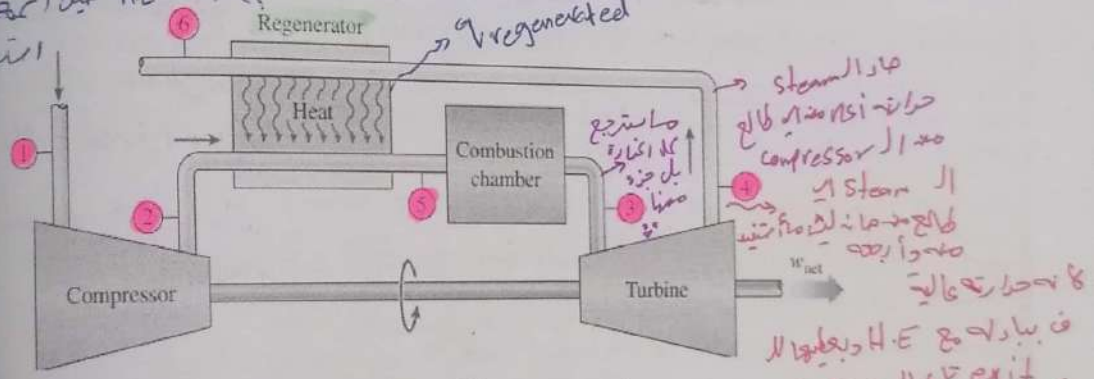
Therefore, the high-pressure air leaving the compressor can be heated by the hot exhaust gases in a counter-flow heat exchanger (a *regenerator*).

The thermal efficiency of the Brayton cycle increases as a result of regeneration since less fuel is used for the same work output.

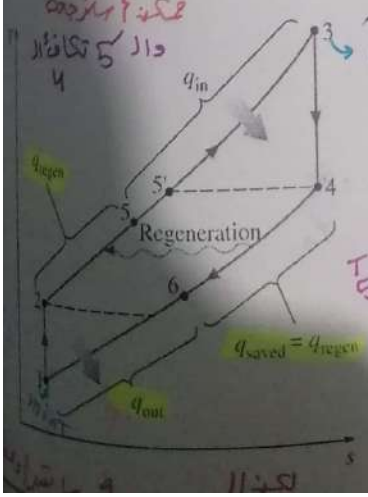


T-s diagram of a Brayton cycle with regeneration.

THE BRAYTON CYCLE WITH REGENERATION-2



A gas-turbine engine with regenerator.



T-s diagram of a Brayton cycle with regeneration.

$$q_{regen,act} = h_5 - h_2$$

$$q_{regen,max} = h_{5'} - h_2 = h_4 - h_2$$

Effectiveness of regenerator:

$$\epsilon = \frac{q_{regen,act}}{q_{regen,max}} = \frac{h_5 - h_2}{h_4 - h_2}$$

CamScanner الممسوحة ضوئيا بـ

Effectiveness under cold-air standard assumptions

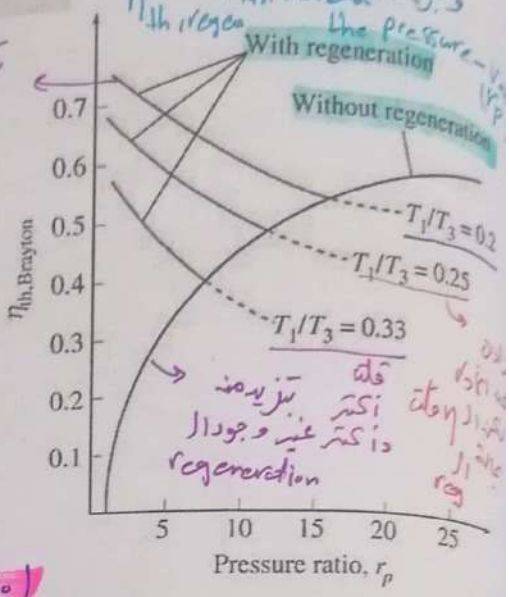
$$\epsilon \cong \frac{T_5 - T_2}{T_4 - T_2}$$

Under cold-air standard assumptions

$$\eta_{th,regen} = 1 - \left(\frac{T_1}{T_3}\right)(r_p)^{(k-1)/k}$$

Can regeneration be used at high pressure ratios?

- The thermal efficiency depends on the ratio of the minimum to maximum temperatures as well as the pressure ratio.
- Regeneration is most effective at lower pressure ratios and low minimum-to-maximum temperature ratios.



Thermal efficiency of the ideal Brayton cycle with and without regeneration.

EXAMPLE 9–1 Derivation of the Efficiency of the Carnot Cycle

Show that the thermal efficiency of a Carnot cycle operating between the temperature limits of T_H and T_L is solely a function of these two temperatures and is given by Eq. 9–2.

SOLUTION It is to be shown that the efficiency of a Carnot cycle depends on the source and sink temperatures alone.

Analysis The *T-s* diagram of a Carnot cycle is redrawn in Fig. 9–7. All four processes that comprise the Carnot cycle are reversible, and thus the area under each process curve represents the heat transfer for that process. Heat is transferred to the system during process 1-2 and rejected during process 3-4. Therefore, the amount of heat input and heat output for the cycle can be expressed as

$$q_{in} = T_H(s_2 - s_1) \quad \text{and} \quad q_{out} = T_L(s_3 - s_4) = T_L(s_2 - s_1)$$

since processes 2-3 and 4-1 are isentropic, and thus $s_2 = s_3$ and $s_4 = s_1$. Substituting these into Eq. 9–1, we see that the thermal efficiency of a Carnot cycle is

$$\eta_{th} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_L(s_2 - s_1)}{T_H(s_2 - s_1)} = 1 - \frac{T_L}{T_H}$$

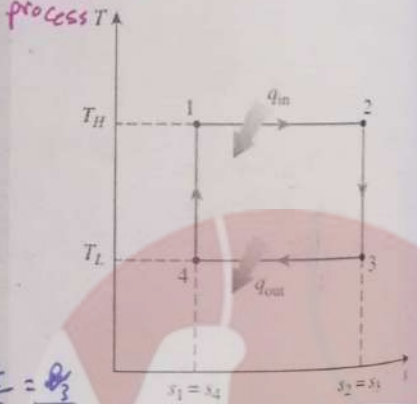


FIGURE 9–7
T-s diagram for Example 9–1.

Discussion Notice that the thermal efficiency of a Carnot cycle is independent of the type of the working fluid used (an ideal gas, steam, etc.) or whether the cycle is executed in a closed or steady-flow system.

CamScanner الممسوحة ضوئيا بـ

Otto Cycle

An ideal Otto cycle has a compression ratio of 8. At the beginning of the compression process, air is at 100 kPa and 17°C, and 800 kJ/kg of heat is transferred to air during the constant-volume heat-addition process. Accounting for the variation of specific heats of air with temperature, determine (*a*) the maximum temperature and pressure that occur during the cycle, (*b*) the net work output, (*c*) the thermal efficiency, and (*d*) the mean effective pressure for the cycle. Also, determine the power output from the cycle, in kW, for an engine that has four cylinders with a total displacement volume of 1.6 L.

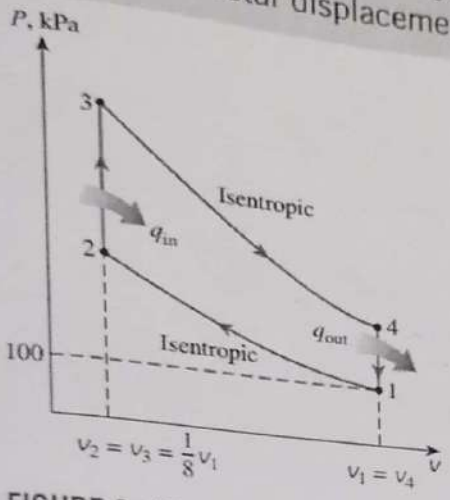


FIGURE 9–19
P-v diagram for the Otto cycle discussed in Example 9–2.

(*a*) The maximum temperature and pressure in an Otto cycle occur at the end of the constant-volume heat-addition process (state 3). But first we need to determine the temperature and pressure of air at the end of the isentropic compression process (state 2), using data from Table A–17:

$$T_1 = 290\ \text{K} \rightarrow u_1 = 206.91\ \text{kJ/kg}, \quad v_{r1} = 676.1$$

Process 1-2 (isentropic compression of an ideal gas):

$$\frac{v_{r2}}{v_{r1}} = \frac{v_2}{v_1} = \frac{1}{r} \rightarrow v_{r2} = \frac{v_{r1}}{r} = \frac{676.1}{8} = 84.51 \rightarrow T_2 = 652.4\ \text{K}, \quad u_2 = 475.11\ \text{kJ/kg}$$

$$\frac{P_2 v_2}{T_2} = \frac{P_1 v_1}{T_1} \rightarrow P_2 = P_1\left(\frac{T_2}{T_1}\right)\left(\frac{v_1}{v_2}\right) = (100\ \text{kPa})\left(\frac{652.4\ \text{K}}{290\ \text{K}}\right)(8) = 1799.7\ \text{kPa}$$

Process 2-3 (constant-volume heat addition):

$$q_{in} = u_3 - u_2$$
$$800\ \text{kJ/kg} = u_3 - 475.11\ \text{kJ/kg}$$
$$u_3 = 1275.11\ \text{kJ/kg} \rightarrow T_3 = 1575.1\ \text{K}, \quad v_{r3} = 6.108$$

Madar
Believe & recieve
CamScanner الممسوحة ضوئيا بـ

$$\frac{P_1 v_1}{T_1} = \frac{P_2 v_2}{T_2} \rightarrow P_2 = P_1\left(\frac{T_2}{T_1}\right)\left(\frac{v_1}{v_2}\right)$$

$$= (1.7997 \text{ MPa})\left(\frac{1575.1 \text{ K}}{652.4 \text{ K}}\right)(1) = 4.345 \text{ MPa}$$

(*b*) The net work output for the cycle is determined either by finding the boundary ($P\,dV$) work involved in each process by integration and adding them or by finding the net heat transfer that is equivalent to the net work done during the cycle. We take the latter approach. However, first we need to find the internal energy of the air at state 4:

Process 3-4 (isentropic expansion of an ideal gas):

$$\frac{v_{r4}}{v_{r3}} = \frac{v_4}{v_3} = r \rightarrow v_{r4} = rv_{r3} = (8)(6.108) = 48.864 \rightarrow T_4 = 795.6 \text{ K}$$

$$u_4 = 588.74 \text{ kJ/kg}$$

Process 4-1 (constant-volume heat rejection):

$$-q_{out} = u_1 - u_4 \rightarrow q_{out} = u_4 - u_1$$

$$q_{out} = 588.74 - 206.91 = 381.83 \text{ kJ/kg}$$

Thus,

$$w_{net} = q_{net} = q_{in} - q_{out} = 800 - 381.83 = \mathbf{418.17 \text{ kJ/kg}}$$

(*c*) The thermal efficiency of the cycle is determined from its definition:

$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{418.17 \text{ kJ/kg}}{800 \text{ kJ/kg}} = 0.523 \text{ or } 52.3\%$$

Under the cold-air-standard assumptions (constant specific heat values at room temperature), the thermal efficiency would be (Eq. 9–8)

$$\eta_{th,Otto} = 1 - \frac{1}{r^{k-1}} = 1 - r^{1-k} = 1 - (8)^{1-1.4} = 0.565 \text{ or } 56.5\%$$

which is considerably different from the value obtained above. Therefore, care should be exercised in utilizing the cold-air-standard assumptions.

(*d*) The mean effective pressure is determined from its definition, Eq. 9–4:

$$\text{MEP} = \frac{w_{net}}{v_1 - v_2} = \frac{w_{net}}{v_1 - v_1/r} = \frac{w_{net}}{v_1(1 - 1/r)}$$

where

$$v_1 = \frac{RT_1}{P_1} = \frac{(0.287 \text{ kPa·m}^3\text{/kg·K})(290 \text{ K})}{100 \text{ kPa}} = 0.8323 \text{ m}^3\text{/kg}$$

Thus,

$$\text{MEP} = \frac{418.17 \text{ kJ/kg}}{(0.8323 \text{ m}^3\text{/kg})(1 - \frac{1}{8})}\left(\frac{1 \text{ kPa·m}^3}{1 \text{ kJ}}\right) = 574 \text{ kPa}$$

CamScanner الممسوحة ضوئيا بـ

(a) The total air mass taken by all four cylinders when they are charged is

$$m = \frac{V_d}{v_1} = \frac{0.0016\ \text{m}^3}{0.8323\ \text{m}^3/\text{kg}} = 0.001922\ \text{kg}$$

The net work produced by the cycle is

$$W_{net} = m w_{net} = (0.001922\ \text{kg})(418.17\ \text{kJ/kg}) = 0.8037\ \text{kJ}$$

That is, the net work produced per thermodynamic cycle is 0.8037 kJ/cycle. Noting that there are two revolutions per thermodynamic cycle (n_{rev} = 2 rev/cycle) in a four-stroke engine (or in the ideal Otto cycle including intake and exhaust strokes), the power produced by the engine is determined from

$$\dot{W}_{net} = \frac{W_{net}\dot{n}}{n_{rev}} = \frac{(0.8037\ \text{kJ/cycle})(4000\ \text{rev/min})}{2\ \text{rev/cycle}}\left(\frac{1\ \text{min}}{60\ \text{s}}\right) = 26.8\ \text{kW}$$

$\frac{P_2}{P_1} = \frac{P_3}{P_4}$

EXAMPLE 9–5 The Simple Ideal Brayton Cycle

A gas-turbine power plant operating on an ideal Brayton cycle has a pressure ratio of 8. The gas temperature is 300 K at the compressor inlet and 1300 K at the turbine inlet. Utilizing the air-standard assumptions, determine (*a*) the gas temperature at the exits of the compressor and the turbine, (*b*) the back work ratio, and (*c*) the thermal efficiency.

SOLUTION A power plant operating on the ideal Brayton cycle is considered. The compressor and turbine exit temperatures, back work ratio, and the thermal efficiency are to be determined.

Assumptions **1** Steady operating conditions exist. **2** The air-standard assumptions are applicable. **3** Kinetic and potential energy changes are negligible. **4** The variation of specific heats with temperature is to be considered.

Analysis The *T-s* diagram of the ideal Brayton cycle described is shown in Fig. 9–35. We note that the components involved in the Brayton cycle are steady-flow devices.

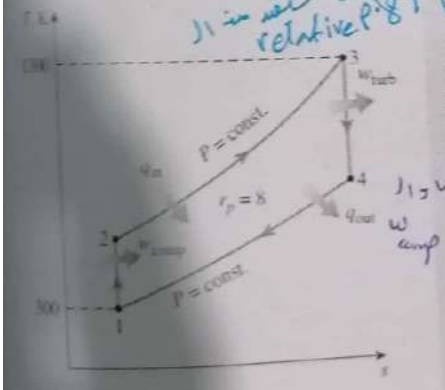


FIGURE 9–35
T-s diagram for the Brayton cycle discussed in Example 9–5.

CamScanner الممسوحة ضوئيا بـ

(*a*) The air temperatures at the compressor and turbine exits are determined from isentropic relations:

Process 1–2 (isentropic compression of an ideal gas):

$$T_1 = 300\ \text{K} \rightarrow h_1 = 300.19\ \text{kJ/kg}$$
$$P_{r1} = 1.386$$

from table

$$P_{r2} = \frac{P_2}{P_1} P_{r1} = (8)(1.386) = 11.09 \rightarrow T_2 = 540\ \text{K} \quad \text{(at compressor exit)}$$
$$h_2 = 544.35\ \text{kJ/kg}$$

Process 3–4 (isentropic expansion of an ideal gas):

$$T_3 = 1300\ \text{K} \rightarrow h_3 = 1395.97\ \text{kJ/kg}$$
$$P_{r3} = 330.9$$

from table

$$P_{r4} = \frac{P_4}{P_3} P_{r3} = \left(\frac{1}{8}\right)(330.9) = 41.36 \rightarrow T_4 = 770\ \text{K} \quad \text{(at turbine exit)}$$
$$h_4 = 789.37\ \text{kJ/kg}$$

(*b*) To find the back work ratio, we need to find the work input to the compressor and the work output of the turbine:

$$w_{\text{comp,in}} = h_2 - h_1 = 544.35 - 300.19 = 244.16\ \text{kJ/kg}$$
$$w_{\text{turb,out}} = h_3 - h_4 = 1395.97 - 789.37 = 606.60\ \text{kJ/kg}$$

$w_{net} = 606.6 - 244.16$

$w_{back} = \frac{606.60}{244.16}$

Thus,

$$r_{\text{bw}} = \frac{w_{\text{comp,in}}}{w_{\text{turb,out}}} = \frac{244.16\ \text{kJ/kg}}{606.60\ \text{kJ/kg}} = 0.403$$

That is, 40.3 percent of the turbine work output is used just to drive the compressor.

(*c*) The thermal efficiency of the cycle is the ratio of the net power output to the total heat input:

difference in enthalpy

$$q_{\text{in}} = h_3 - h_2 = 1395.97 - 544.35 = 851.62\ \text{kJ/kg}$$
$$w_{\text{net}} = w_{\text{out}} - w_{\text{in}} = 606.60 - 244.16 = 362.4\ \text{kJ/kg}$$

Thus,

$q_{in} - q_{out}$

$$\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}} = \frac{362.4\ \text{kJ/kg}}{851.62\ \text{kJ/kg}} = 0.426 \text{ or } 42.6\%$$

The thermal efficiency could also be determined from

$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}}$$

where

$$q_{\text{out}} = h_4 - h_1 = 789.37 - 300.19 = 489.2\ \text{kJ/kg}$$

Radar give & recieve

الممسوحة ضوئيا بـ CamScanner

Assuming a compressor efficiency of 80 percent and a turbine efficiency of 85 percent, determine (*a*) the back work ratio, (*b*) the thermal efficiency, and (*c*) the turbine exit temperature of the gas-turbine cycle discussed in Example 9–5.

SOLUTION The Brayton cycle discussed in Example 9–5 is reconsidered. For specified turbine and compressor efficiencies, the back work ratio, the thermal efficiency, and the turbine exit temperature are to be determined.

Analysis (*a*) The *T*-*s* diagram of the cycle is shown in Fig. 9–37. The actual compressor work and turbine work are determined by using the definitions of compressor and turbine efficiencies, Eqs. 9–19 and 9–20:

Compressor:
$$w_{comp,in} = \frac{w_s}{\eta_C} = \frac{244.16 \text{ kJ/kg}}{0.80} = 305.20 \text{ kJ/kg}$$

Turbine:
$$w_{turb,out} = \eta_T w_s = (0.85)(606.60 \text{ kJ/kg}) = 515.61 \text{ kJ/kg}$$

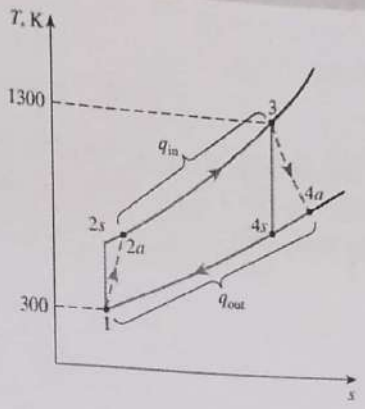


FIGURE 9–37
T-*s* diagram of the gas-turbine cycle discussed in Example 9–6.

Thus,
$$r_{bw} = \frac{w_{comp,in}}{w_{turb,out}} = \frac{305.20 \text{ kJ/kg}}{515.61 \text{ kJ/kg}} = 0.592$$

That is, the compressor is now consuming 59.2 percent of the work produced by the turbine (up from 40.3 percent). This increase is due to the irreversibilities that occur within the compressor and the turbine.

(*b*) In this case, air leaves the compressor at a higher temperature and enthalpy, which are determined to be

$$w_{comp,in} = h_{2a} - h_1 \rightarrow h_{2a} = h_1 + w_{comp,in}$$
$$= 300.19 + 305.20$$
$$= 605.39 \text{ kJ/kg} \quad (\text{and } T_{2a} = 598 \text{ K})$$

Thus,
$$q_{in} = h_3 - h_{2a} = 1395.97 - 605.39 = 790.58 \text{ kJ/kg}$$
$$w_{net} = w_{out} - w_{in} = 515.61 - 305.20 = 210.41 \text{ kJ/kg}$$

and
$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{210.41 \text{ kJ/kg}}{790.58 \text{ kJ/kg}} = 0.266 \text{ or } 26.6\%$$

Madar ask & believe & recieve
CamScanner الممسوحة ضوئيا بـ

That is, the irreversibilities occurring within the turbine and compressor caused the thermal efficiency of the gas turbine cycle to drop from 42.6 to 26.6 percent. This example shows how sensitive the performance of a gas-turbine power plant is to the efficiencies of the compressor and the turbine. In fact, gas-turbine efficiencies did not reach competitive values until significant improvements were made in the design of gas turbines and compressors.

(*c*) The air temperature at the turbine exit is determined from an energy balance on the turbine:

$$w_{\text{turb,out}} = h_3 - h_{4a} \rightarrow h_{4a} = h_3 - w_{\text{turb,out}}$$
$$= 1395.97 - 515.61$$
$$= 880.36 \text{ kJ/kg}$$

Then, from Table A–17,

$$T_{4a} = 853 \text{ K}$$

Discussion The temperature at turbine exit is considerably higher than that at the compressor exit ($T_{2a} = 598$ K), which suggests the use of regeneration to reduce fuel cost.

CamScanner الممسوحة ضوئيا بـ



Chapter 10

VAPOR & COMBINED POWER CYCLES

Thermodynamics: An Engineering Approach

Yunus A. Cengel, Michael A. Boles, Mehmet Kanoglu
McGraw-Hill

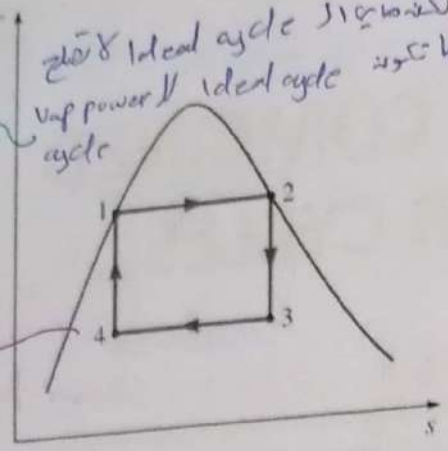
Dr. Ahmad M. AbuYaghi
October 2023

THE CARNOT VAPOR CYCLE

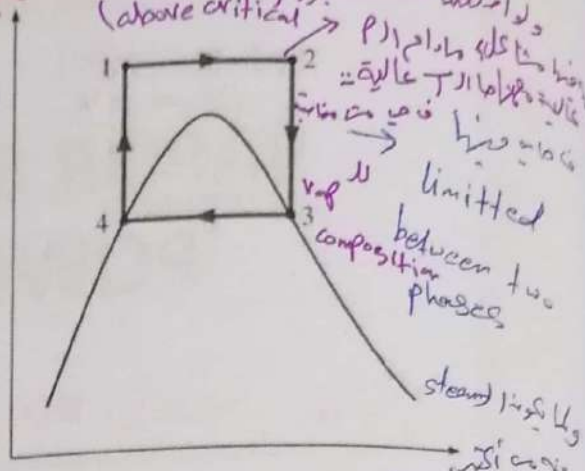
- The Carnot cycle is the most efficient cycle operating between two specified temperature limits, but it is not a suitable model for power cycles. Because:
  - Process 1-2 Limiting the heat transfer processes to two-phase systems severely limits the maximum temperature that can be used in the cycle (374°C for water)
  - Process 2-3 The turbine cannot handle steam with a high moisture content because of the impingement of liquid droplets on the turbine blades causing erosion and wear.
  - Process 4-1 It is not practical to design a compressor that handles two phases.
- The **cycle in (b)** is not suitable since it requires isentropic compression to extremely high pressures and isothermal heat transfer at variable pressures.

ask : believe & recieve
CamScanner الممسوحة ضوئيا بـ

THE CARNOT VAPOR CYCLE



(a)



(b)

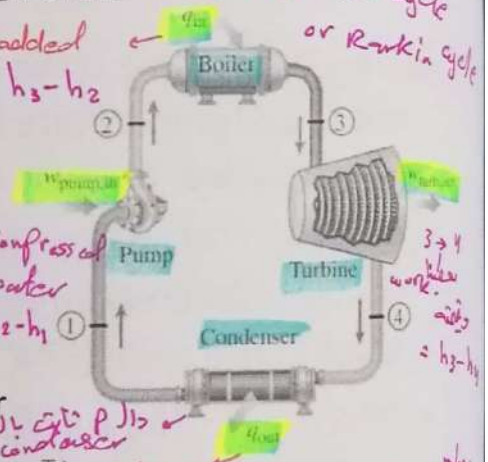
T-s diagram of two Carnot vapor cycles.

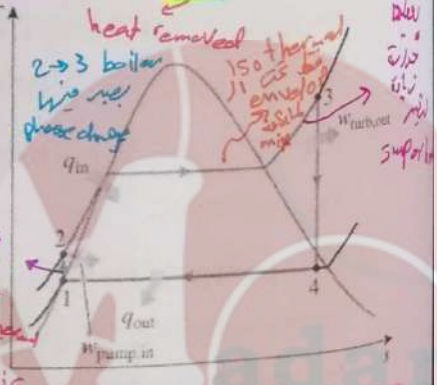
1-2 isothermal heat addition in a boiler
2-3 isentropic expansion in a turbine
3-4 isothermal heat rejection in a condenser
4-1 isentropic compression in a compressor

RANKINE CYCLE:

THE IDEAL CYCLE FOR VAPOR POWER CYCLES

- Many of the impracticalities associated with the Carnot cycle can be eliminated by superheating the steam in the boiler and condensing it completely in the condenser.
- The cycle that results is the **Rankine cycle**, which is the ideal cycle for vapor power plants. The ideal Rankine cycle does not involve any internal irreversibilities.





The simple ideal Rankine cycle.

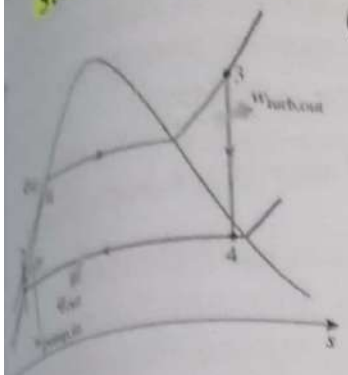
1-2	Isentropic compression in a pump
2-3	Constant pressure heat addition in a boiler
3-4	Isentropic expansion in a turbine
4-1	Constant pressure heat rejection in a condenser

CamScanner الممسوحة ضوئيا بـ

The Ideal Rankine Cycle

Steady-flow energy equation

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i \quad \text{(kJ/kg)}$$



Pump ($q = 0$):

$$w_{pump,in} = (h_2 - h_1) \qquad \text{Specific volume}$$
$$w_{pump,in} = v(P_2 - P_1)$$

$h_1 = h_{f@P_1}$ and $v \cong v_1 = v_{f@P_1}$

Boiler ($w = 0$):

$$q_{in} = h_3 - h_2$$

Turbine ($q = 0$):

$$w_{turb,out} = h_3 - h_4$$

Condenser ($w = 0$):

$$q_{out} = h_4 - h_1$$

$$w_{net} = q_{in} - q_{out} = w_{turb,out} - w_{pump,in}$$

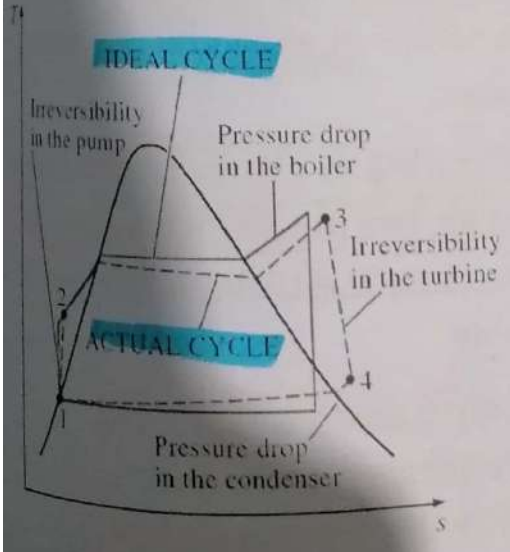
$$\eta_{th} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

The thermal efficiency can be interpreted as the ratio of the area enclosed by the cycle on a *T-s* diagram to the area under the heat-addition process.

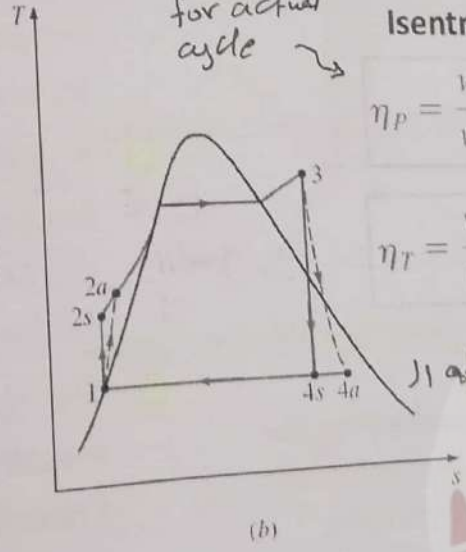
DEVIATION OF ACTUAL VAPOR POWER CYCLES FROM IDEALIZED ONES

The actual vapor power cycle differs from the ideal Rankine cycle as a result of irreversibilities in various components.

Fluid friction and heat loss to the surroundings are the two common sources of irreversibilities.



(a)



(b)

Isentropic efficiencies

$$\eta_P = \frac{w_s}{w_a} = \frac{h_{2s} - h_1}{h_{2a} - h_1}$$

$$\eta_T = \frac{w_a}{w_s} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$

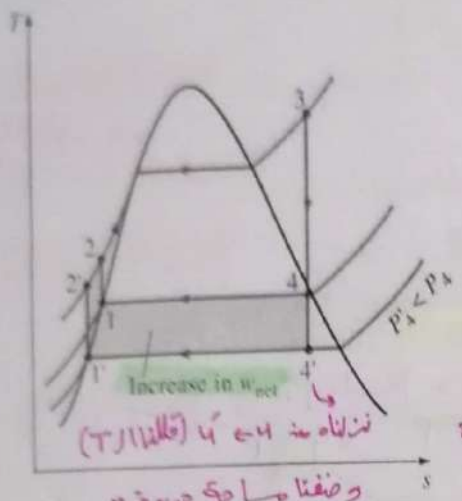
(a) Deviation of actual vapor power cycle from the ideal Rankine cycle.
(b) The effect of pump and turbine irreversibilities on the ideal Rankine cycle.

CamScanner الممسوحة ضوئيا بـ

HOW CAN WE INCREASE THE EFFICIENCY OF THE RANKINE CYCLE?

- The basic idea behind all the modifications to increase the thermal efficiency of a power cycle is the same: *Increase the average temperature at which heat is transferred to the working fluid in the boiler or decrease the average temperature at which heat is rejected from the working fluid in the condenser.*

Lowering the Condenser Pressure (*Lowers* $T_{low,avg}$)

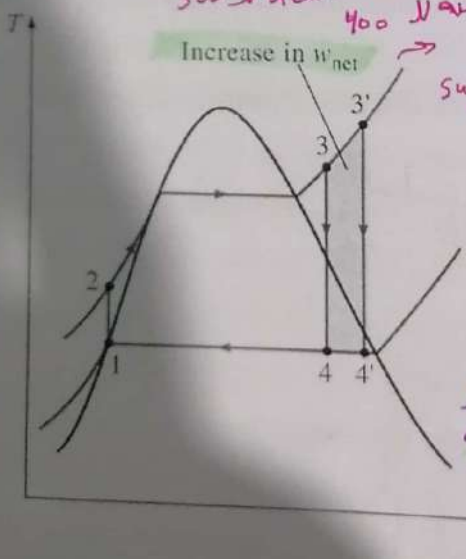


1) To take advantage of the increased efficiencies at low pressures, the condensers of steam power plants usually operate well below the atmospheric pressure. There is a lower limit to this pressure depending on the temperature of the cooling medium

2) **Side effect:** Lowering the condenser pressure increases the moisture content of the steam at the final stages of the turbine.

The effect of lowering the condenser pressure on the ideal Rankine cycle.

Superheating the Steam to High Temperatures (*Increases* $T_{high,avg}$)



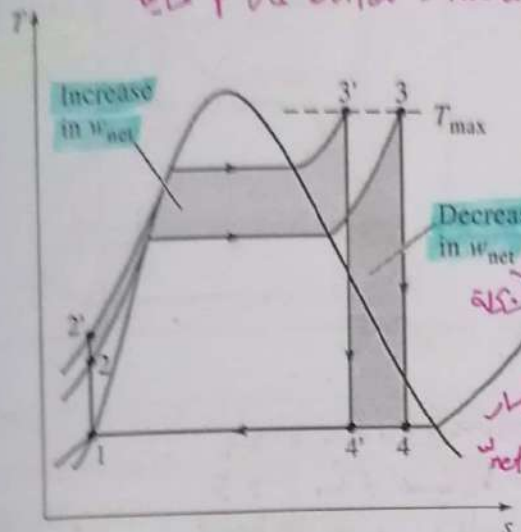
The effect of superheating the steam to higher temperatures on the ideal Rankine cycle.

- Both the net work and heat input increase as a result of superheating the steam to a higher temperature. The overall effect is an increase in thermal efficiency since the average temperature at which heat is added increases.
- Superheating to higher temperatures decreases the moisture content of the steam at the turbine exit, which is desirable.
- The temperature is limited by metallurgical considerations. Presently the highest steam temperature allowed at the turbine inlet is about 620°C.

الممسوحة ضوئيا بـ CamScanner

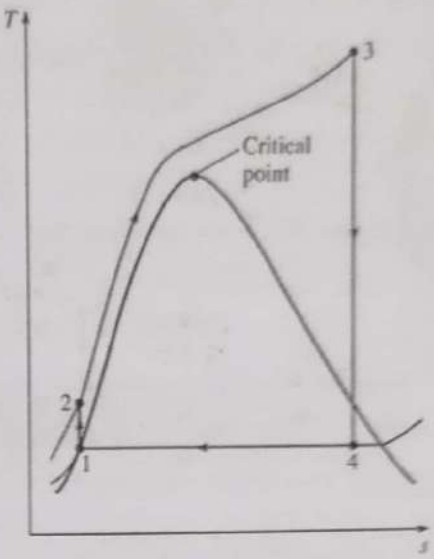
Increasing the Boiler Pressure (*Increases* $T_{high,avg}$)

- For a fixed turbine inlet temperature, the cycle shifts to the left and the moisture content of steam at the turbine exit increases.
- This side effect can be corrected by reheating the steam.



The effect of increasing the boiler pressure on the ideal Rankine cycle.

Today many modern steam power plants operate at supercritical pressures ($P > 22.06$ MPa) and have thermal efficiencies of about 40% for fossil-fuel plants and 34% for nuclear plants.



A supercritical Rankine cycle.

THE IDEAL REHEAT RANKINE CYCLE

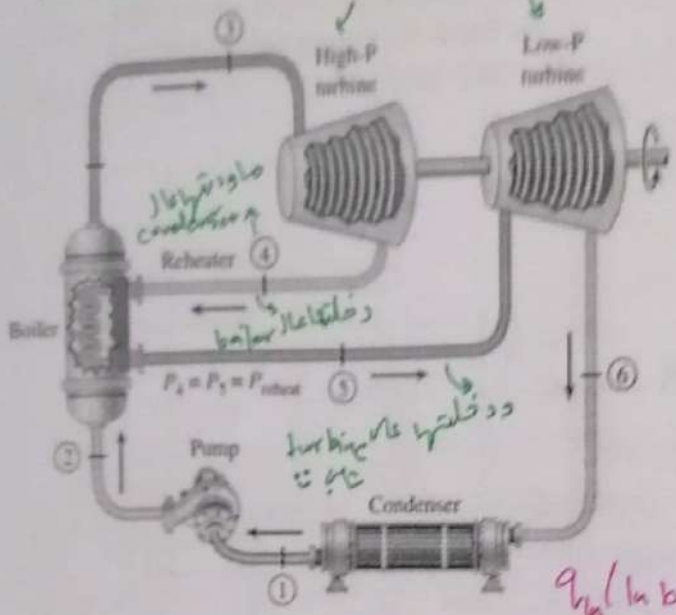
- How can we take advantage of the increased efficiencies at higher boiler pressures without facing the problem of excessive moisture at the final stages of the turbine?
  1. Superheat the steam to very high temperatures. It is limited metallurgically.
  2. Expand the steam in the turbine in two stages and reheat it in between (reheat).

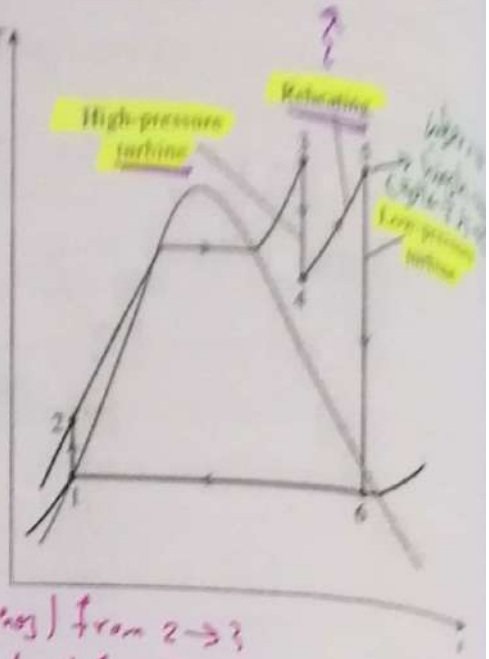
$$q_{in} = q_{primary} + q_{reheat} = (h_3 - h_2) + (h_5 - h_4)$$

$$w_{turb,out} = w_{turb\,I} + w_{turb\,II} = (h_3 - h_4) + (h_5 - h_6)$$

CamScanner الممسوحة ضوئيا بـ

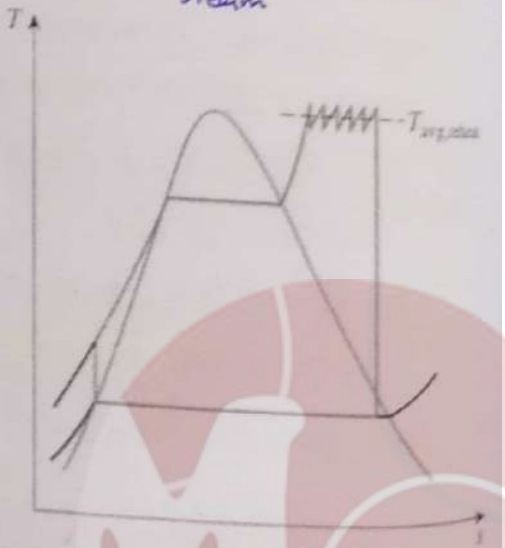
THE IDEAL REHEAT RANKINE CYCLE





$w_{out} = w_1 + w_2$

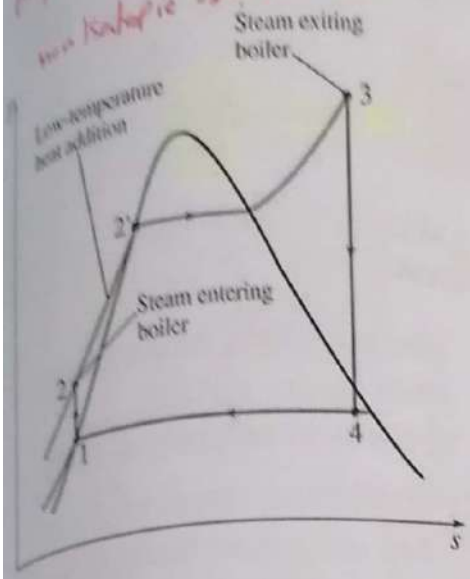
- The single reheat in a modern power plant improves the cycle efficiency by 4 to 5% by increasing the average temperature at which heat is transferred to the steam.
- The average temperature during the reheat process can be increased by increasing the number of expansion and reheat stages. As the number of stages is increased, the expansion and reheat processes approach an isothermal process at the maximum temperature. The use of more than two reheat stages is not practical. The theoretical improvement in efficiency from the second reheat is about half of that which results from a single reheat.
- The reheat temperatures are very close or equal to the turbine inlet temperature.
- The optimum reheat pressure is about one-fourth of the maximum cycle pressure.



The average temperature at which heat is transferred during reheating increases as the number of reheat stages is

CamScanner الممسوحة ضوئيا بـ

THE IDEAL REGENERATIVE RANKINE CYCLE

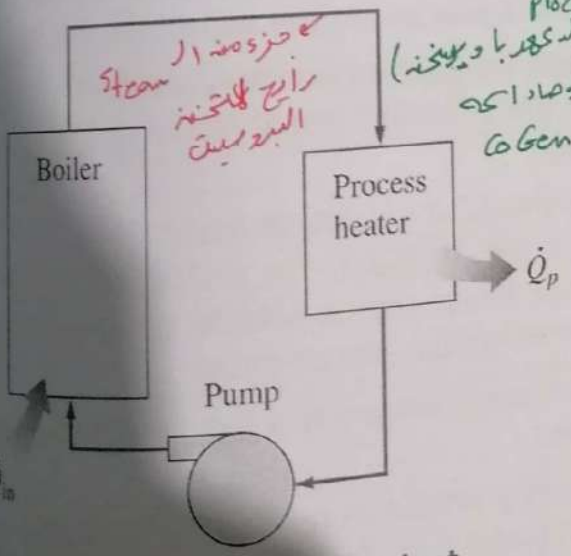


The first part of the heat-addition process in the boiler takes place at relatively low temperatures.

- Heat is transferred to the working fluid during process 2-2 at a relatively low temperature. This lowers the average heat-addition temperature and thus the cycle efficiency.
- In steam power plants, steam is extracted from the turbine at various points. This steam, which could have produced more work by expanding further in the turbine, is used to heat the feedwater instead. The device where the feedwater is heated by regeneration is called a **regenerator**, or a **feedwater heater (FWH)**.
- A feedwater heater is basically a heat exchanger where heat is transferred from the steam to the feedwater either by mixing the two fluid streams (open feedwater heaters) or without mixing them (closed feedwater heaters).

COGENERATION

- Many industries require energy input in the form of heat, called *process heat*. Process heat in these industries is usually supplied by steam at 5 to 7 atm and 150 to 200°C. Energy is usually transferred to the steam by burning coal, oil, natural gas, or another fuel in a furnace.



A simple process-heating plant.

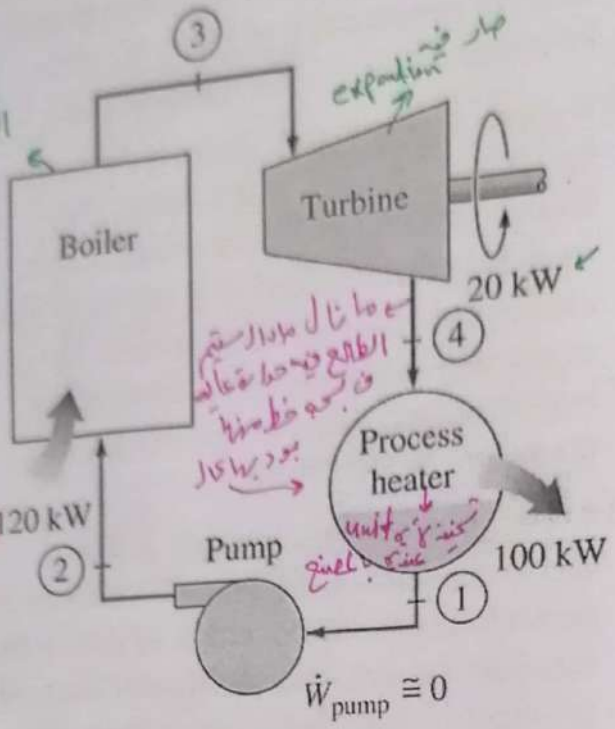
- Industries that use large amounts of process heat also consume a large amount of electric power.
- It makes sense to use the already-existing work potential to produce power instead of letting it go to waste.
- The result is a plant that produces electricity while meeting the process-heat requirements of certain industrial processes (**cogeneration plant**)

Cogeneration: The production of *more than one useful form* of energy (such as process heat and electric power) from the same energy source.

CamScanner الممسوحة ضوئيا بـ

Utilization Factor:

$$\epsilon_u = \frac{\text{Net work output} + \text{Process heat delivered}}{\text{Total heat input}} = \frac{\dot{W}_{net} + \dot{Q}_{out}}{\dot{Q}_{in}}$$



An ideal cogeneration plant.

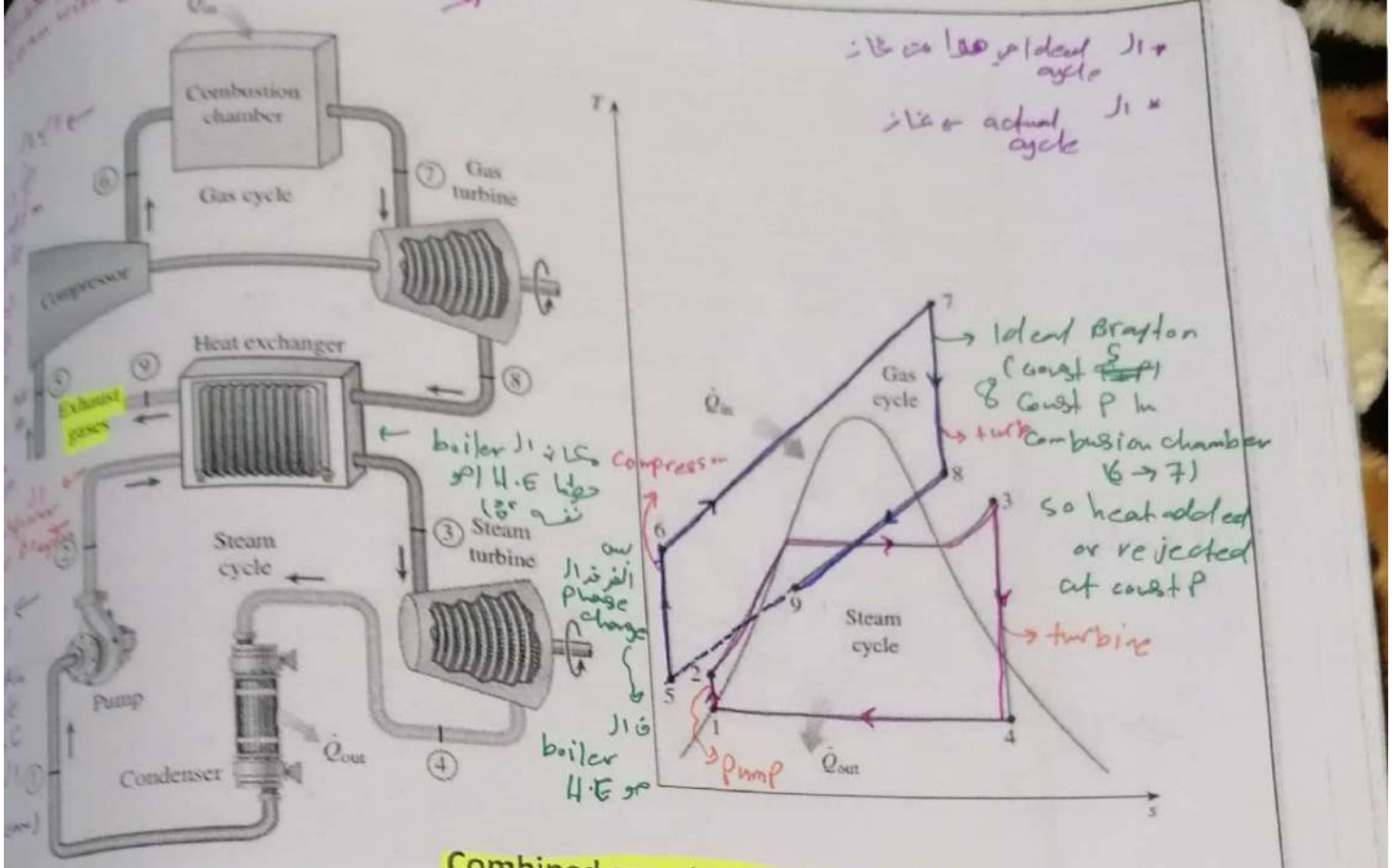
$$\epsilon_u = 1 - \frac{\dot{Q}_{out}}{\dot{Q}_{in}}$$

- The utilization factor of the ideal steam-turbine cogeneration plant is 100%.
- Actual cogeneration plants have utilization factors as high as 80%.
- Some recent cogeneration plants have even higher utilization factors.

COMBINED GAS–VAPOR POWER CYCLES

1) The continued quest for higher thermal efficiencies has resulted in rather innovative modifications to conventional power plants.
2) A popular modification involves a gas power cycle topping a vapor power cycle, which is called the **combined gas–vapor cycle**, or just the **combined cycle**.
3) The combined cycle of greatest interest is the gas-turbine (Brayton) cycle topping a steam-turbine (Rankine) cycle, which has a higher thermal efficiency than either of the cycles executed individually.
4) It makes engineering sense to take advantage of the very desirable characteristics of the gas-turbine cycle at high temperatures *and* to use the high-temperature exhaust gases as the energy source for the bottoming cycle such as a steam power cycle. The result is a combined gas–steam cycle.
5) Recent developments in gas-turbine technology have made the combined gas-steam cycle economically very attractive.
6) The combined cycle increases the efficiency without increasing the initial cost greatly. Consequently, many new power plants operate on combined cycles, and many more existing steam- or gas-turbine plants are being converted to combined-cycle power plants.
7) Thermal efficiencies over 50% are reported.

الممسوحة ضوئيا بـ CamScanner



Combined gas–steam power plant.

Isentropic efficiency ← actual

Rankin cycle ← ideal

$w_{net} = q_{in} - q_{out}$

Combined ← cycle

EXAMPLE 10–1 The Simple Ideal Rankine Cycle

Consider a steam power plant operating on the simple ideal Rankine cycle. Steam enters the turbine at 3 MPa and 350°C and is condensed in the condenser at a pressure of 75 kPa. Determine the thermal efficiency of this cycle.

$P_1 = P_4$ ← P_1 , T_3 , T_1 , P_2 → $P_2 = P_3$

SOLUTION A steam power plant operating on the simple ideal Rankine cycle is considered. The thermal efficiency of the cycle is to be determined.

Assumptions 1 Steady operating conditions exist. 2 Kinetic and potential energy changes are negligible.

Analysis The schematic of the power plant and the *T-s* diagram of the cycle are shown in Fig. 10–3. We note that the power plant operates on the ideal Rankine cycle. Therefore, the pump and the turbine are isentropic, there are no pressure drops in the boiler and condenser, and steam leaves the condenser and enters the pump as saturated liquid at the condenser pressure. First we determine the enthalpies at various points in the cycle, using data from steam tables (Tables A–4, A–5, and A–6):

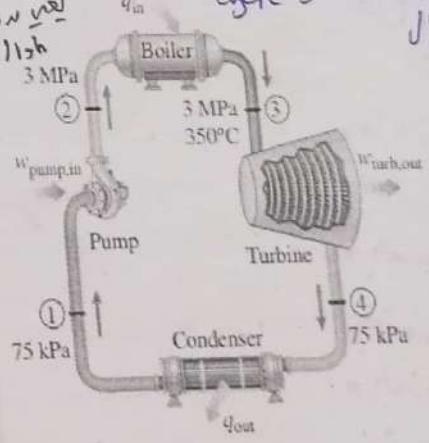
State 1: $P_1 = 75$ kPa, Sat. liquid

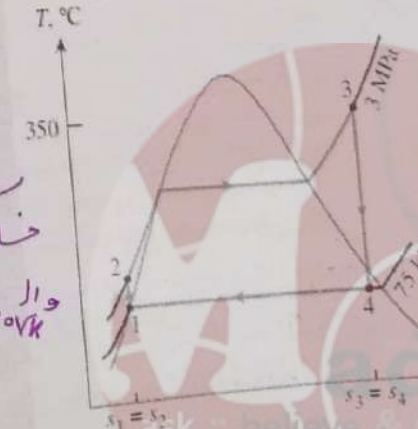
$h_1 = h_{f\,@\,75\,kPa} = 384.44$ kJ/kg

$v_1 = v_{f\,@\,75\,kPa} = 0.001037$ m³/kg

State 2: $P_2 = 3$ MPa

$s_2 = s_1$





$\eta = 1 - \frac{q_{out}}{q_{in}}$

Medar
ask & believe & recieve

الممسوحة ضوئيا بـ CamScanner

$$w_{\text{pump,in}} = v_1(P_2 - P_1) = (0.001037\ \text{m}^3/\text{kg})[(3000 - 75)\ \text{kPa}]\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right)$$

$$= 3.03\ \text{kJ/kg}$$

$$h_2 = h_1 + w_{\text{pump,in}} = (384.44 + 3.03)\ \text{kJ/kg} = 387.47\ \text{kJ/kg}$$

State 3: $P_3 = 3\ \text{MPa}$, $T_3 = 350°\text{C}$ $\Rightarrow$ $h_3 = 3116.1\ \text{kJ/kg}$, $s_3 = 6.7450\ \text{kJ/kg}\cdot\text{K}$

State 4: $P_4 = 75\ \text{kPa}$ (sat. mixture)

$$s_4 = s_3$$

$$x_4 = \frac{s_4 - s_f}{s_{fg}} = \frac{6.7450 - 1.2132}{6.2426} = 0.8861$$

$$h_4 = h_f + x_4 h_{fg} = 384.44 + 0.8861(2278.0) = 2403.0\ \text{kJ/kg}$$

Thus,

$$q_{\text{in}} = h_3 - h_2 = (3116.1 - 387.47)\ \text{kJ/kg} = 2728.6\ \text{kJ/kg}$$

$$q_{\text{out}} = h_4 - h_1 = (2403.0 - 384.44)\ \text{kJ/kg} = 2018.6\ \text{kJ/kg}$$

and

$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{2018.6\ \text{kJ/kg}}{2728.6\ \text{kJ/kg}} = 0.260 \text{ or } 26.0\%$$

The thermal efficiency could also be determined from

$$w_{\text{turb,out}} = h_3 - h_4 = (3116.1 - 2403.0)\ \text{kJ/kg} = 713.1\ \text{kJ/kg}$$

$$w_{\text{net}} = w_{\text{turb,out}} - w_{\text{pump,in}} = (713.1 - 3.03)\ \text{kJ/kg} = 710.1\ \text{kJ/kg}$$

or

$$w_{\text{net}} = q_{\text{in}} - q_{\text{out}} = (2728.6 - 2018.6)\ \text{kJ/kg} = 710.0\ \text{kJ/kg}$$

and

$$\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}} = \frac{710.0\ \text{kJ/kg}}{2728.6\ \text{kJ/kg}} = 0.260 \text{ or } 26.0\%$$

That is, this power plant converts 26 percent of the heat it receives in the boiler to net work. An actual power plant operating between the same temperature and pressure limits will have a lower efficiency because of the irreversibilities such as friction.

Discussion Notice that the back work ratio ($r_{\text{bw}} = w_{\text{in}}/w_{\text{out}}$) of this power plant is 0.004, and thus only 0.4 percent of the turbine work output is required to operate the pump. Having such low back work ratios is characteristic of vapor power cycles. This is in contrast to the gas power cycles, which typically involve very high back work ratios (about 40 to 80 percent).

It is also interesting to note the thermal efficiency of a Carnot cycle operating between the same temperature limits

$$\eta_{\text{th,Carnot}} = 1 - \frac{T_{\min}}{T_{\max}} = 1 - \frac{(91.76 + 273)\ \text{K}}{(350 + 273)\ \text{K}} = 0.415$$

The difference between the two efficiencies is due to the large external irreversibility in the Rankine cycle caused by the large temperature difference between steam and combustion gases in the furnace.

CamScanner الممسوحة ضوئيا بـ

EXAMPLE 10–2 An Actual Steam Power Cycle

A steam power plant operates on the cycle shown in Fig. 10–5. If the isentropic efficiency of the turbine is 87 percent and the isentropic efficiency of the pump is 85 percent, determine (a) the thermal efficiency of the cycle and (b) the net power output of the plant for a mass flow rate of 15 kg/s.

SOLUTION A steam power cycle with specified turbine and pump efficiencies is considered. The thermal efficiency and the net power output are to be determined.

Assumptions 1 Steady operating conditions exist. 2 Kinetic and potential energy changes are negligible.

Analysis The schematic of the power plant and the *T*-*s* diagram of the cycle are shown in Fig. 10–5. The temperatures and pressures of steam at various points are also indicated on the figure. We note that the power plant involves steady-flow components and operates on the Rankine cycle, but the imperfections at various components are accounted for.

(a) The thermal efficiency of a cycle is the ratio of the net work output to the heat input, and it is determined as follows:

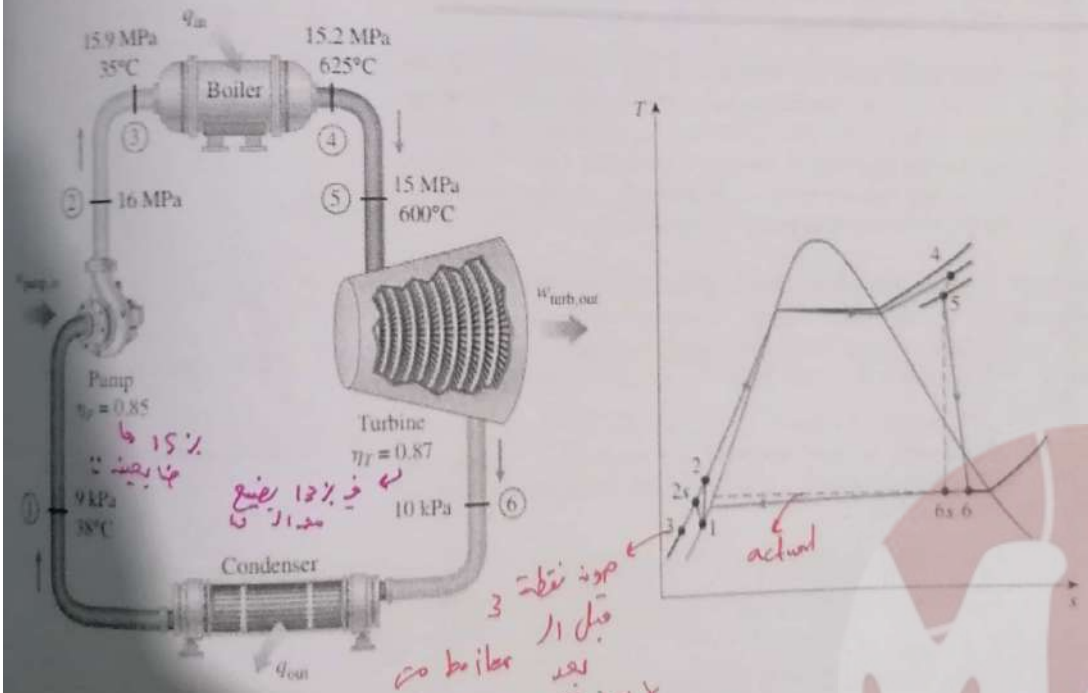


FIGURE 10–5
Schematic and *T*-*s* diagram for Example 10–2.

Madar ask & believe & recieve
الممسوحة ضوئيا بـ CamScanner

EXAMPLE 10–2 **An Actual Steam Power Cycle**

A steam power plant operates on the cycle shown in Fig. 10–5. If the isentropic efficiency of the turbine is 87 percent and the isentropic efficiency of the pump is 85 percent, determine (a) the thermal efficiency of the cycle and (b) the net power output of the plant for a mass flow rate of 15 kg/s.

SOLUTION A steam power cycle with specified turbine and pump efficiencies is considered. The thermal efficiency and the net power output are to be determined.

Assumptions 1 Steady operating conditions exist. 2 Kinetic and potential energy changes are negligible.

Analysis The schematic of the power plant and the *T*-*s* diagram of the cycle are shown in Fig. 10–5. The temperatures and pressures of steam at various points are also indicated on the figure. We note that the power plant involves steady-flow components and operates on the Rankine cycle, but the imperfections at various components are accounted for.

(a) The thermal efficiency of a cycle is the ratio of the net work output to the heat input, and it is determined as follows:

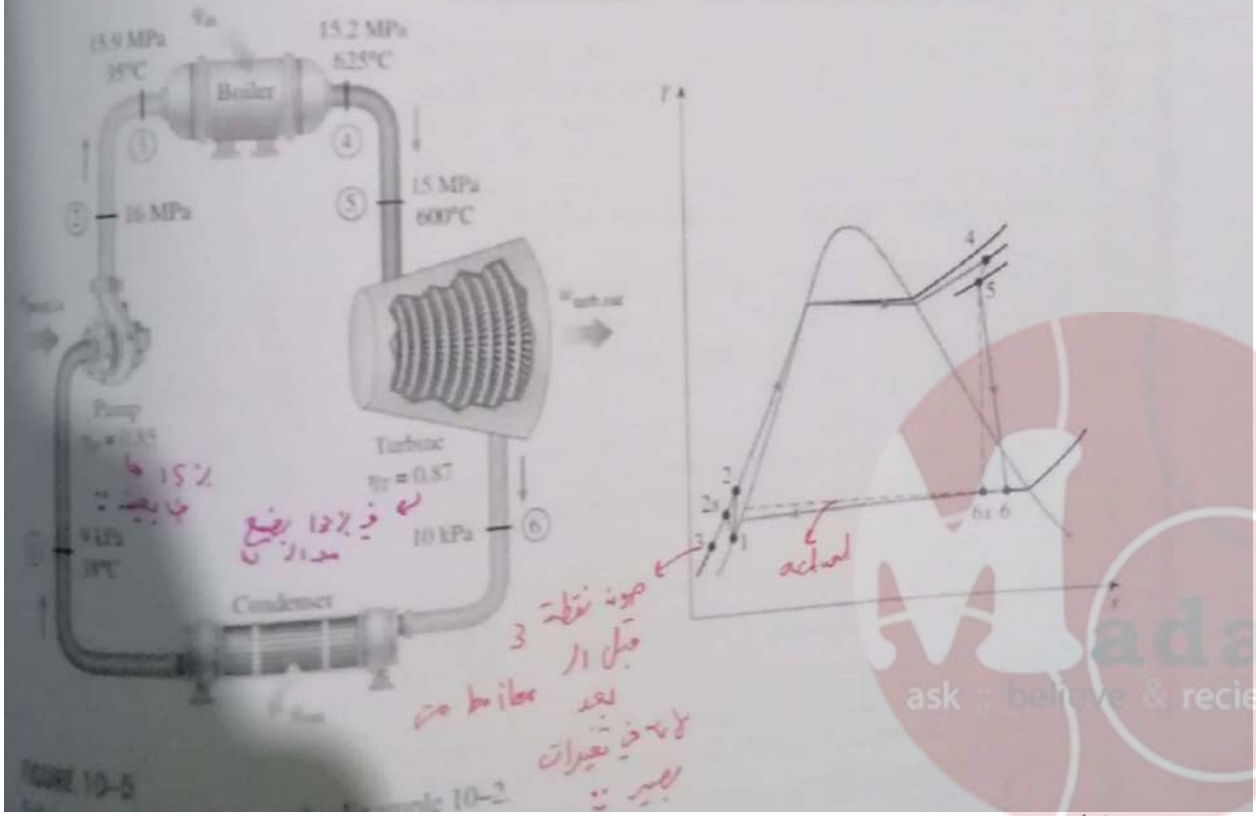


FIGURE 10–5

CamScanner الممسوحة ضوئيا بـ

Pump work input:

$$w_{\text{pump,in}} = \frac{w_{s,\text{pump,in}}}{\eta_P} = \frac{v_1(P_2 - P_1)}{\eta_P}$$

$$= \frac{(0.001009\ \text{m}^3/\text{kg})[(16{,}000 - 9)\ \text{kPa}]}{0.85}\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right)$$

$$= 19.0\ \text{kJ/kg}$$

Turbine work output:

$$w_{\text{turb,out}} = \eta_T w_{s,\text{turb,out}}$$

$$= \eta_T(h_5 - h_{6s}) = 0.87(3583.1 - 2115.3)\ \text{kJ/kg}$$

$$= 1277.0\ \text{kJ/kg}$$

Boiler heat input: $q_{\text{in}} = h_4 - h_3 = (3647.6 - 160.1)\ \text{kJ/kg} = 3487.5\ \text{kJ/kg}$

Thus,

$$w_{\text{net}} = w_{\text{turb,out}} - w_{\text{pump,in}} = (1277.0 - 19.0)\ \text{kJ/kg} = 1258.0\ \text{kJ/kg}$$

$$\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}} = \frac{1258.0\ \text{kJ/kg}}{3487.5\ \text{kJ/kg}} = 0.361 \text{ or } 36.1\%$$

(*b*) The power produced by this power plant is

$$\dot{W}_{\text{net}} = \dot{m}\, w_{\text{net}} = (15\ \text{kg/s})(1258.0\ \text{kJ/kg}) = 18.9\ \text{MW}$$

Discussion Without the irreversibilities, the thermal efficiency of this cycle would be 43.0 percent (see Example 10–3*c*).

EXAMPLE 10–3 Effect of Boiler Pressure and Temperature on Efficiency

Consider a steam power plant operating on the ideal Rankine cycle. Steam enters the turbine at 3 MPa and 350°C and is condensed in the condenser at a pressure of 10 kPa. Determine (*a*) the thermal efficiency of this power plant, (*b*) the thermal efficiency if steam is superheated to 600°C instead of 350°C, and (*c*) the thermal efficiency if the boiler pressure is raised to 15 MPa while the turbine inlet temperature is maintained at 600°C.

SOLUTION A steam power plant operating on the ideal Rankine cycle is considered. The effects of superheating the steam to a higher temperature and raising the boiler pressure on thermal efficiency are to be investigated.

Analysis The *T-s* diagrams of the cycle for all three cases are given in Fig. 10–10.

(*a*) This is the steam power plant discussed in Example 10–1, except that the condenser pressure is lowered to 10 kPa. The thermal efficiency is determined in a similar manner:

State 1: $P_1 = 10\ \text{kPa}$, Sat. liquid $\Rightarrow h_1 = h_{f@10\ \text{kPa}} = 191.81\ \text{kJ/kg}$, $v_1 = v_{f@10\ \text{kPa}} = 0.00101\ \text{m}^3/\text{kg}$

State 2: $P_2 = 3\ \text{MPa}$, $s_2 = s_1$

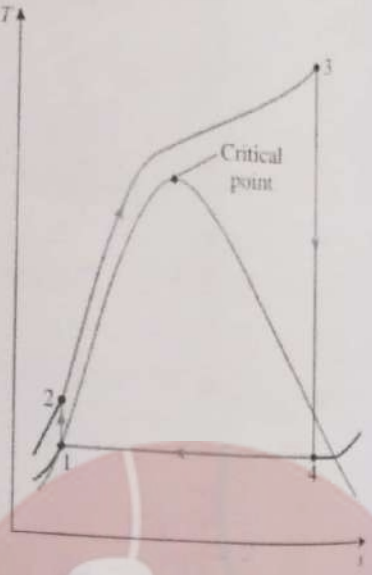


FIGURE 10–9
A supercritical Rankine cycle.

CamScanner الممسوحة ضوئيا بـ

$= v_1(P_2 - P_1) = (0.00101\ \text{m}^3/\text{kg})[(3000 - 10)\ \text{kPa}]\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right)$

$= 3.02\ \text{kJ/kg}$

$= h_1 + w_{\text{pump in}} = (191.81 + 3.02)\ \text{kJ/kg} = 194.83\ \text{kJ/kg}$

$P_3 = 3\ \text{MPa}$, $T_3 = 350°\text{C}$ $\Rightarrow$ $h_3 = 3116.1\ \text{kJ/kg}$, $s_3 = 6.7450\ \text{kJ/kg·K}$

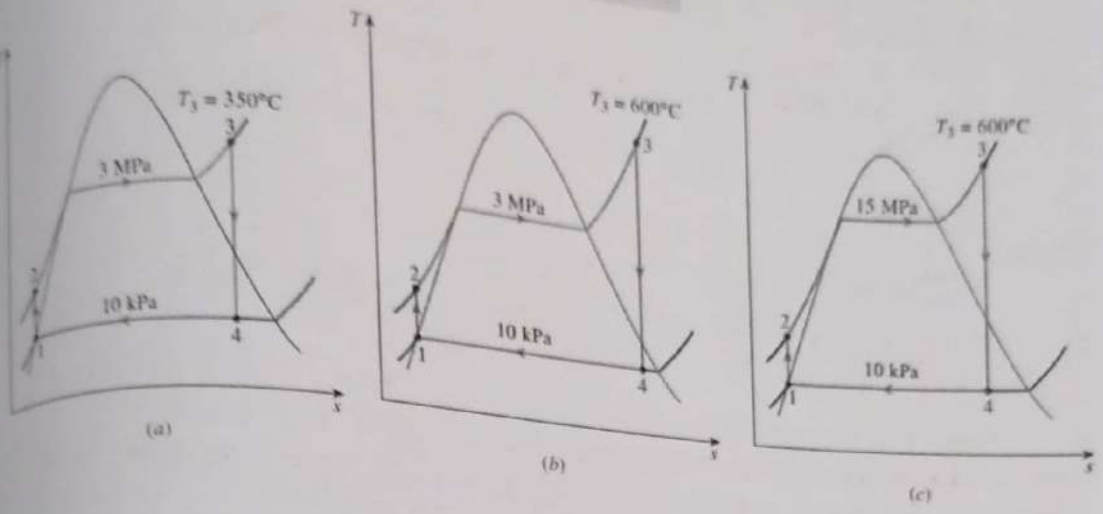


FIGURE 10–10
T-s diagrams of the three cycles discussed in Example 10–3.

State 4: $P_4 = 10\ \text{kPa}$ (sat. mixture)

$$s_4 = s_3$$

$$x_4 = \frac{s_4 - s_f}{s_{fg}} = \frac{6.7450 - 0.6492}{7.4996} = 0.8128$$

Thus,

$$h_4 = h_f + x_4 h_{fg} = 191.81 + 0.8128(2392.1) = 2136.1\ \text{kJ/kg}$$

$$q_{\text{in}} = h_3 - h_2 = (3116.1 - 194.83)\ \text{kJ/kg} = 2921.3\ \text{kJ/kg}$$

$$q_{\text{out}} = h_4 - h_1 = (2136.1 - 191.81)\ \text{kJ/kg} = 1944.3\ \text{kJ/kg}$$

and

$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{1944.3\ \text{kJ/kg}}{2921.3\ \text{kJ/kg}} = 0.334 \text{ or } 33.4\%$$

Therefore, the thermal efficiency increases from 26.0 to 33.4 percent as a result of lowering the condenser pressure from 75 to 10 kPa. At the same time, however, the quality of the steam decreases from 88.6 to 81.3 percent (in other words, the moisture content increases from 11.4 to 18.7 percent).

CamScanner الممسوحة ضوئيا بـ

(*b*) States 1 and 2 remain the same in this case, and the enthalpies at state 3 (3 MPa and 600°C) and state 4 (10 kPa and $s_4 = s_3$) are determined to be

$$h_3 = 3682.8 \text{ kJ/kg}$$

$$h_4 = 2380.3 \text{ kJ/kg} \quad (x_4 = 0.915)$$

Thus,

$$q_{in} = h_3 - h_2 = 3682.8 - 194.83 = 3488.0 \text{ kJ/kg}$$

$$q_{out} = h_4 - h_1 = 2380.3 - 191.81 = 2188.5 \text{ kJ/kg}$$

and

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{2188.5 \text{ kJ/kg}}{3488.0 \text{ kJ/kg}} = 0.373 \text{ or } 37.3\%$$

Therefore, the thermal efficiency increases from 33.4 to 37.3 percent as a result of superheating the steam from 350 to 600°C. At the same time, the quality of the steam increases from 81.3 to 91.5 percent (in other words, the moisture content decreases from 18.7 to 8.5 percent).

(*c*) State 1 remains the same in this case, but the other states change. The enthalpies at state 2 (15 MPa and $s_2 = s_1$), state 3 (15 MPa and 600°C), and state 4 (10 kPa and $s_4 = s_3$) are determined in a similar manner to be

$$h_2 = 206.95 \text{ kJ/kg}$$

$$h_3 = 3583.1 \text{ kJ/kg}$$

$$h_4 = 2115.3 \text{ kJ/kg} \quad (x_4 = 0.804)$$

Thus,

$$q_{in} = h_3 - h_2 = 3583.1 - 206.95 = 3376.2 \text{ kJ/kg}$$

$$q_{out} = h_4 - h_1 = 2115.3 - 191.81 = 1923.5 \text{ kJ/kg}$$

and

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{1923.5 \text{ kJ/kg}}{3376.2 \text{ kJ/kg}} = 0.430 \text{ or } 43.0\%$$

Discussion The thermal efficiency increases from 37.3 to 43.0 percent as a result of raising the boiler pressure from 3 to 15 MPa while maintaining the turbine inlet temperature at 600°C. At the same time, however, the quality of the steam decreases from 91.5 to 80.4 percent (in other words, the moisture content increases from 8.5 to 19.6 percent).

CamScanner الممسوحة ضوئيا بـ

Chapter 11

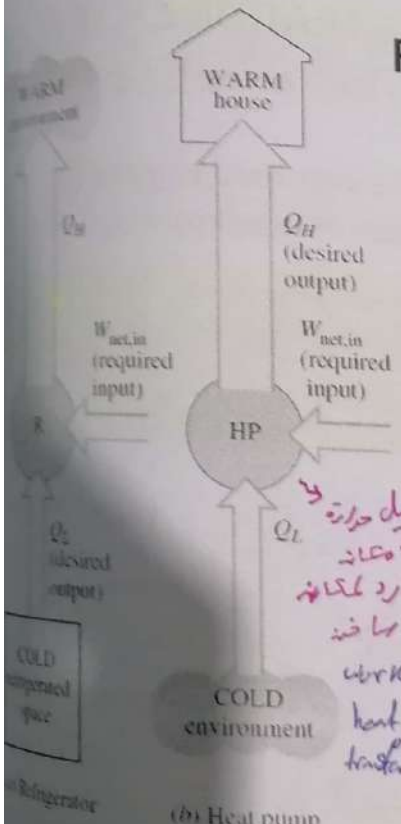
REFRIGERATION CYCLES

Thermodynamics: An Engineering Approach
Yunus A. Cengel, Michael A. Boles, Mehmet Kanoglu
McGraw-Hill

Dr. Ahmad M. AbuYaghi
October 2023

REFRIGERATORS AND HEAT PUMPS

- The transfer of heat from a low-temperature region to a high-temperature one requires special devices called refrigerators.
- Refrigerators and heat pumps are essentially the same devices; they differ in their objectives only.



$$COP_R = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Cooling effect}}{\text{Work input}} = \frac{Q_L}{W_{net,in}}$$

$$COP_{HP} = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Heating effect}}{\text{Work input}} = \frac{Q_H}{W_{net,in}}$$

$$COP_{HP} = COP_R + 1 \quad \text{for fixed values of } Q_L \text{ and } Q_H$$

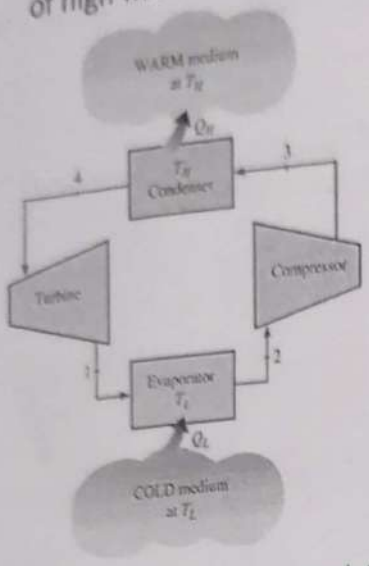
The objective of a refrigerator is to remove heat (Q_L) from the cold medium;
The objective of a heat pump is to supply heat (Q_H) to a warm medium.

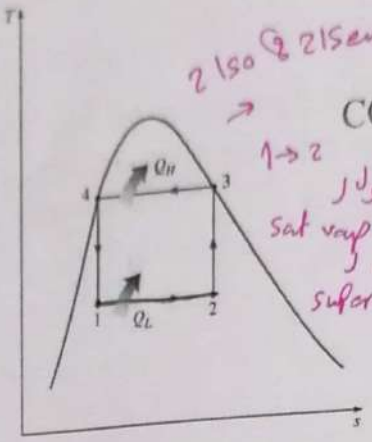
THE REVERSED CARNOT CYCLE

- The reversed Carnot cycle is the *most efficient* refrigeration cycle operating between T_L and T_H.
- However, it is not a suitable model for refrigeration cycles since processes 2-3 and 4-1 are not practical because
- Process 2-3 involves the compression of a liquid–vapor mixture, which requires a compressor that will handle two phases, and process 4-1 involves the expansion of high-moisture-content refrigerant in a turbine.

$$COP_{R,Carnot} = \frac{1}{T_H/T_L - 1}$$

$$COP_{HP,Carnot} = \frac{1}{1 - T_L/T_H}$$





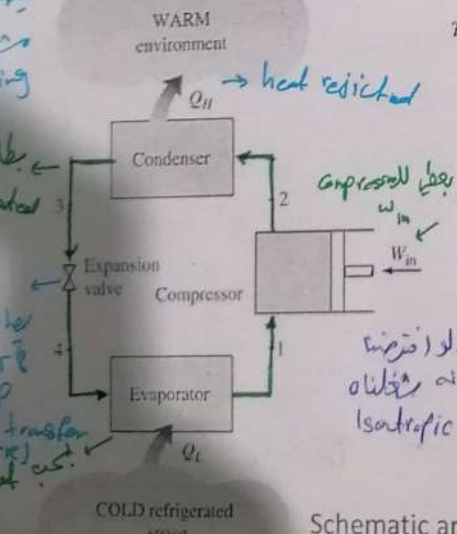
Both COPs increase as the difference between the two temperatures decreases, that is, as T_L rises or T_H falls.

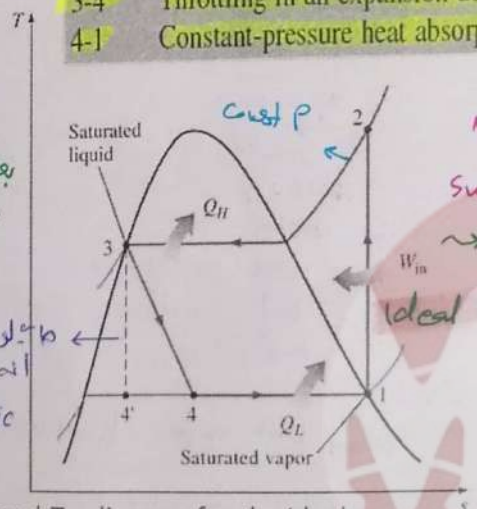
Schematic of a Carnot refrigerator and *T-s* diagram of the reversed Carnot cycle.

THE IDEAL VAPOR-COMPRESSION REFRIGERATION CYCLE-1

- The **vapor-compression refrigeration cycle** is the ideal model for refrigeration systems.
- Unlike the reversed Carnot cycle, the refrigerant is vaporized completely before it is compressed, and the turbine is replaced with a throttling device.

1-2	Isentropic compression in a compressor
2-3	Constant-pressure heat rejection in a condenser
3-4	Throttling in an expansion device
4-1	Constant-pressure heat absorption in an evaporator





This is the most widely used cycle for refrigerators, A-C systems, and heat pumps.

Schematic and *T-s* diagram for the ideal vapor-compression refrigeration cycle.

CamScanner الممسوحة ضوئيا بـ

THE IDEAL VAPOR-COMPRESSION REFRIGERATION CYCLE-2

- The ideal vapor-compression refrigeration cycle involves an irreversible (throttling) process to make it a more realistic model for the actual systems.
- Replacing the expansion valve by a turbine is not practical since the added benefits cannot justify the added cost and complexity.

Steady-flow energy balance:

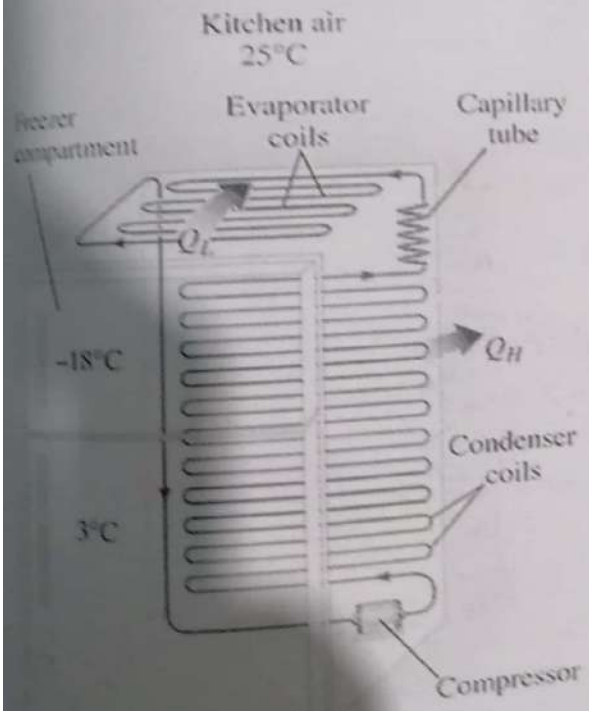
$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i$$

$$\text{COP}_R = \frac{q_L}{w_{net,in}} = \frac{h_1 - h_4}{h_2 - h_1}$$

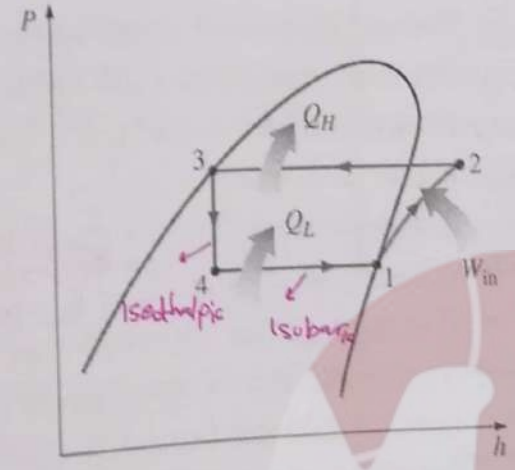
$$\text{COP}_{HP} = \frac{q_H}{w_{net,in}} = \frac{h_2 - h_3}{h_2 - h_1}$$

$h_1 = h_{g\,@\,P_1}$ and $h_3 = h_{f\,@\,P_3}$ for the ideal case

THE IDEAL VAPOR-COMPRESSION REFRIGERATION CYCLE-3



An ordinary household refrigerator.

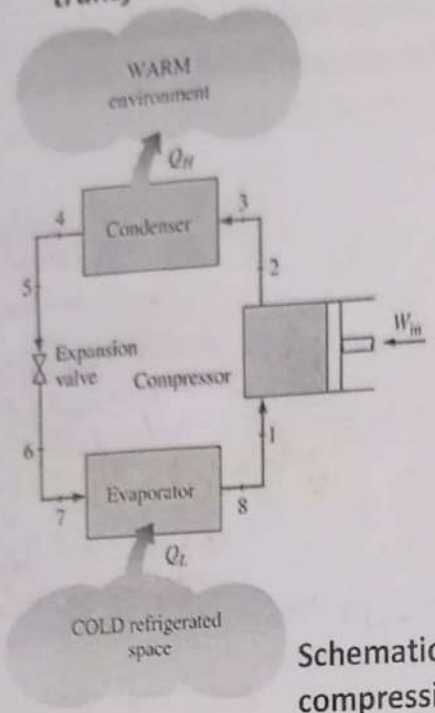


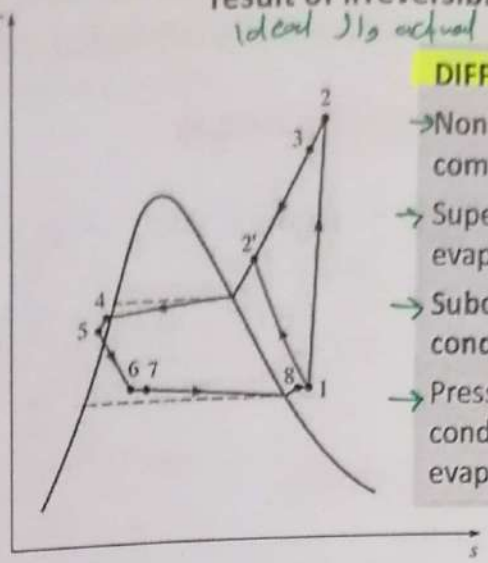
The *P-h* diagram of an ideal vapor-compression refrigeration cycle.

Mostaqar
ask | believe & recieve
الممسوحة ضوئيا بـ CamScanner

ACTUAL VAPOR-COMPRESSION REFRIGERATION CYCLE

- An actual vapor-compression refrigeration cycle differs from the ideal one in several ways, owing mostly to the irreversibilities that occur in various components, mainly due to ***fluid friction*** (causes pressure drops) and ***heat transfer to or from the surroundings.***
- The COP decreases as a result of irreversibilities.





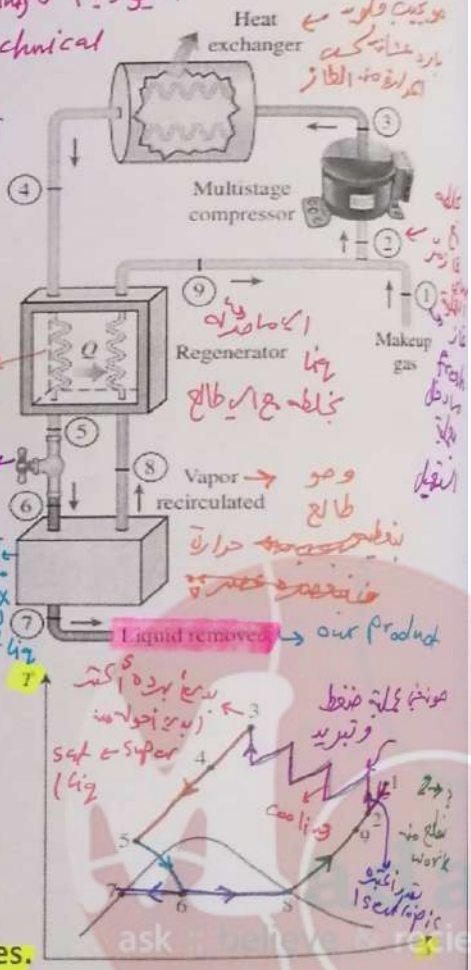
DIFFERENCES

- Non-isentropic compression
- Superheated vapor at evaporator exit
- Subcooled liquid at condenser exit
- Pressure drops in condenser and evaporator

Schematic and *T-s* diagram for the actual vapor-compression refrigeration cycle.

Liquefaction of Gases

- Many important scientific and engineering processes at cryogenic temperatures (below about 100°C) depend on liquefied gases including the separation of oxygen and nitrogen from air, preparation of liquid propellants for rockets, the study of material properties at low temperatures, and the study of superconductivity.
- The storage (i.e., hydrogen) and transportation of some gases (i.e., natural gas) are done after they are liquefied at very low temperatures.
- Several innovative cycles are used for the liquefaction of gases.



Linde-Hampson system for liquefying gases.

الممسوحة ضوئيا بـ CamScanner

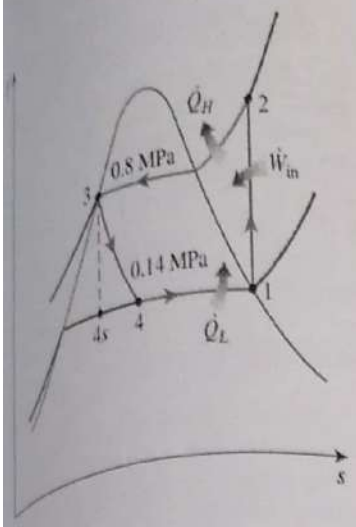


FIGURE 11–6
T-s diagram of the ideal vapor-compression refrigeration cycle described in Example 11–1.

EXAMPLE 11–1 The Ideal Vapor-Compression Refrigeration Cycle

A refrigerator uses refrigerant-134a as the working fluid and operates on an ideal vapor-compression refrigeration cycle between 0.14 and 0.8 MPa. If the mass flow rate of the refrigerant is 0.05 kg/s, determine (*a*) the rate of heat removal from the refrigerated space and the power input to the compressor, (*b*) the rate of heat rejection to the environment, and (*c*) the COP of the refrigerator.

SOLUTION A refrigerator operates on an ideal vapor-compression refrigeration cycle between two specified pressure limits. The rate of refrigeration, the power input, the rate of heat rejection, and the COP are to be determined.

Assumptions 1 Steady operating conditions exist. 2 Kinetic and potential energy changes are negligible.

Analysis The T-s diagram of the refrigeration cycle is shown in Fig. 11–6. We note that this is an ideal vapor-compression refrigeration cycle, and thus the compressor is isentropic and the refrigerant leaves the condenser as a saturated liquid and enters the compressor as saturated vapor. From the refrigerant-134a tables, the enthalpies of the refrigerant at all four states are determined as follows:

$$P_1 = 0.14\ \text{MPa} \longrightarrow h_1 = h_{g\,@\,0.14\,\text{MPa}} = 239.19\ \text{kJ/kg}$$
$$s_1 = s_{g\,@\,0.14\,\text{MPa}} = 0.94467\ \text{kJ/kg-K}$$

$$\left.\begin{aligned} P_2 &= 0.8\ \text{MPa} \\ s_2 &= s_1 \end{aligned}\right\} \longrightarrow h_2 = 275.40\ \text{kJ/kg}$$

$$P_3 = 0.8\ \text{MPa} \longrightarrow h_3 = h_{f\,@\,0.8\,\text{MPa}} = 95.48\ \text{kJ/kg}$$

$$h_4 \cong h_3\ \text{(throttling)} \longrightarrow h_4 = 95.48\ \text{kJ/kg}$$

(*a*) The rate of heat removal from the refrigerated space and the power input to the compressor are determined from their definitions:

$$\dot{Q}_L = \dot{m}(h_1 - h_4) = (0.05\ \text{kg/s})[(239.19 - 95.48)\ \text{kJ/kg}] = \boxed{7.19\ \text{kW}}$$

and

$$\dot{W}_{in} = \dot{m}(h_2 - h_1) = (0.05\ \text{kg/s})[(275.40 - 239.19)\ \text{kJ/kg}] = \boxed{1.81\ \text{kW}}$$

(*b*) The rate of heat rejection from the refrigerant to the environment is

$$\dot{Q}_H = \dot{m}(h_2 - h_3) = (0.05\ \text{kg/s})[(275.40 - 95.48)\ \text{kJ/kg}] = 9.00\ \text{kW}$$

It could also be determined from

$$\dot{Q}_H = \dot{Q}_L + \dot{W}_{in} = 7.19 + 1.81 = 9.00\ \text{kW}$$

(*c*) The coefficient of performance of the refrigerator is

$$\text{COP}_R = \frac{\dot{Q}_L}{\dot{W}_{in}} = \frac{7.19\ \text{kW}}{1.81\ \text{kW}} = 3.97$$

That is, this refrigerator removes about 4 units of thermal energy from the refrigerated space for each unit of electric energy it consumes.

ask recieve
CamScanner المسوحة ضوئيا بـ

EXAMPLE 11–2 The Actual Vapor-Compression Refrigeration Cycle

Refrigerant-134a enters the compressor of a refrigerator as superheated vapor at 0.14 MPa and −10°C at a rate of 0.05 kg/s and leaves at 0.8 MPa and 50°C. The refrigerant is cooled in the condenser to 26°C and 0.72 MPa and is throttled to 0.15 MPa. Disregarding any heat transfer and pressure drops in the connecting lines between the components, determine (a) the rate of heat removal from the refrigerated space and the power input to the compressor, (b) the isentropic efficiency of the compressor, and (c) the coefficient of performance of the refrigerator.

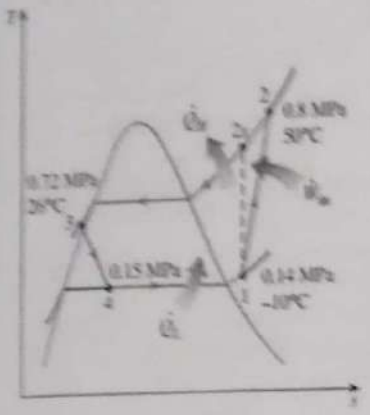


FIGURE 11–8
T-s diagram for Example 11–2.

SOLUTION A refrigerator operating on a vapor-compression cycle is considered. The rate of refrigeration, the power input, the compressor efficiency, and the COP are to be determined.

Assumptions 1 Steady operating conditions exist. 2 Kinetic and potential energy changes are negligible.

Analysis The *T-s* diagram of the refrigeration cycle is shown in Fig. 11–8. We note that the refrigerant leaves the condenser as a compressed liquid and enters the compressor as superheated vapor. The enthalpies of the refrigerant at various states are determined from the refrigerant tables to be

$$\left.\begin{aligned} P_1 &= 0.14\ \text{MPa} \\ T_1 &= -10^\circ\text{C} \end{aligned}\right\} \quad h_1 = 246.37\ \text{kJ/kg}$$

$$\left.\begin{aligned} P_2 &= 0.8\ \text{MPa} \\ T_2 &= 50^\circ\text{C} \end{aligned}\right\} \quad h_2 = 286.71\ \text{kJ/kg}$$

$$\left.\begin{aligned} P_3 &= 0.72\ \text{MPa} \\ T_3 &= 26^\circ\text{C} \end{aligned}\right\} \quad h_3 \cong h_{f\,@\,26^\circ\text{C}} = 87.83\ \text{kJ/kg}$$

$$h_4 \cong h_3\ \text{(throttling)} \longrightarrow h_4 = 87.83\ \text{kJ/kg}$$

(a) The rate of heat removal from the refrigerated space and the power input to the compressor are determined from their definitions:

$$\dot{Q}_L = \dot{m}(h_1 - h_4) = (0.05\ \text{kg/s})[(246.37 - 87.83)\ \text{kJ/kg}] = 7.93\ \text{kW}$$

and

$$\dot{W}_{in} = \dot{m}(h_2 - h_1) = (0.05\ \text{kg/s})[(286.71 - 246.37)\ \text{kJ/kg}] = 2.02\ \text{kW}$$

(b) The isentropic efficiency of the compressor is determined from

$$\eta_C \cong \frac{h_{2s} - h_1}{h_2 - h_1}$$

where the enthalpy at state 2s (P_{2s} = 0.8 MPa and $s_{2s} = s_1 = 0.9724$ kJ/kg·K) is 284.20 kJ/kg. Thus,

$$\eta_C = \frac{284.20 - 246.37}{286.71 - 246.37} = 0.938 \text{ or } 93.8\%$$

(c) The coefficient of performance of the refrigerator is

$$\text{COP}_R = \frac{\dot{Q}_L}{\dot{W}_{in}} = \frac{7.93\ \text{kW}}{2.02\ \text{kW}} = 3.93$$

CamScanner الممسوحة ضوئيا بـ

Chapter 12

THERMODYNAMIC PROPERTY RELATIONS

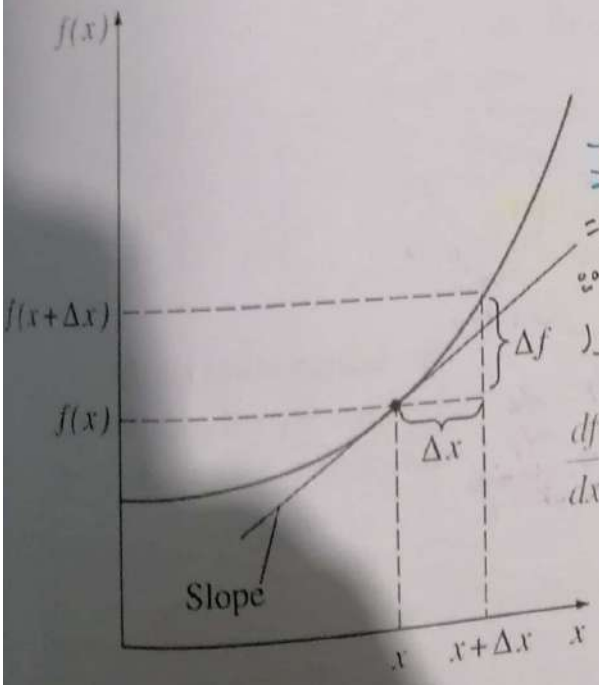
Thermodynamics: An Engineering Approach
Yunus A. Cengel, Michael A. Boles, Mehmet Kanoglu
McGraw-Hill

Dr. Ahmad M. AbuYaghi
October 2023

LITTLE MATH: PARTIAL DERIVATIVES AND ASSOCIATED RELATIONS

The state postulate:

- The state of a simple, compressible substance is completely specified by any two independent, intensive properties.
- All other properties at that state can be expressed in terms of those two properties.



$$z = z(x, y)$$

$$f = f(x)$$

$$\frac{df}{dx} = \lim_{\Delta x \to 0} \frac{\Delta f}{\Delta x} = \lim_{\Delta x \to 0} \frac{f(x + \Delta x) - f(x)}{\Delta x}$$

The derivative of a function $f(x)$ with respect to x represents the rate of change of f with x.

The derivative of a function at a specified point

CamScanner الممسوحة ضوئيا بـ

To obtain a relation for the total differential change in $z(x, y)$ for simultaneous changes in x and y, consider a small portion of the surface $z(x, y)$ shown in Fig. 12–4. When the independent variables x and y change by Δx and Δy, respectively, the dependent variable z changes by Δz, which can be expressed as

$$\Delta z = z(x + \Delta x, y + \Delta y) - z(x, y)$$

Adding and subtracting $z(x, y + \Delta y)$, we get

$$\Delta z = z(x + \Delta x, y + \Delta y) - z(x, y + \Delta y) + z(x, y + \Delta y) - z(x, y)$$

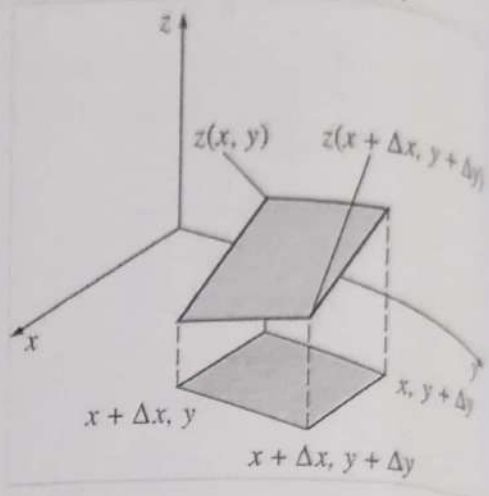
or

$$\Delta z = \frac{z(x + \Delta x, y + \Delta y) - z(x, y + \Delta y)}{\Delta x} \Delta x + \frac{z(x, y + \Delta y) - z(x, y)}{\Delta y} \Delta y$$

Taking the limits as $\Delta x \to 0$ and $\Delta y \to 0$ and using the definitions of partial derivatives, we obtain

$$dz = \left(\frac{\partial z}{\partial x}\right)_y dx + \left(\frac{\partial z}{\partial y}\right)_x dy$$

This is the fundamental relation for the **total differential** of a dependent variable in terms of its partial derivatives with respect to the independent variables.



Geometric representation of total derivative *dz* for a function *z*(*x*, *y*).

Partial Differential Relations

$$dz = M\,dx + N\,dy$$

$$M = \left(\frac{\partial z}{\partial x}\right)_y \quad \text{and} \quad N = \left(\frac{\partial z}{\partial y}\right)_x$$

$$\left(\frac{\partial M}{\partial y}\right)_x = \frac{\partial^2 z}{\partial x\,\partial y} \quad \text{and} \quad \left(\frac{\partial N}{\partial x}\right)_y = \frac{\partial^2 z}{\partial y\,\partial x}$$

- ☐ **The order of differentiation is immaterial for properties since they are continuous point functions and have exact differentials.**
- ☐ **Thus,**

$$\left(\frac{\partial M}{\partial y}\right)_x = \left(\frac{\partial N}{\partial x}\right)_y$$

Function: $z + 2xy - 3y^2z = 0$

1) $z = \dfrac{2xy}{3y^2 - 1} \rightarrow \left(\dfrac{\partial z}{\partial x}\right)_y = \dfrac{2y}{3y^2 - 1}$

2) $x = \dfrac{3y^2z - z}{2y} \rightarrow \left(\dfrac{\partial x}{\partial z}\right)_y = \dfrac{3y^2 - 1}{2y}$

Thus, $\left(\dfrac{\partial z}{\partial x}\right)_y = \dfrac{1}{\left(\dfrac{\partial x}{\partial z}\right)_y}$

Demonstration of the reciprocity relation for the function $z + 2xy - 3y^2z = 0$.

$$\left(\frac{\partial x}{\partial z}\right)_y \left(\frac{\partial z}{\partial x}\right)_y = 1 \rightarrow \left(\frac{\partial x}{\partial z}\right)_y = \frac{1}{(\partial z/\partial x)_y}$$

Reciprocity relation

$$\left(\frac{\partial z}{\partial x}\right)_y \left(\frac{\partial x}{\partial y}\right)_z = -\left(\frac{\partial x}{\partial y}\right)_z \rightarrow \left(\frac{\partial x}{\partial y}\right)_z \left(\frac{\partial y}{\partial z}\right)_x \left(\frac{\partial z}{\partial x}\right)_y = -1$$

Cyclic relation

CamScanner الممسوحة ضوئيا بـ

THE MAXWELL RELATIONS

- The equations that relate the partial derivatives of properties ***P, v, T,* and *s*** of a simple compressible system to each other are called the ***Maxwell relations***.
- They are obtained from the four Gibbs equations by exploiting the exactness of the differentials of thermodynamic properties.

$$du = T\,ds - P\,dv$$

$$dh = T\,ds + v\,dP$$

$$a = u - Ts$$ **Helmholtz function**

$$g = h - Ts$$ **Gibbs function**

$$da = du - T\,ds - s\,dT$$

$$dg = dh - T\,ds - s\,dT$$

$$da = -s\,dT - P\,dv$$

$$dg = -s\,dT + v\,dP$$

$$dz = M\,dx + N\,dy$$

$$\left(\frac{\partial M}{\partial y}\right)_x = \left(\frac{\partial N}{\partial x}\right)_y$$

THE MAXWELL RELATIONS

The *Maxwell relations* are

	Differential expression	
U	$dU = T\,ds - P\,dv$	$\left(\frac{\partial T}{\partial v}\right)_s = -\left(\frac{\partial P}{\partial s}\right)_v$
H	$dH = T\,ds + v\,dP$	$\left(\frac{\partial T}{\partial P}\right)_s = \left(\frac{\partial v}{\partial s}\right)_P$
A	$dA = -s\,dT - P\,dv$	$\left(\frac{\partial s}{\partial v}\right)_T = \left(\frac{\partial P}{\partial T}\right)_v$
G	$dG = -s\,dT + v\,dP$	$\left(\frac{\partial s}{\partial P}\right)_T = -\left(\frac{\partial v}{\partial T}\right)_P$

- **Maxwell relations** are extremely valuable in thermodynamics because they provide a means of determining the change in entropy, which cannot be measured directly, by simply measuring the changes in properties *P*, *v*, and *T*.
- *These **Maxwell relations** are limited to simple compressible systems.*

CamScanner الممسوحة ضوئيا بـ

THE CLAPEYRON EQUATION

Consider the third Maxwell relation, Eq. 12–18:

$$\left(\frac{\partial P}{\partial T}\right)_v = \left(\frac{\partial s}{\partial v}\right)_T$$

During a phase-change process, the pressure is the saturation pressure, which depends on the temperature only and is independent of the specific volume. That is, $P_{sat} = f(T_{sat})$. Therefore, the partial derivative $(\partial P/\partial T)_v$ can be expressed as a total derivative $(dP/dT)_{sat}$, which is the slope of the saturation curve on a P-T diagram at a specified saturation state (Fig. 12–9). This slope is independent of the specific volume, and thus it can be treated as a constant during the integration of Eq. 12–18 between two saturation states at the same temperature. For an isothermal liquid–vapor phase-change process, for example, the integration yields

$$s_g - s_f = \left(\frac{dP}{dT}\right)_{sat}(v_g - v_f) \qquad (12\text{–}20)$$

or

$$\left(\frac{dP}{dT}\right)_{sat} = \frac{s_{fg}}{v_{fg}} \qquad (12\text{–}21)$$

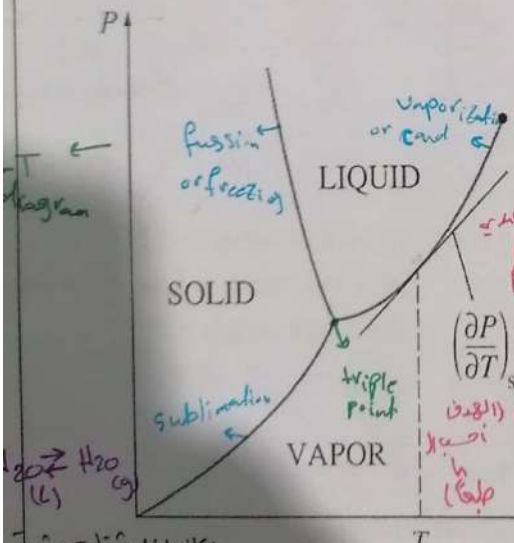
During this process the pressure also remains constant. Therefore, from Eq. 12–11,

$$dh = T\,ds + v\,dP \xrightarrow{0} \int_f^g dh = \int_f^g T\,ds \rightarrow h_{fg} = Ts_{fg}$$

Substituting this result into Eq. 12–21, we obtain

$$\left(\frac{dP}{dT}\right)_{sat} = \frac{h_{fg}}{Tv_{fg}} \qquad (12\text{–}22)$$

$$\left(\frac{dP}{dT}\right)_{sat} = \frac{h_{fg}}{Tv_{fg}}$$ **Clapeyron equation**



- The **Clapeyron equation** enables us to determine the enthalpy of vaporization h_{fg} at a given temperature by simply measuring the slope of the saturation curve on a P-T diagram and the specific volume of saturated liquid and saturated vapor at the given temperature.

The slope of the saturation curve on a P-T diagram is constant at a constant T or P.

$$\left(\frac{dP}{dT}\right)_{sat} = \frac{h_{12}}{Tv_{12}}$$

General form of the Clapeyron equation when the subscripts 1 and 2 indicate the two phases.

الممسوحة ضوئيا بـ CamScanner

❑ The Clapeyron equation can be simplified for liquid–vapor and solid–vapor phase changes by utilizing some approximations.

At low pressures

$$v_g \gg v_f \rightarrow v_{fg} \cong v_g$$

Treating vapor as an ideal gas

$$v_g = RT/P$$

Substituting these equations into the Clapeyron equation

$$\left(\frac{dP}{dT}\right)_{sat} = \frac{Ph_{fg}}{RT^2}$$

$$\left(\frac{dP}{P}\right)_{sat} = \frac{h_{fg}}{R}\left(\frac{dT}{T^2}\right)_{sat}$$

Integrating between two saturation states

$$\ln\left(\frac{P_2}{P_1}\right)_{sat} \cong \frac{h_{fg}}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)_{sat}$$

❑ The Clapeyron–Clausius equation can be used to determine the variation of saturation pressure with temperature.

❑ It can also be used in the solid–vapor region by replacing h_{fg} by h_{ig} (the enthalpy of sublimation) of the substance.

Clapeyron–Clausius equation

GENERAL RELATIONS FOR *du*, *dh*, *ds*, c_v, AND c_p

) The state postulate established that the state of a simple compressible system is completely specified by two independent, intensive properties.

) Therefore, we should be able to calculate all the properties of a system such as internal energy, enthalpy, and entropy at any state once two independent, intensive properties are available.

) The calculation of these properties from measurable ones depends on the availability of simple and accurate relations between the two groups.

) In this section we develop general relations for changes in internal energy, enthalpy, and entropy in terms of pressure, specific volume, temperature, and specific heats alone.

) We also develop some general relations involving specific heats.

) The relations developed will enable us to determine the *changes* in these properties.

) The property values at specified states can be determined only after the selection of a reference state, the choice of which is quite arbitrary.

CamScanner الممسوحة ضوئيا بـ

Internal Energy Changes

We choose the internal energy to be a function of T and v; that is, $u = u(T, v)$ and take its total differential (Eq. 12–3):

$$du = \left(\frac{\partial u}{\partial T}\right)_v dT + \left(\frac{\partial u}{\partial v}\right)_T dv$$

Using the definition of c_v, we have

$$du = c_v\, dT + \left(\frac{\partial u}{\partial v}\right)_T dv \qquad (12\text{–}25)$$

Now we choose the entropy to be a function of T and v; that is, $s = s(T, v)$ and take its total differential,

$$ds = \left(\frac{\partial s}{\partial T}\right)_v dT + \left(\frac{\partial s}{\partial v}\right)_T dv \qquad (12\text{–}26)$$

Substituting this into the $T\,ds$ relation $du = T\,ds - P\,dv$ yields

$$du = T\left(\frac{\partial s}{\partial T}\right)_v dT + \left[T\left(\frac{\partial s}{\partial v}\right)_T - P\right] dv \qquad (12\text{–}27)$$

Equating the coefficients of dT and dv in Eqs. 12–25 and 12–27 gives

$$\left(\frac{\partial s}{\partial T}\right)_v = \frac{c_v}{T}$$

$$\left(\frac{\partial u}{\partial v}\right)_T = T\left(\frac{\partial s}{\partial v}\right)_T - P \qquad (12\text{–}28)$$

Using the third Maxwell relation (Eq. 12–18), we get

$$\left(\frac{\partial u}{\partial v}\right)_T = T\left(\frac{\partial P}{\partial T}\right)_v - P$$

Substituting this into Eq. 12–25, we obtain the desired relation for du:

$$du = c_v\, dT + \left[T\left(\frac{\partial P}{\partial T}\right)_v - P\right] dv \qquad (12\text{–}29)$$

The change in internal energy of a simple compressible system associated with a change of state from (T_1, v_1) to (T_2, v_2) is determined by integration:

$$u_2 - u_1 = \int_{T_1}^{T_2} c_v\, dT + \int_{v_1}^{v_2} \left[T\left(\frac{\partial P}{\partial T}\right)_v - P\right] dv$$

CamScanner الممسوحة ضوئيا بـ

The general relation for dh is determined in exactly the same manner. This time we choose the enthalpy to be a function of T and P, that is, $h = h(T, P)$ and take its total differential,

$$dh = \left(\frac{\partial h}{\partial T}\right)_P dT + \left(\frac{\partial h}{\partial P}\right)_T dP$$

Using the definition of c_p, we have

$$dh = c_p\, dT + \left(\frac{\partial h}{\partial P}\right)_T dP \qquad (12\text{–}31)$$

Now we choose the entropy to be a function of T and P; that is, we take $s = s(T, P)$ and take its total differential,

$$ds = \left(\frac{\partial s}{\partial T}\right)_P dT + \left(\frac{\partial s}{\partial P}\right)_T dP \qquad (12\text{–}32)$$

Substituting this into the $T\,ds$ relation $dh = T\,ds + v\,dP$ gives

$$dh = T\left(\frac{\partial s}{\partial T}\right)_P dT + \left[v + T\left(\frac{\partial s}{\partial P}\right)_T\right] dP \qquad (12\text{–}33)$$

Equating the coefficients of dT and dP in Eqs. 12–31 and 12–33, we obtain

$$\left(\frac{\partial s}{\partial T}\right)_P = \frac{c_p}{T}$$

$$\left(\frac{\partial h}{\partial P}\right)_T = v + T\left(\frac{\partial s}{\partial P}\right)_T \qquad (12\text{–}34)$$

Using the fourth Maxwell relation (Eq. 12–19), we have

$$\left(\frac{\partial h}{\partial P}\right)_T = v - T\left(\frac{\partial v}{\partial T}\right)_P$$

Substituting this into Eq. 12–31, we obtain the desired relation for dh:

$$dh = c_p\, dT + \left[v - T\left(\frac{\partial v}{\partial T}\right)_P\right] dP \qquad (12\text{–}35)$$

The change in enthalpy of a simple compressible system associated with a change of state from (T_1, P_1) to (T_2, P_2) is determined by integration:

$$h_2 - h_1 = \int_{T_1}^{T_2} c_p\, dT + \int_{P_1}^{P_2} \left[v - T\left(\frac{\partial v}{\partial T}\right)_P\right] dP \qquad (12\text{–}36)$$

In reality, one needs only to determine either $u_2 - u_1$ from Eq. 12–30 or $h_2 - h_1$ from Eq. 12–36, depending on which is more suitable to the data at hand. The other can easily be determined by using the definition of enthalpy $h = u + Pv$:

$$h_2 - h_1 = u_2 - u_1 + (P_2 v_2 - P_1 v_1) \qquad (12\text{–}37)$$

The first relation is obtained by replacing the first partial derivative in the total differential ds (Eq. 12–26) by Eq. 12–28 and the second partial derivative by the third Maxwell relation (Eq. 12–18), yielding

$$ds = \frac{c_v}{T}\,dT + \left(\frac{\partial P}{\partial T}\right)_v dv \tag{12–38}$$

and

$$s_2 - s_1 = \int_{T_1}^{T_2} \frac{c_v}{T}\,dT + \int_{v_1}^{v_2} \left(\frac{\partial P}{\partial T}\right)_v dv \tag{12–39}$$

The second relation is obtained by replacing the first partial derivative in the total differential of ds (Eq. 12–32) by Eq. 12–34, and the second partial derivative by the fourth Maxwell relation (Eq. 12–19), yielding

$$ds = \frac{c_P}{T}\,dT - \left(\frac{\partial v}{\partial T}\right)_P dP \tag{12–40}$$

and

$$s_2 - s_1 = \int_{T_1}^{T_2} \frac{c_p}{T}\,dT - \int_{P_1}^{P_2} \left(\frac{\partial v}{\partial T}\right)_P dP \tag{12–41}$$

Either relation can be used to determine the entropy change. The proper choice depends on the available data.

Specific Heats c_v and c_p

At low pressures gases behave as ideal gases, and their specific heats essentially depend on temperature only. These specific heats are called *zero pressure*, or *ideal-gas, specific heats* (denoted c_{v0} and c_{p0}), and they are relatively easier to determine. Thus it is desirable to have some general relations that enable us to calculate the specific heats at higher pressures (or lower specific volumes) from a knowledge of c_{v0} or c_{p0} and the P-v-T behavior of the substance. Such relations are obtained by applying the test of exactness (Eq. 12–5) on Eqs. 12–38 and 12–40, which yields

$$\left(\frac{\partial c_v}{\partial v}\right)_T = T\left(\frac{\partial^2 P}{\partial T^2}\right)_v \tag{12–42}$$

and

$$\left(\frac{\partial c_p}{\partial P}\right)_T = -T\left(\frac{\partial^2 v}{\partial T^2}\right)_P \tag{12–43}$$

The deviation of c_p from c_{p0} with increasing pressure, for example, is determined by integrating Eq. 12–43 from zero pressure to any pressure P along an isothermal path:

$$(c_p - c_{p0})_T = -T\int_0^P \left(\frac{\partial^2 v}{\partial T^2}\right)_P dP \tag{12–44}$$

CamScanner الممسوحة ضوئيا بـ

Another desirable general relation involving specific heats is one that relates the two specific heats c_p and c_v. The advantage of such a relation is obvious: We will need to determine only one specific heat (usually c_p) and calculate the other one using that relation and the P-v-T data of the substance. We start the development of such a relation by equating the two ds relations (Eqs. 12–38 and 12–40) and solving for dT:

$$dT = \frac{T(\partial P/\partial T)_v}{c_p - c_v}\,dv + \frac{T(\partial v/\partial T)_P}{c_p - c_v}\,dP$$

for ideal gas

Choosing $T = T(v, P)$ and differentiating, we get

$$dT = \left(\frac{\partial T}{\partial v}\right)_P dv + \left(\frac{\partial T}{\partial P}\right)_v dP$$

Equating the coefficient of either dv or dP of the above two equations gives the desired result:

$$c_p - c_v = T\left(\frac{\partial v}{\partial T}\right)_P^2 \left(\frac{\partial P}{\partial T}\right)_v \qquad (12\text{–}45)$$

c_v و c_p بين ال العلاقة

$\beta = \frac{1}{v}\left(\frac{\partial v}{\partial T}\right)_P$ } التغير بالحجم مع T

$\alpha = -\frac{1}{v}\left(\frac{\partial v}{\partial P}\right)_T$

β : volume expansivity

α : Isothermal compressibility

$c_p - c_v = \frac{v T \beta^2}{\alpha}$ ← So $c_p - c_v = \frac{v T \beta^2}{\alpha}$

THE JOULE-THOMSON COEFFICIENT

بسبب قوى التجاذب بين الجزيئات Interaction

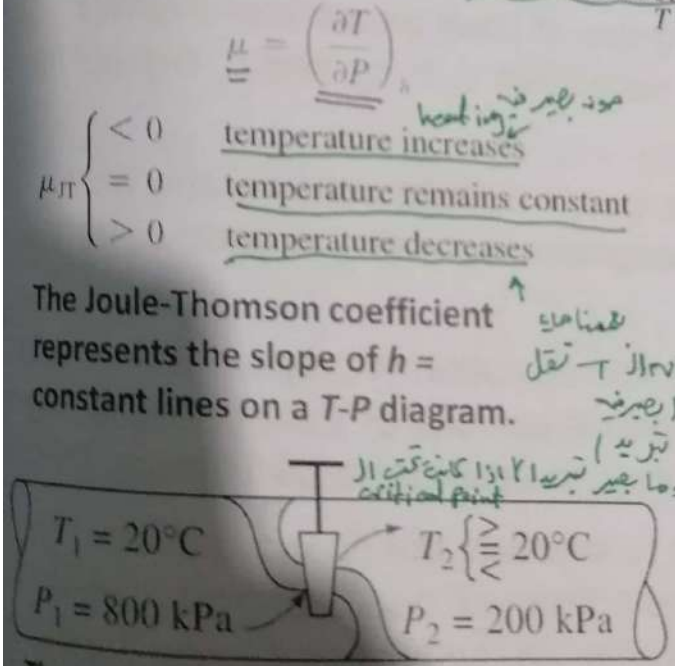
- The temperature behavior of a fluid during a throttling (h = constant) process is described by the Joule-Thomson coefficient μ

$$\mu = \left(\frac{\partial T}{\partial P}\right)_h$$

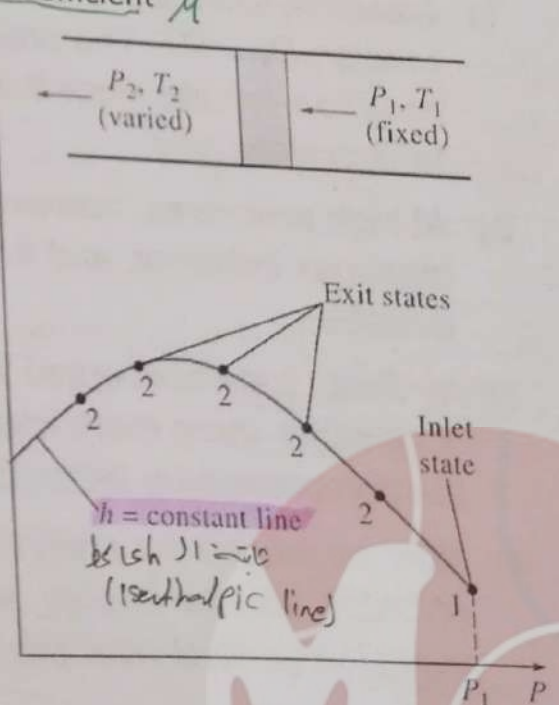
heating موجب

$$\mu_{JT}\begin{cases} < 0 & \text{temperature increases} \\ = 0 & \text{temperature remains constant} \\ > 0 & \text{temperature decreases} \end{cases}$$

The Joule-Thomson coefficient represents the slope of h = constant lines on a T-P diagram.



The temperature of a fluid may increase, decrease, or remain constant during a throttling process.



The development of an h = constant line on a P-T diagram.

CamScanner الممسوحة ضوئيا بـ

Next we would like to develop a general relation for the Joule-Thomson coefficient in terms of the specific heats, pressure, specific volume, and temperature. This is easily accomplished by modifying the generalized relation for enthalpy change (Eq. 12–35)

$$dh = c_p\,dT + \left[v - T\left(\frac{\partial v}{\partial T}\right)_P\right] dP$$

For an h = constant process we have $dh = 0$. Then this equation can be rearranged to give

$$-\frac{1}{c_p}\left[v - T\left(\frac{\partial v}{\partial T}\right)_P\right] = \left(\frac{\partial T}{\partial P}\right)_h = \mu_{JT} \qquad (12\text{–}52)$$

which is the desired relation. Thus, the Joule-Thomson coefficient can be determined from a knowledge of the constant-pressure specific heat and the P-v-T behavior of the substance. Of course, it is also possible to predict the constant-pressure specific heat of a substance by using the Joule-Thomson coefficient, which is relatively easy to determine, together with the P-v-T data for the substance.

THE Δh, Δu, AND Δs OF REAL GASES

1) Gases at low pressures behave as ideal gases and obey the relation $Pv = RT$. The properties of ideal gases are relatively easy to evaluate since the properties u, h, c_v, and c_p depend on temperature only.
2) At high pressures, however, gases deviate considerably from ideal-gas behavior, and it becomes necessary to account for this deviation.
3) In Chap. 3 we accounted for the deviation in properties P, v, and T by either using more complex equations of state or evaluating the compressibility factor Z from the compressibility charts.
4) Now we extend the analysis to evaluate the changes in the enthalpy, internal energy, and entropy of nonideal (real) gases, using the general relations for du, dh, and ds developed earlier.

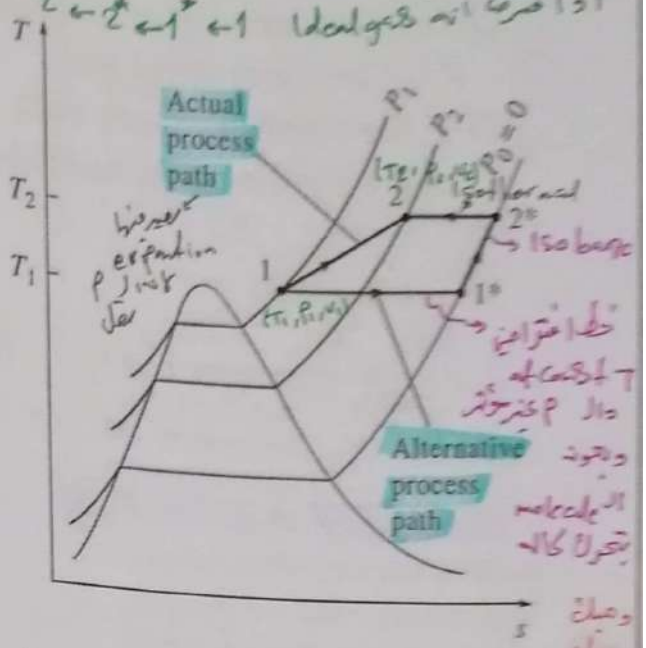
CamScanner الممسوحة ضوئيا بـ

Enthalpy Changes of Real Gases

- The enthalpy of a real gas, in general, depends on the pressure as well as on the temperature.
- Thus, the enthalpy change of a real gas during a process can be evaluated from the general relation for dh

$$h_2 - h_1 = \int_{T_1}^{T_2} c_p\, dT + \int_{P_1}^{P_2} \left[v - T\left(\frac{\partial v}{\partial T}\right)_P \right] dP$$

- For an isothermal process $dT = 0$, and the first term vanishes.
- For a constant-pressure process, $dP = 0$, and the second term vanishes.



An alternative process path to evaluate the enthalpy changes of real gases.

- Using a superscript asterisk (*) to denote an ideal-gas state, we can express the enthalpy change of a real gas during process 1-2 as:

$$h_2 - h_1 = (h_2 - h_2^*) + (h_2^* - h_1^*) + (h_1^* - h_1)$$

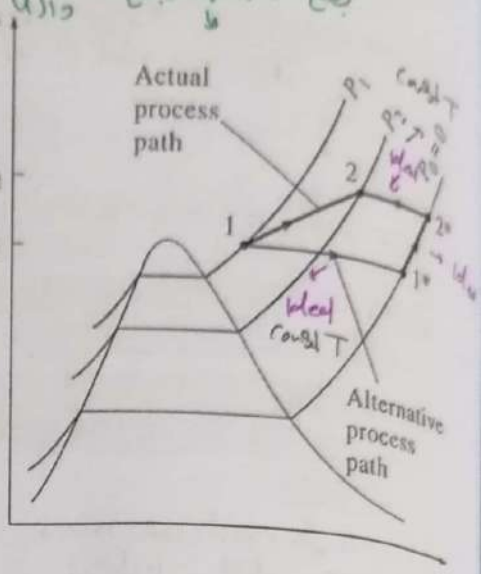
$$h_2 - h_2^* = 0 + \int_{P_2^*}^{P_2} \left[v - T\left(\frac{\partial v}{\partial T}\right)_P \right]_{T=T_2} dP = \int_{P_0}^{P_2} \left[v - T\left(\frac{\partial v}{\partial T}\right)_P \right]_{T=T_2} dP$$

$$h_2^* - h_1^* = \int_{T_1}^{T_2} c_p\, dT + 0 = \int_{T_1}^{T_2} c_{p0}(T)\, dT$$

$$h_1^* - h_1 = 0 + \int_{P_1}^{P_1^*} \left[v - T\left(\frac{\partial v}{\partial T}\right)_P \right]_{T=T_1} dP = -\int_{P_0}^{P_1} \left[v - T\left(\frac{\partial v}{\partial T}\right)_P \right]_{T=T_1} dP$$

CamScanner المسوحة ضوئيا بـ

- The difference between h and h^* is called the **enthalpy departure**, and it represents the variation of the enthalpy of a gas with pressure at a fixed temperature.
- The calculation of enthalpy departure requires a knowledge of the P-v-T behavior of the gas.
- In the absence of such data, we can use the relation $Pv = ZRT$, where Z is the compressibility factor.



- Substituting,

$$(h^* - h)_T = -RT^2 \int_0^P \left(\frac{\partial Z}{\partial T}\right)_P \frac{dP}{P}$$

$T = T_{cr}T_R$ and $P = P_{cr}P_R$

$$Z_h = \frac{(h^* - \bar{h})_T}{R_u T_{cr}} = T_R^2 \int_0^{P_R} \left(\frac{\partial Z}{\partial T_R}\right)_{P_R} d(\ln P_R)$$

Enthalpy departure factor

- The values of Z_h are presented in graphical form as a function of P_R (reduced pressure) and T_R (reduced temperature) in the **generalized enthalpy departure chart**.
- Z_h is used to determine the deviation of the enthalpy of a gas at a given P and T from the enthalpy of an ideal gas at the same T.

$$\bar{h}_2 - \bar{h}_1 = (\bar{h}_2 - \bar{h}_1)_{\text{ideal}} - R_u T_{cr}(Z_{h_2} - Z_{h_1})$$

$$h_2 - h_1 = (h_2 - h_1)_{\text{ideal}} - RT_{cr}(Z_{h_2} - Z_{h_1})$$

For a real gas during a process 1-2

$(\bar{h}_2 - \bar{h}_1)_{\text{ideal}}$ **from ideal gas tables**

Internal Energy Changes of Real Gases

Using the definition $\bar{h} = \bar{u} + P\bar{v} = \bar{u} + ZR_uT$:

$$\bar{u}_2 - \bar{u}_1 = (\bar{h}_2 - \bar{h}_1) - R_u(Z_2T_2 - Z_1T_1)$$

CamScanner الممسوحة ضوئيا بـ

Entropy Changes of Real Gases

General relation for *ds*

$$s_2 - s_1 = \int_{T_1}^{T_2} \frac{c_p}{T}\,dT - \int_{P_1}^{P_2} \left(\frac{\partial v}{\partial T}\right)_P dP$$

Using the approach in the figure

$$s_2 - s_1 = (s_2 - s_b^*) + (s_b^* - s_2^*) + (s_2^* - s_1^*) + (s_1^* - s_a^*) + (s_a^* - s_1)$$

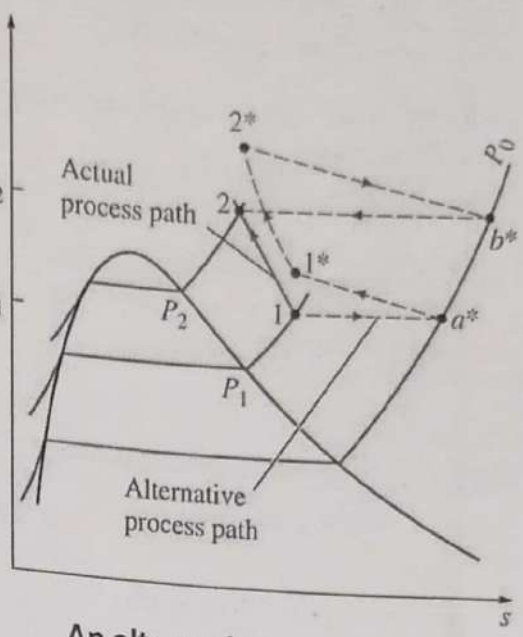
During isothermal process

$$(s_P - s_P^*)_T = (s_P - s_0^*)_T + (s_0^* - s_P^*)_T$$

$$= -\int_0^P \left(\frac{\partial v}{\partial T}\right)_P dP - \int_P^0 \left(\frac{\partial v^*}{\partial T}\right)_P dP$$

$$v = ZRT/P \qquad v^* = v_{\text{ideal}} = RT/P$$

$$(s_P - s_P^*)_T = \int_0^P \left[\frac{(1-Z)R}{P} - \frac{RT}{P}\left(\frac{\partial Z_r}{\partial T}\right)_P\right] dP$$



An alternative process path to evaluate the entropy changes of real gases during process 1-2.

$$T = T_{cr}T_R \quad \text{and} \quad P = P_{cr}P_R$$

$$Z_s = \frac{(\bar{s}^* - \bar{s})_{T,P}}{R_u} = \int_0^{P_R} \left[Z - 1 + T_R\left(\frac{\partial Z}{\partial T_R}\right)_{P_R}\right] d(\ln P_R)$$

Entropy departure factor

$$(\bar{s}^* - \bar{s})_{T,P}$$

Entropy departure

- The values of Z_s are presented in graphical form as a function of P_R (reduced pressure) and T_R (reduced temperature) in the **generalized entropy departure chart**.
- Z_s is used to determine the deviation of the entropy of a gas at a given P and T from the entropy of an ideal gas at the same P and T.

$$\bar{s}_2 - \bar{s}_1 = (\bar{s}_2 - \bar{s}_1)_{\text{ideal}} - R_u(Z_{s_2} - Z_{s_1})$$

$$s_2 - s_1 = (s_2 - s_1)_{\text{ideal}} - R(Z_{s_2} - Z_{s_1})$$

For a real gas during a process 1-2

$(s_2 - s_1)_{\text{ideal}}$ **from the ideal gas relations**

CamScanner الممسوحة ضوئيا بـ

EXAMPLE 12–1 **Approximating Differential Quantities by Differences**

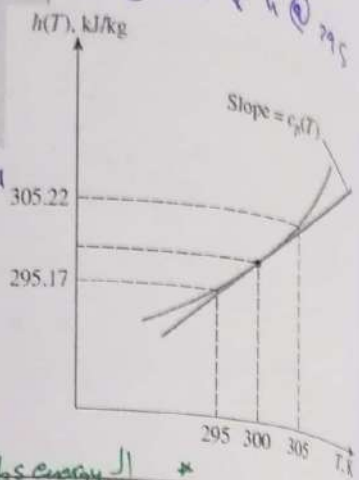
The c_p of ideal gases depends on temperature only, and it is expressed as $c_p(T) = dh(T)/dT$. Determine the c_p of air at 300 K, using the enthalpy data from Table A–17, and compare it to the value listed in Table A–2b.

SOLUTION The c_p value of air at a specified temperature is to be determined using enthalpy data.

Analysis The c_p value of air at 300 K is listed in Table A–2b to be 1.005 kJ/kg·K. This value could also be determined by differentiating the function $h(T)$ with respect to T and evaluating the result at $T = 300$ K. However, the function $h(T)$ is not available. But, we can still determine the c_p value approximately by replacing the differentials in the $c_p(T)$ relation by differences in the neighborhood of the specified point (Fig. 12–2):

$$c_p(300\text{ K}) = \left[\frac{dh(T)}{dT}\right]_{T=300\text{ K}} \cong \left[\frac{\Delta h(T)}{\Delta T}\right]_{T=300\text{ K}} = \frac{h(305\text{ K}) - h(295\text{ K})}{(305 - 295)\text{ K}}$$

$$= \frac{(305.22 - 295.17)\text{ kJ/kg}}{(305 - 295)\text{ K}} = 1.005\text{ kJ/kg·K}$$



EXAMPLE 12–3 **Verification of Cyclic and Reciprocity Relations**

Using the ideal-gas equation of state, verify (*a*) the cyclic relation, and (*b*) the reciprocity relation at constant P.

SOLUTION The cyclic and reciprocity relations are to be verified for an ideal gas.

Analysis The ideal-gas equation of state $Pv = RT$ involves the three variables P, v, and T. Any two of these can be taken as the independent variables, with the remaining one being the dependent variable.

(*a*) Replacing x, y, and z in Eq. 12–9 by P, v, and T, respectively, we can express the cyclic relation for an ideal gas as

$$\left(\frac{\partial P}{\partial v}\right)_T \left(\frac{\partial v}{\partial T}\right)_P \left(\frac{\partial T}{\partial P}\right)_v = -1$$

where

$$P = P(v, T) = \frac{RT}{v} \rightarrow \left(\frac{\partial P}{\partial v}\right)_T = -\frac{RT}{v^2}$$

$$v = v(P, T) = \frac{RT}{P} \rightarrow \left(\frac{\partial v}{\partial T}\right)_P = \frac{R}{P}$$

$$T = T(P, v) = \frac{Pv}{R} \rightarrow \left(\frac{\partial T}{\partial P}\right)_v = \frac{v}{R}$$

CamScanner الممسوحة ضوئيا بـ

$cp = dh/dT \rightarrow h = f(T)$ only } for ideal gas ←

Substituting yields

$$\left(-\frac{RT}{v^2}\right)\left(\frac{R}{P}\right)\left(\frac{v}{R}\right) = -\frac{RT}{Pv} = -1$$

which is the desired result.

(*b*) The reciprocity rule for an ideal gas at P = constant can be expressed as

$$\left(\frac{\partial v}{\partial T}\right)_P = \frac{1}{(\partial T/\partial v)_P}$$

Performing the differentiations and substituting, we have

$$\frac{R}{P} = \frac{1}{P/R} \rightarrow \frac{R}{P} = \frac{R}{P}$$

Thus the proof is complete.

for cyclic relation:-

$Pv = RT$

$*\left(\frac{\partial P}{\partial v}\right)_T = -\frac{RT}{v^2} \rightarrow P = \frac{RT}{v} \rightarrow \frac{dP}{dv} = RT \times \frac{1}{v}$ $\quad *\left(\frac{dT}{dP}\right)_v = \frac{v}{R} \rightarrow T = \frac{Pv}{R} \rightarrow dT =$

$*\left(\frac{\partial v}{\partial T}\right)_P = \frac{R}{P} \rightarrow v = \frac{RT}{P} \rightarrow dv = \frac{R}{P}\,dT$

EXAMPLE 12–4 **Verification of the Maxwell Relations**

Verify the validity of the last Maxwell relation (Eq. 12–19) for steam at 250°C and 300 kPa.

Analysis The last Maxwell relation states that for a simple compressible substance, the change in entropy with pressure at constant temperature is equal to the negative of the change in specific volume with temperature at constant pressure.

$$\left(\frac{\partial s}{\partial P}\right)_T \stackrel{?}{=} -\left(\frac{\partial v}{\partial T}\right)_P \leftarrow$$ steam

$$\left(\frac{\Delta s}{\Delta P}\right)_{T = 250°C} \stackrel{?}{\cong} -\left(\frac{\Delta v}{\Delta T}\right)_{P = 300\ \text{kPa}}$$ Steam table

$$\left[\frac{s_{400\ \text{kPa}} - s_{200\ \text{kPa}}}{(400 - 200)\ \text{kPa}}\right]_{T = 250°C} \stackrel{?}{\cong} -\left[\frac{v_{300°C} - v_{200°C}}{(300 - 200)°C}\right]_{P = 300\ \text{kPa}}$$

$$\frac{(7.3804 - 7.7100)\ \text{kJ/kg·K}}{(400 - 200)\ \text{kPa}} \stackrel{?}{\cong} -\frac{(0.87535 - 0.71643)\ \text{m}^3\text{/kg}}{(300 - 200)°C}$$

$$-0.00165\ \text{m}^3\text{/kg·K} \cong -0.00159\ \text{m}^3\text{/kg·K}$$

CamScanner الممسوحة ضوئيا بـ

EXAMPLE 12–5 Evaluating ... the *P-v-T* Data

Using the Clapeyron equation, estimate the value of the enthalpy of vaporization of refrigerant-134a at 20°C and compare it with the tabulated value.

SOLUTION The h_{fg} of refrigerant-134a is to be determined using the Clapeyron equation.

Analysis From Eq. 12–22,

$$h_{fg} = Tv_{fg}\left(\frac{dP}{dT}\right)_{sat}$$

where, from Table A–11,

$$v_{fg} = (v_g - v_f)_{@\ 20°C} = 0.036012 - 0.0008160 = 0.035196\ \text{m}^3/\text{kg}$$

$$\left(\frac{dP}{dT}\right)_{sat,20°C} \cong \left(\frac{\Delta P}{\Delta T}\right)_{sat,20°C} = \frac{P_{sat\ @\ 24°C} - P_{sat\ @\ 16°C}}{24°C - 16°C}$$

$$= \frac{646.18 - 504.58\ \text{kPa}}{8°C} = 17.70\ \text{kPa/K}$$

since $\Delta T(°C) = \Delta T(\text{K})$. Substituting, we get

$$h_{fg} = (293.15\ \text{K})(0.035196\ \text{m}^3/\text{kg})(17.70\ \text{kPa/K})\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right)$$

$$\cong 182.62\ \text{kJ/kg}$$

The tabulated value of h_{fg} at 20°C is 182.33 kJ/kg. The small difference between the two values is due to the approximation used in determining the slope of the saturation curve at 20°C.

31

EXAMPLE 12–7 Internal Energy Change of a van der Waals Gas

Derive a relation for the internal energy change as a gas that obeys the van der Waals equation of state. Assume that in the range of interest c_v varies according to the relation $c_v = c_1 + c_2T$, where c_1 and c_2 are constants.

Analysis The change in internal energy of any simple compressible system in any phase during any process can be determined from Eq. 12–30:

$$u_2 - u_1 = \int_{T_1}^{T_2} c_v\,dT + \int_{v_1}^{v_2}\left[T\left(\frac{\partial P}{\partial T}\right)_v - P\right]dv$$

The van der Waals equation of state is

$$P = \frac{RT}{v-b} - \frac{a}{v^2}$$

Then

$$\left(\frac{\partial P}{\partial T}\right)_v = \frac{R}{v-b}$$

Thus,

$$T\left(\frac{\partial P}{\partial T}\right)_v - P = \frac{RT}{v-b} - \frac{RT}{v-b} + \frac{a}{v^2} = \frac{a}{v^2}$$

Substituting gives

$$u_2 - u_1 = \int_{T_1}^{T_2}(c_1 + c_2T)\,dT + \int_{v_1}^{v_2}\frac{a}{v^2}\,dv$$

Integrating yields

$$u_2 - u_1 = c_1(T_2 - T_1) + \frac{c_2}{2}(T_2^2 - T_1^2) + a\left(\frac{1}{v_1} - \frac{1}{v_2}\right)$$

which is the desired relation.

32

CamScanner الممسوحة ضوئيا بـ

EXAMPLE 12–9 **The Specific Heat Difference of an Ideal Gas**

Show that $c_p - c_v = R$ for an ideal gas.

SOLUTION It is to be shown that the specific heat difference for an ideal gas is equal to its gas constant.

Analysis This relation is easily proved by showing that the right-hand side of Eq. 12–46 is equivalent to the gas constant R of the ideal gas:

$$c_p - c_v = -T\left(\frac{\partial v}{\partial T}\right)_p^2\left(\frac{\partial P}{\partial v}\right)_T$$

$$P = \frac{RT}{v} \rightarrow \left(\frac{\partial P}{\partial v}\right)_T = -\frac{RT}{v^2} = -\frac{P}{v}$$

$$v = \frac{RT}{P} \rightarrow \left(\frac{\partial v}{\partial T}\right)_P^2 = \left(\frac{R}{P}\right)^2$$

Substituting,

$$-T\left(\frac{\partial v}{\partial T}\right)_p^2\left(\frac{\partial P}{\partial v}\right)_T = -T\left(\frac{R}{P}\right)^2\left(-\frac{P}{v}\right) = R$$

Therefore,

$$c_p - c_v = R$$

EXAMPLE 12–10 **Joule-Thomson Coefficient of an Ideal Gas**

Show that the Joule-Thomson coefficient of an ideal gas is zero.

SOLUTION It is to be shown that $\mu_{JT} = 0$ for an ideal gas.

Analysis For an ideal gas $v = RT/P$, and thus

$$\left(\frac{\partial v}{\partial T}\right)_P = \frac{R}{P}$$

Substituting this into Eq. 12–52 yields

$$\mu_{JT} = \frac{-1}{c_p}\left[v - T\left(\frac{\partial v}{\partial T}\right)_P\right] = \frac{-1}{c_p}\left[v - T\frac{R}{P}\right] = -\frac{1}{c_p}(v - v) = 0$$

Discussion This result is not surprising since the enthalpy of an ideal gas is a function of temperature only, $h = h(T)$, which requires that the temperature remain constant when the enthalpy remains constant. Therefore, a throttling process cannot be used to lower the temperature of an ideal gas (Fig. 12–14).

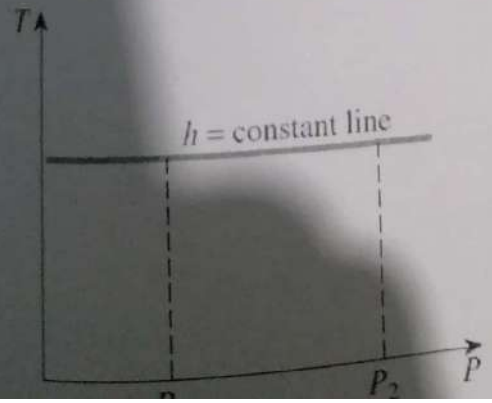


FIGURE 12–14
The temperature of an ideal gas remains constant during a throttling process since h = constant and T = constant lines on a T-P diagram coincide.

CamScanner الممسوحة ضوئيا بـ

Example 12-11 In 6th edition

$T_1 = 270\,K$ & $P_1 = 5\,MPa$ $T_2 = 300\,K$ & $P_2 = 10\,MPa$

high Pressure & real gas الـ oxygen

a) from table A-19 for oxygen

b) deviation from ideality

* So for ideal gas → enthalpy الـ تتغير

Z_h الـ real الـ ideal

$$\bar{S} = \bar{S}_0 - R \ln \frac{P_2}{P_1}$$ → أضافة بسيطة

Nadar
ask & believe & recieve

الممسوحة ضوئيا بـ CamScanner