Chapter 2

ENERGY ANALYSIS & FIRST LAW

Thermodynamics: An Engineering Approach

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October 2023

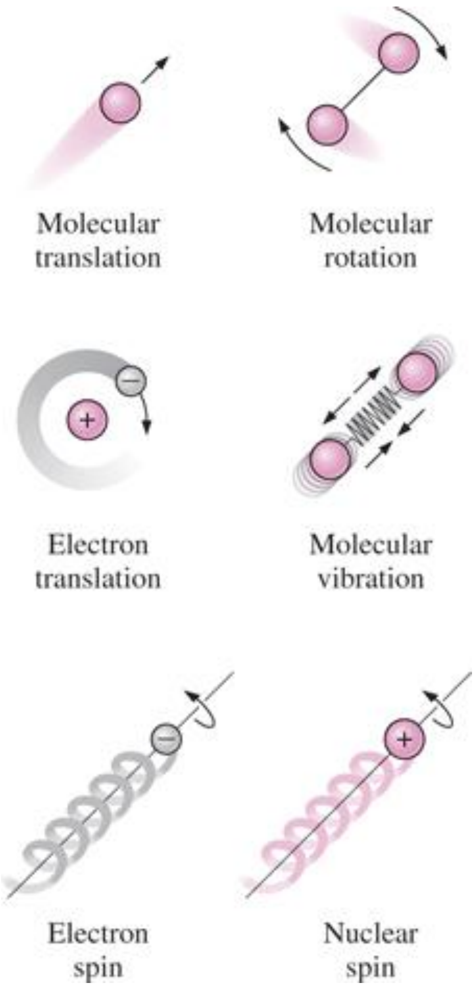
Forms of Energy

- 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.*

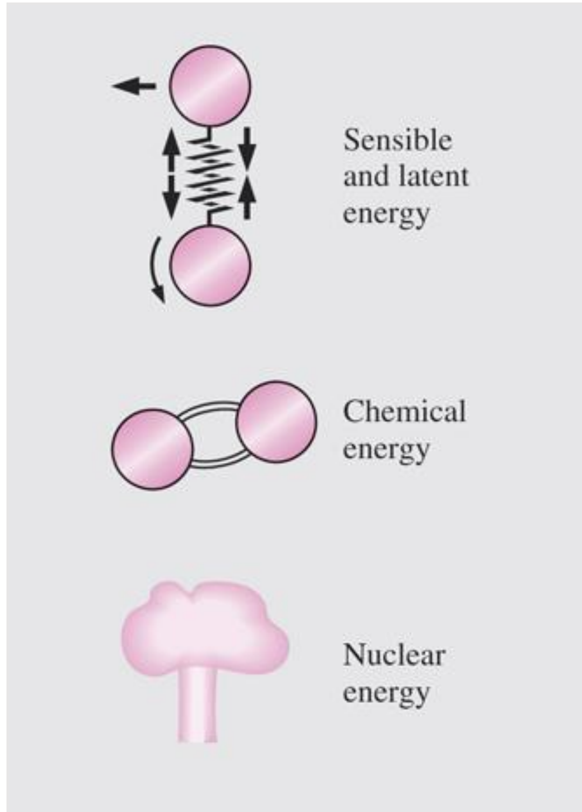
- **Kinetic energy, KE**: The energy that a system possesses as a result of its motion relative to some reference frame.
- **Potential energy, PE**: The energy that a system possesses as a result of its elevation in a gravitational field.

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

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 atomic bonds in a molecule.

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

Thermal = Sensible + Latent
Internal = Sensible + Latent + Chemical + Nuclear

Energy of A System vs Energy Interaction

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**.

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

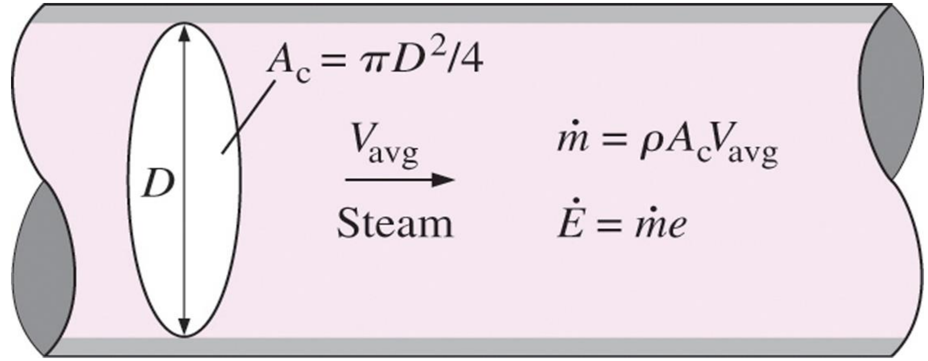
   - The dynamic forms of energy are recognized at the system boundary as they cross it, and they represent the *energy gained or lost by a system during a process.*

   - 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.

Energy of A System
(Definitions/ Expressions)



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

Mass flow rate

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

Energy flow rate

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

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

Mechanical Energy

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

- **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

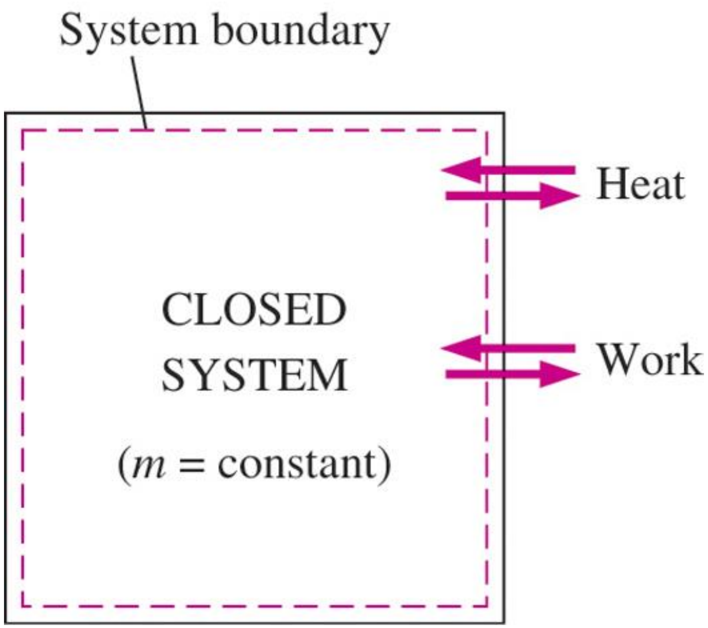
$$\Delta e_{\text{mech}} = \frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \qquad (\text{kJ/kg})$$

Rate of mechanical energy change of a fluid during incompressible flow

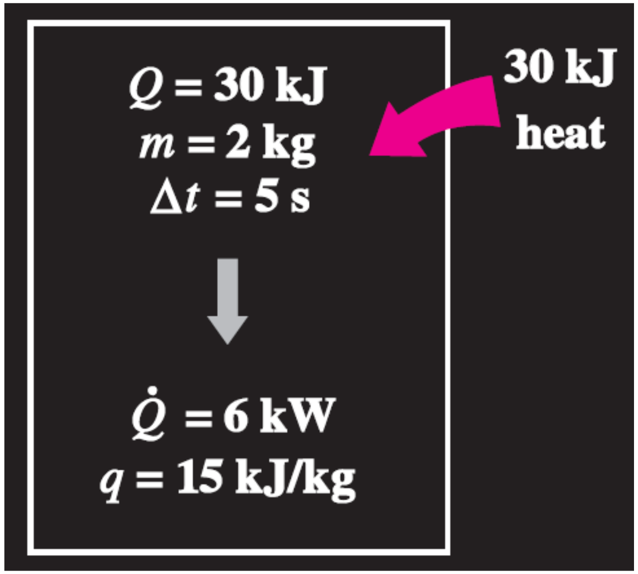
$$\Delta \dot{E}_{\text{mech}} = \dot{m} \Delta e_{\text{mech}} = \dot{m}\left(\frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right) \qquad (\text{kW})$$

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**

ENERGY TRANSFER BY HEAT

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

Heat transfer per unit mass

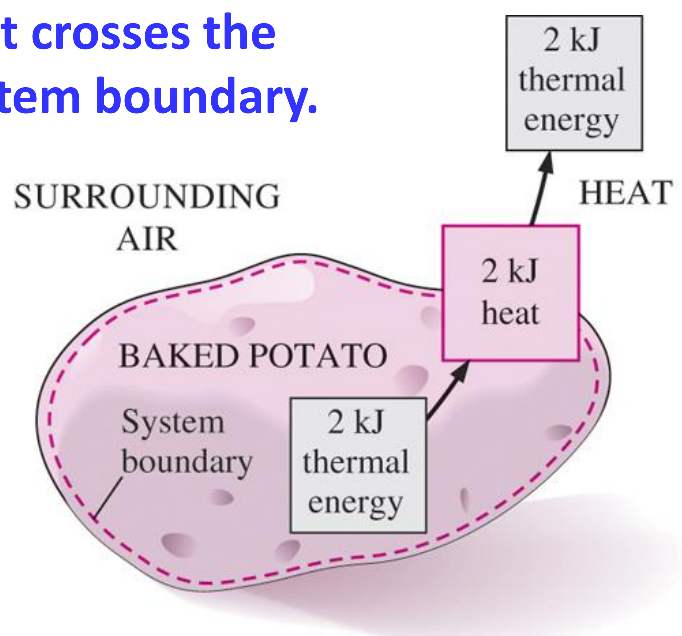
$$Q = \dot{Q}\,\Delta t \qquad (\text{kJ})$$

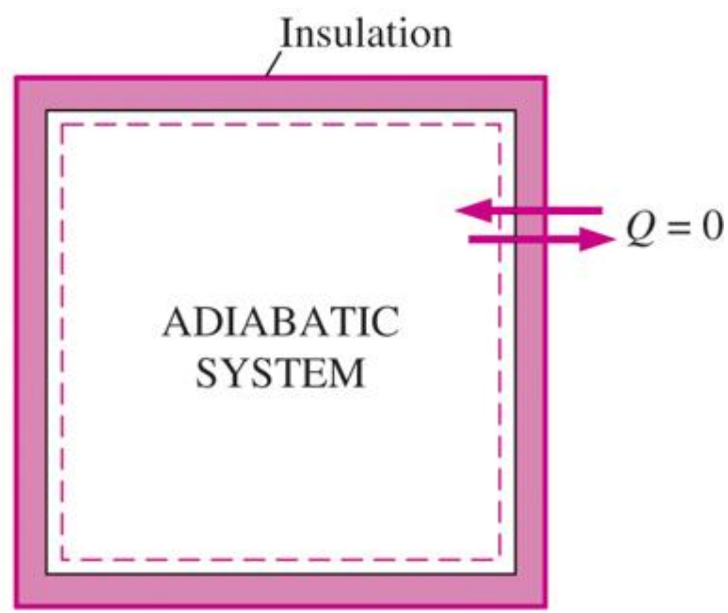
Amount of **heat transfer** when heat transfer rate is constant

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

Amount of **heat transfer** when heat transfer rate changes with time

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





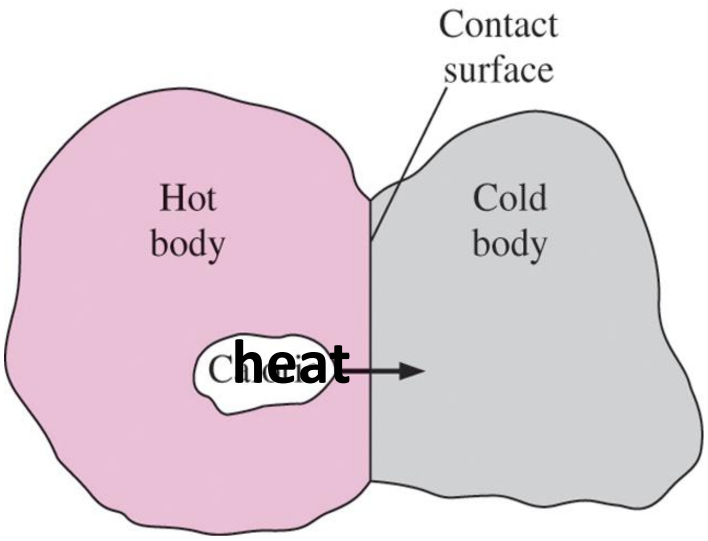
During an adiabatic process, a system exchanges <u>no</u> heat with its surroundings.

Historical Background on Heat

- **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.

Heat transfer 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).

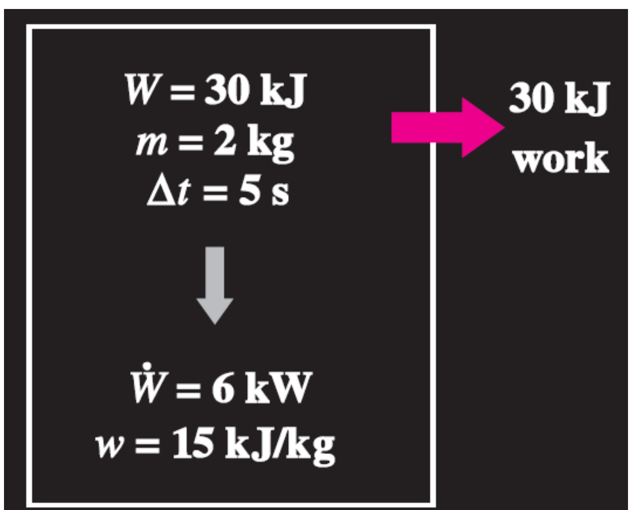


ENERGY TRANSFER BY WORK

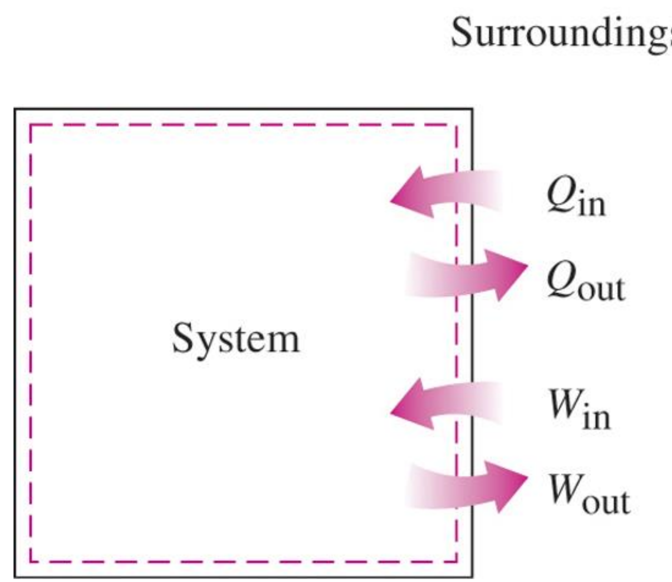
- **Work**: The energy transfer associated with a *force acting through a distance*.
  - **A rising piston, a rotating shaft,** and **an electric wire crossing the system boundaries** are all associated with work interactions.
- **Formal sign convention**: *Heat transfer to a system and work done by 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.

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

Work done per unit mass



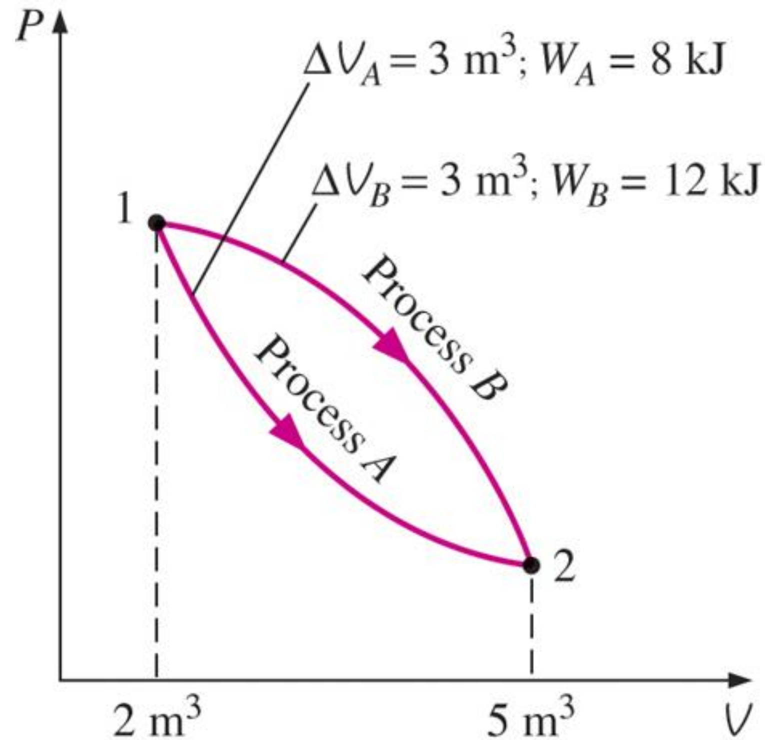
Power is the work done per unit time (kW)



Specifying the directions of heat and work.

Heat and Work

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).



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

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

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

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

Path functions have inexact differentials (δ)

Forms of Work

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

› ***Electrical work*:** $W_e = VI\Delta t$ **(kJ)**

› ***Boundary 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 work***
(stirring, turbine, etc.) $W_{sh} = 2\pi n \tau$

Electrical Work

Electrical work

$$W_e = \mathbf{V}N$$

Electrical power

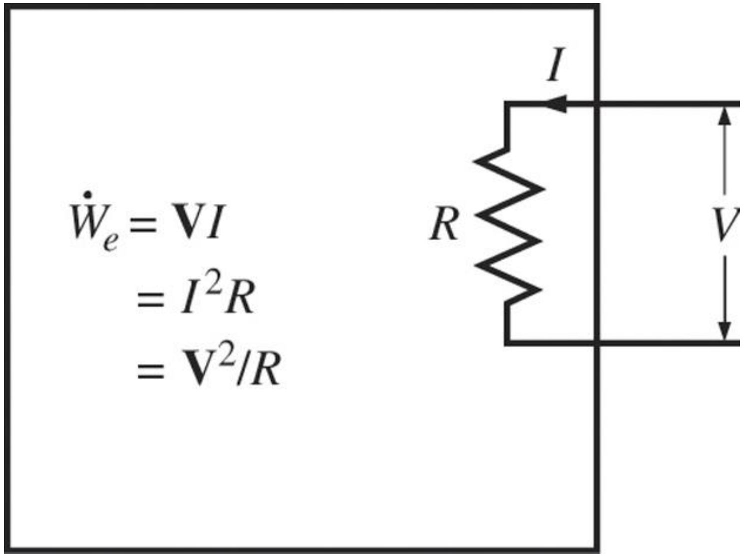
$$\dot{W}_e = \mathbf{V}I \qquad (\mathrm{W})$$

When potential difference and current change with time

$$W_e = \int_1^2 \mathbf{V}I\,dt \qquad (\mathrm{kJ})$$

When potential difference and current remain constant

$$W_e = \mathbf{V}I\,\Delta t \qquad (\mathrm{kJ})$$



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. Δt

1 Coulomb = 1 Ampere* 1 Second

Ohms Law: V = I.R

1 Joule = 1 Volt* 1 Coulomb

MECHANICAL FORMS OF WORK

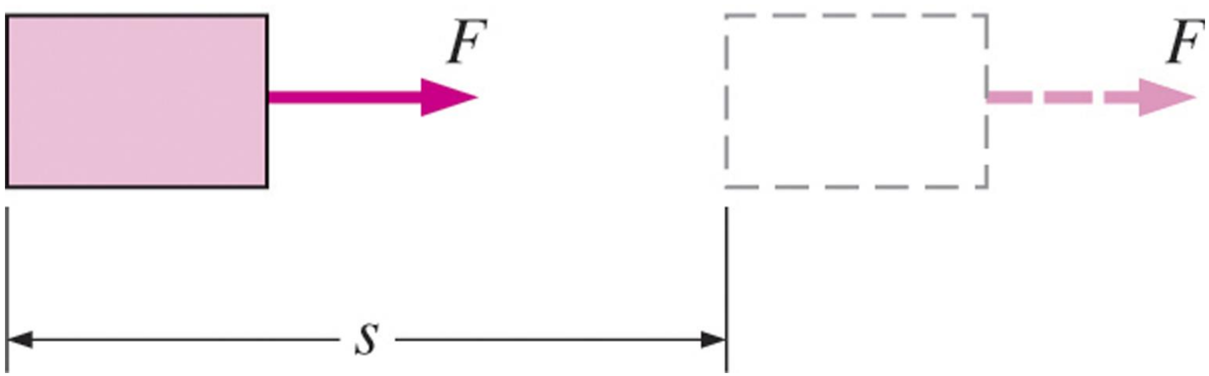
- There are two requirements for a work interaction between a system and its surroundings to exist:
  - there must be a ***force*** acting on the boundary.
  - the boundary must ***move***.

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*).

Shaft Work

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

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

This force acts through a distance *s*

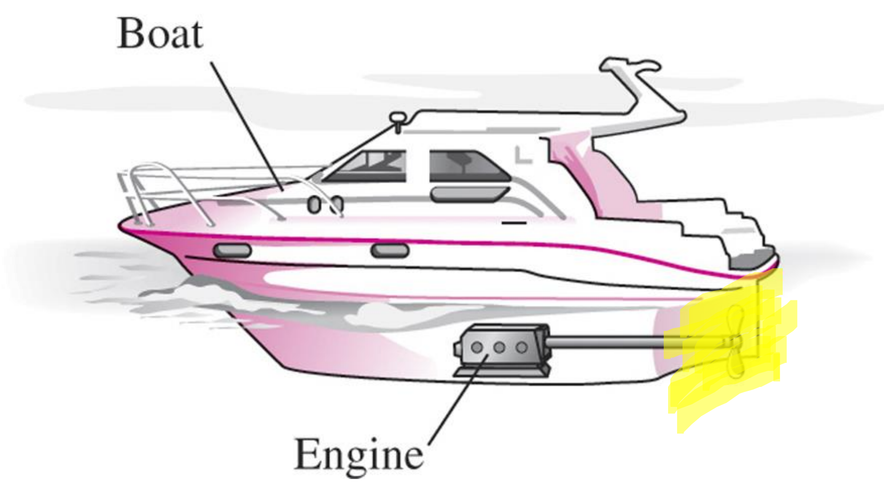
$$s = (2\pi r)n$$

Shaft work:

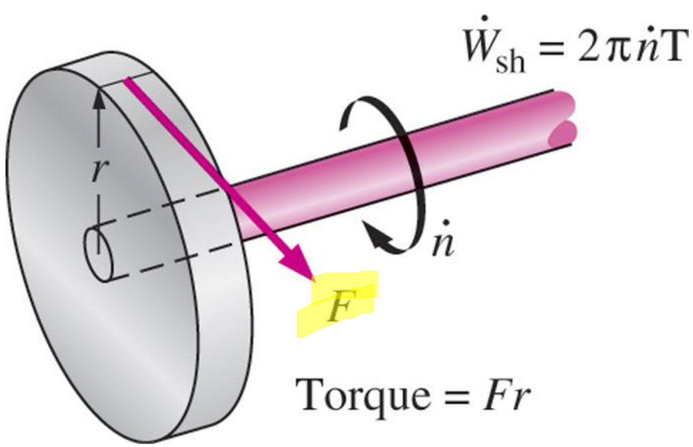
$$W_{sh} = Fs = \left(\frac{\mathrm{T}}{r}\right)(2\pi rn) = 2\pi n\mathrm{T} \qquad (\mathrm{kJ})$$

The <u>power</u> transmitted through the shaft is the shaft work done per unit time

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



Energy transmission through rotating shafts is commonly encountered in practice.



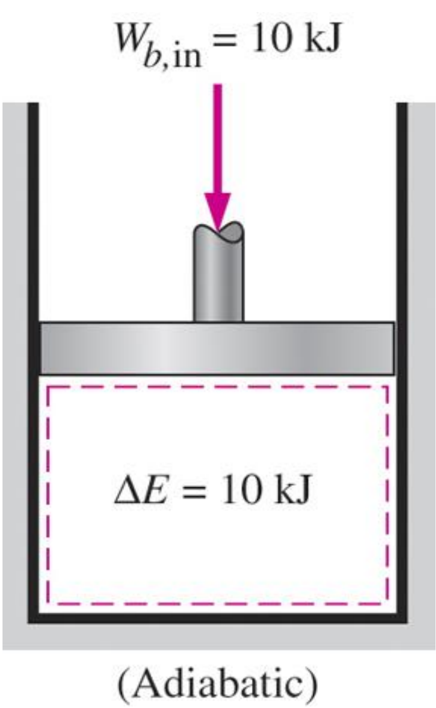
Shaft work is proportional to the torque applied and the number of revolutions of the shaft.

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.*

$$\left(\begin{array}{c}\text{Total energy}\\ \text{entering the system}\end{array}\right) - \left(\begin{array}{c}\text{Total energy}\\ \text{leaving the system}\end{array}\right) = \left(\begin{array}{c}\text{Change in the total}\\ \text{energy of the system}\end{array}\right)$$

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



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

ΔE = ΔU = Q – W

= 0 - (-10)

= 10

OR: ΔE = ΔU = Win –Wout

= 10 - 0

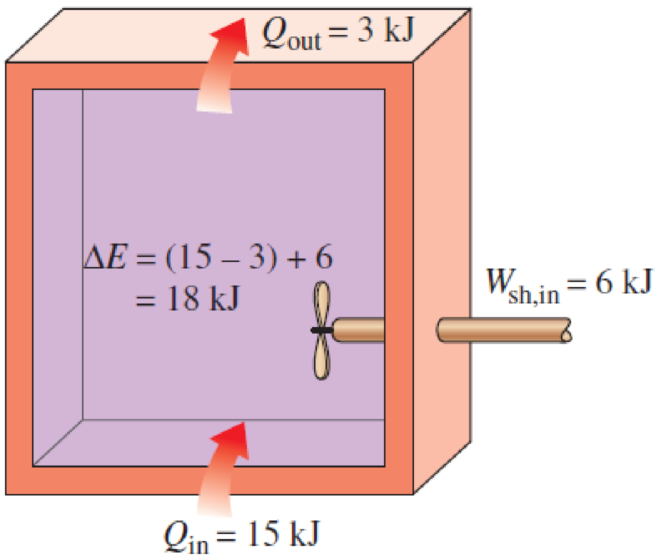


FIGURE 2–45
The energy change of a system during a process is equal to the *net* work and heat transfer between the system and its surroundings.

Energy Change of a System, ΔE_{system}

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

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

$$\boxed{\Delta E = \Delta U + \Delta KE + \Delta PE}$$

Internal, kinetic, and potential energy changes

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

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

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

Stationary Systems

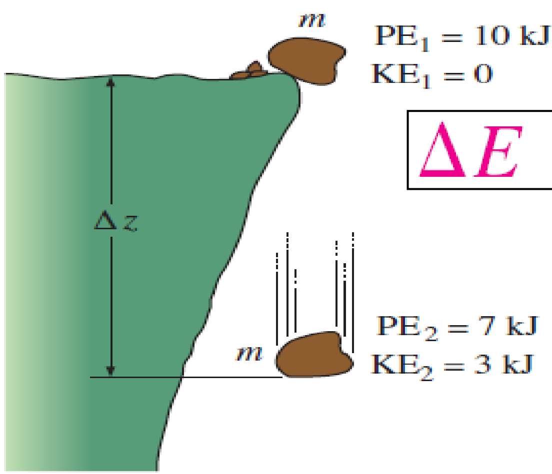
$$z_1 = z_2 \rightarrow \Delta PE = 0$$

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

$$\Delta E = \Delta U$$

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.



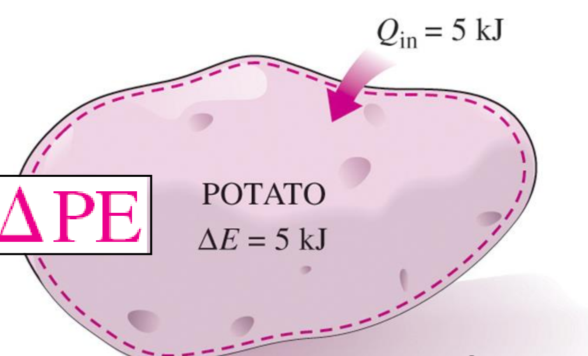
$$\Delta E = \Delta U + \Delta KE + \Delta PE$$

Q = 0, W = 0

E1 = 0 + 10

E2 = 3 + 7

ΔE = E2 - E1 = 0



ΔKE = 0, ΔPE = 0

ΔE = ΔU = Q – W

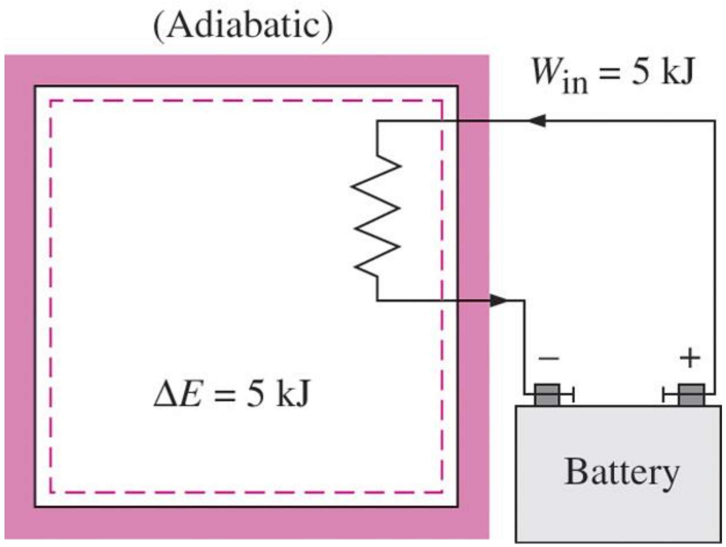
ΔE = Q = 5

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.

FIRST LAW OF THERMODYNAMICS

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



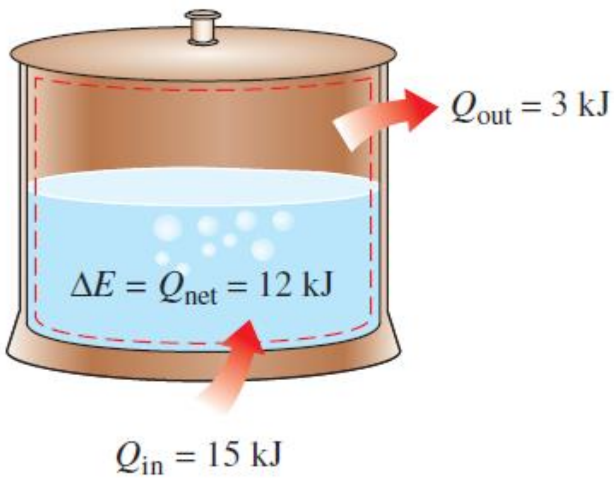
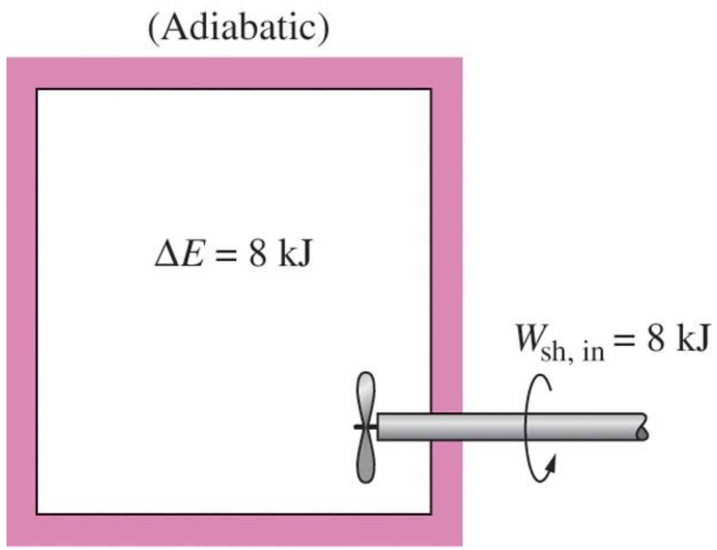


FIGURE 2–41
In the absence of any work interactions, the energy change of a system is equal to the net heat transfer.



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

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

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

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

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

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

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

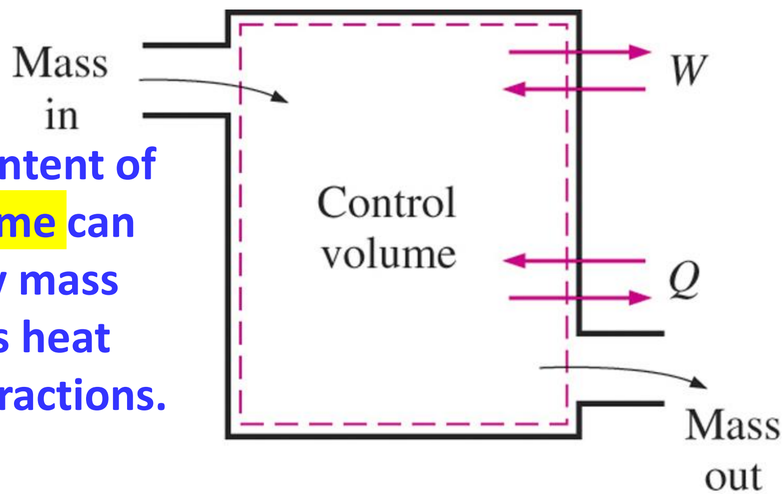
$$W = \dot{W}\,\Delta t$$

$$\Delta E = (dE/dt)\,\Delta t$$

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

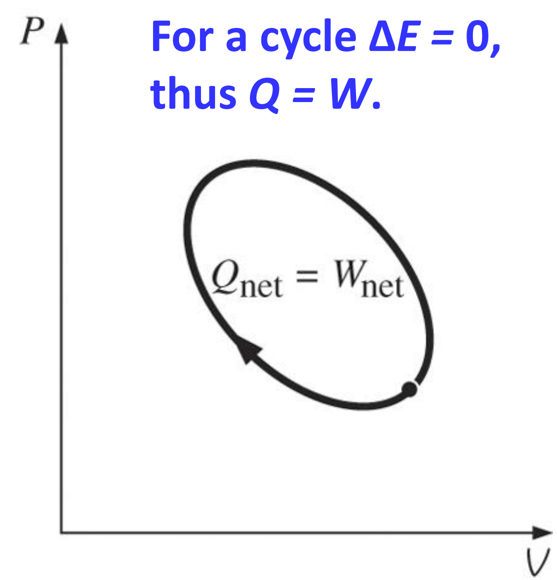
$$e_{in} - e_{out} = \Delta e_{system} \quad \text{(kJ/kg)}$$

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



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

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

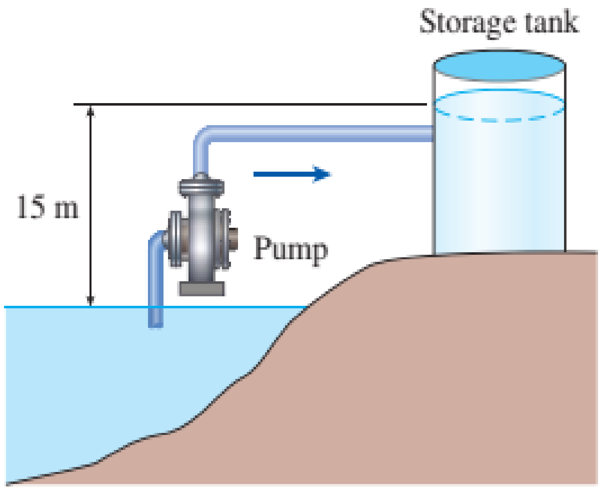


ENERGY CONVERSION EFFICIENCIES

1) *Efficiency* is one of the most frequently used terms in thermodynamics, and it indicates how well an energy conversion or transfer process is accomplished.
2) *Efficiency* is also one of the most frequently misused terms in thermo-dynamics, because it is often used without being properly defined.
3) *Efficiency* can be expressed in terms of the desired output and the required input:

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

<u>Example:</u>



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

Efficiencies of Mechanical and Electrical Devices

Mechanical efficiency

u: useful
e: extracted

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

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:

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

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

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

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

- The mechanical efficiency should not be confused with the **motor efficiency** and the **generator efficiency**, which are defined as:

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

Motor efficiency

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

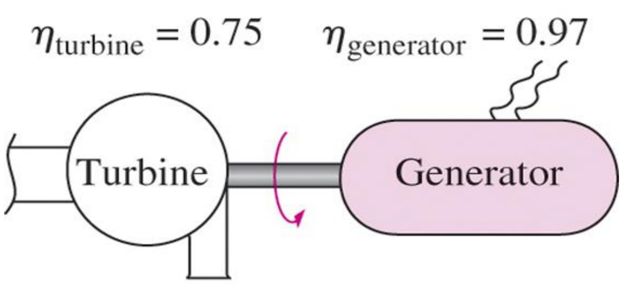
Generator efficiency

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

Pump-Motor <u>overall</u> efficiency

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

Turbine-Generator <u>overall</u> efficiency



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

The overall efficiency of a turbine–generator is **<u>the product of</u>** 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.

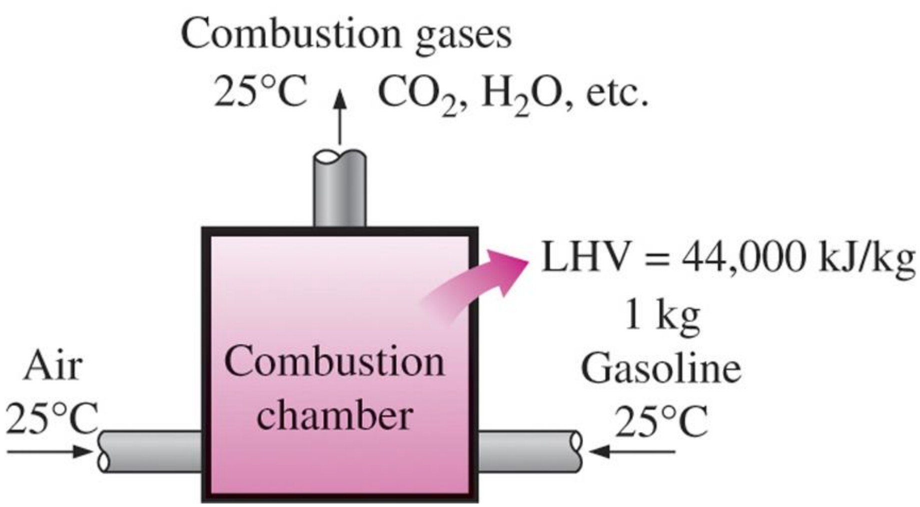
Combustion

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

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.*

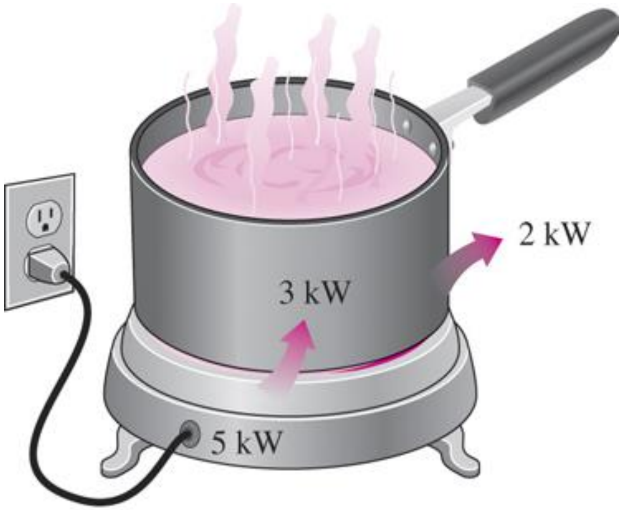
Higher heating value (HHV): When the water in the combustion gases is *completely condensed* and thus the heat of vaporization is also recovered.



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.

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

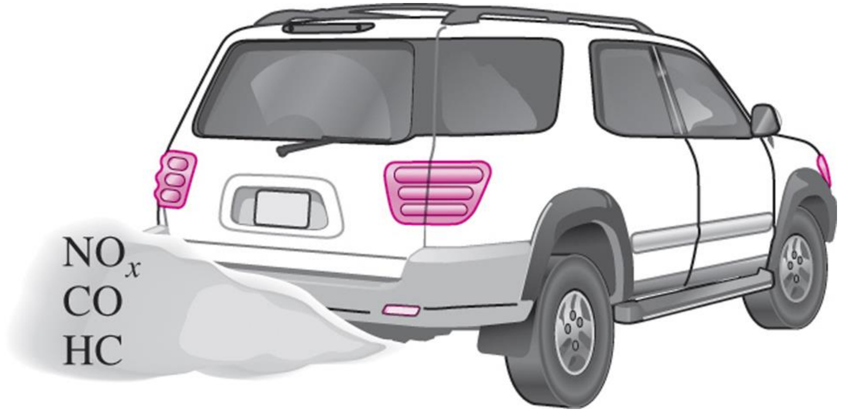
- **Generator:** A device that converts mechanical energy to electrical energy.
- **Generator efficiency:** The ratio of the electrical power output to the mechanical power input.
- **Thermal efficiency of a power plant:**

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

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

ENERGY AND ENVIRONMENT

- 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**.



Motor vehicles are the largest source of air pollution.

Energy conversion processes are often accompanied by environmental 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

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

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

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

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

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

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

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

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

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

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

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

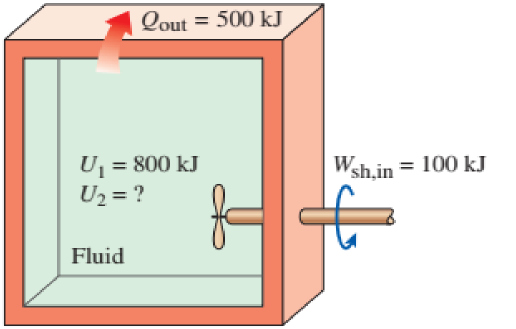


FIGURE 2–49
Schematic for Example 2–10.

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.

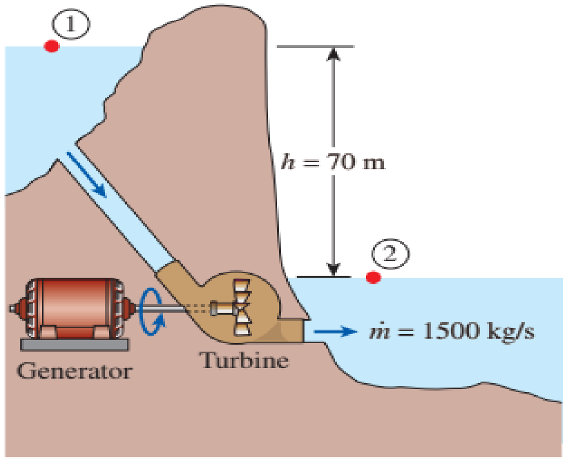


FIGURE 2–60
Schematic for Example 2–15.

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

$$\mathrm{pe}_1 = gz_1 = (9.81\ \mathrm{m/s^2})(70\ \mathrm{m})\left(\frac{1\ \mathrm{kJ/kg}}{1000\ \mathrm{m^2/s^2}}\right) = 0.687\ \mathrm{kJ/kg}$$

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

$$\begin{aligned} |\Delta \dot{E}_{\mathrm{mech,fluid}}| &= \dot{m}(e_{\mathrm{mech,in}} - e_{\mathrm{mech,out}}) = \dot{m}(\mathrm{pe}_1 - 0) = \dot{m}\mathrm{pe}_1 \\ &= (1500\ \mathrm{kg/s})(0.687\ \mathrm{kJ/kg}) \\ &= 1031\ \mathrm{kW} \end{aligned}$$

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

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

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