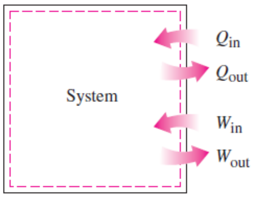
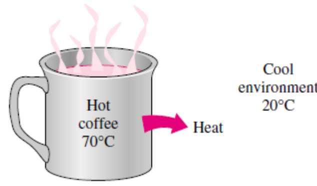
University Of Jordan

Faculty of Engineering and Technology

Department of Chemical Engineering



Thermodynamics I

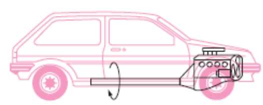


Energy, Heat and Work

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

$$\int_1^2 \delta W = W_{12}$$

Dr.-Eng. Zayed Al-Hamamre



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Contents

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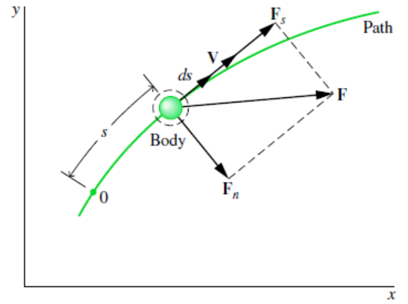
Work and Kinetic Energy

- A body of mass m (a closed system) the velocity of the center of mass of the body is **V**.
- The body is acted on by a resultant force **F**,



$$F_s = m\frac{dV}{dt}$$

Using the chain rule,

$$F_s = m\frac{dV}{ds}\frac{ds}{dt} = mV\frac{dV}{ds}$$

where $V = ds/dt$.

Rearranging and integrating from s_1 to s_2 gives

$$\int_{V_1}^{V_2} mV\,dV = \int_{s_1}^{s_2} F_s\,ds$$

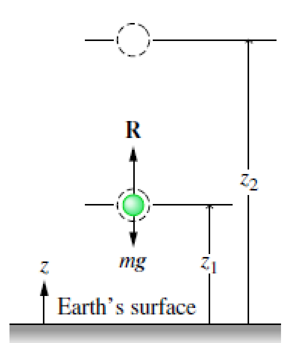
$$\int_{V_1}^{V_2} mV\,dV = \frac{1}{2}mV^2\Big]_{V_1}^{V_2} = \frac{1}{2}m(V_2^2 - V_1^2)$$ The *change* in kinetic energy,

Work and Kinetic Energy

$$W = \int_{s_1}^{s_2} \mathbf{F}\cdot d\mathbf{s}$$

$$\frac{1}{2}m(V_2^2 - V_1^2) = \int_{s_1}^{s_2} \mathbf{F}\cdot d\mathbf{s}$$

Potential Energy



- A body of mass m that moves vertically from an elevation z_1 to an elevation z_2 relative to the surface of the earth.
- Two forces are shown acting on the system: a downward force due to gravity with magnitude mg and a vertical force with magnitude R representing the resultant of all *other* forces acting on the system

Potential Energy

$$\frac{1}{2}m(V_2^2 - V_1^2) = \int_{z_1}^{z_2} R\, dz - \int_{z_1}^{z_2} mg\, dz$$

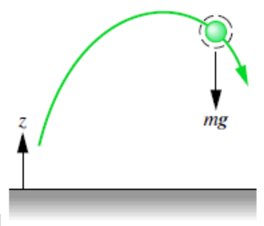
The second integral

$$\int_{z_1}^{z_2} mg\, dz = mg(z_2 - z_1)$$ The *change* in potential energy

rearranging

$$\frac{1}{2}m(V_2^2 - V_1^2) + mg(z_2 - z_1) = \int_{z_1}^{z_2} R\, dz$$

- The macroscopic energy of an object changes with velocity and elevation



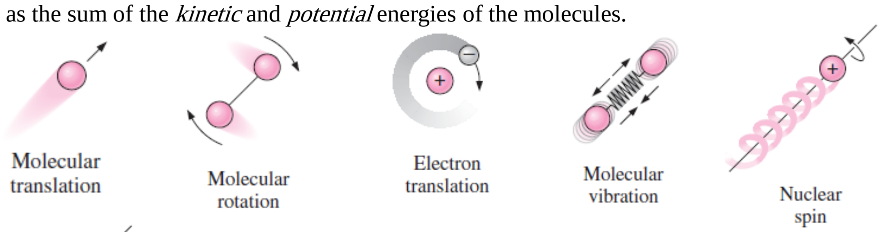
$$\frac{1}{2}mV_2^2 + mgz_2 = \frac{1}{2}mV_1^2 + mgz_1$$

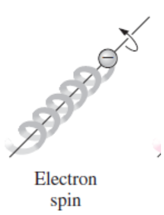
The sum of the kinetic and gravitational potential energies remains constant.

CONSERVATION OF ENERGY IN MECHANICS

Internal Energy

- Internal energy is defined earlier as the sum of all the *microscopic* forms of energy of a system.
- It is related to the *molecular structure* and the degree of *molecular activity* and can be viewed as the sum of the *kinetic* and *potential* energies of the molecules.





- The internal energy associated with the phase of a system is called the **latent energy**
- The internal energy associated with the atomic bonds in a molecule is called **chemical energy**
- The amount of energy associated with the strong bonds within the nucleus of the atom itself is called **nuclear energy**

Mechanical Energy

- The **mechanical energy** can be defined as *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 are the familiar forms of mechanical energy.
- Thermal energy is not mechanical energy.
- The mechanical energy of a flowing fluid can be expressed on a unit mass basis as

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

and

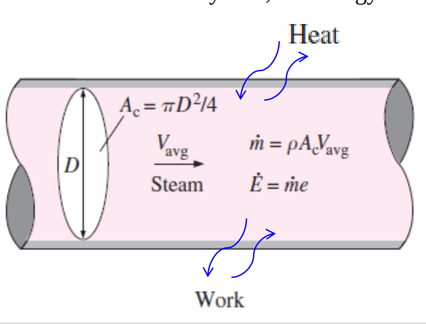
$$\dot{E}_{\text{mech}} = \dot{m} e_{\text{mech}} = \dot{m}\left(\frac{P}{\rho} + \frac{V^2}{2} + gz\right)$$

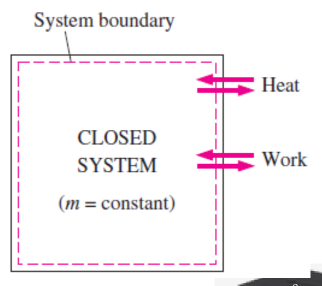
and

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

Heat and work

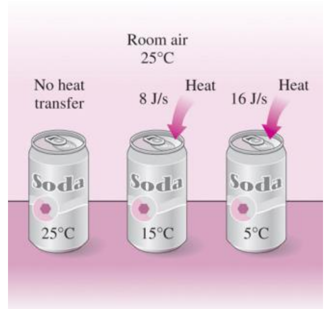
- The only two forms of energy interactions associated with a closed system are **heat transfer** and **work.**
- An energy interaction is heat transfer if its driving force is a temperature difference.
- Otherwise it is work.
- A control volume can also exchange energy via mass transfer since any time mass is transferred into or out of a system, the energy content of the mass is also transferred with it.





Energy Transfer by heat

- **Heat** is defined as *the form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a temperature difference.*
- Temperature difference is the driving force for heat transfer. The larger the temperature difference, the higher is the rate of heat transfer.
- Heat is energy in transition. It is recognized only as it crosses the boundary of a system



- A process during which there is no heat transfer is called an **adiabatic process.**
- There are two ways a process can be adiabatic:
  1. Either the system is well insulated so that only a negligible amount of heat can pass through the boundary, or
  2. Both the system and the surroundings are at the same temperature and therefore there is no driving force (temperature difference) for heat transfer.

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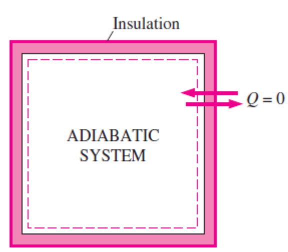
Energy Transfer by Heat

- Even though there is no heat transfer during an adiabatic process, the energy content and thus the temperature of a system can still be changed by other means such as work.
- The amount of heat transferred during the process between two states (states 1 and 2) is denoted by Q_{12}, or just Q.
- Heat transfer *per unit mass* of a system is denoted q and is determined from



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

- The heat transfer rate is denoted $\dot{Q}$, where the over dot stands for the time derivative, or “per unit time.” The heat transfer rate $\dot{Q}$ has the unit kJ/s, which is equivalent to kW.
- When $\dot{Q}$ varies with time, the amount of heat transfer during a process is determined by integrating $\dot{Q}$ over the time interval of the process:

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Energy Transfer by Heat

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

The net *rate of heat transfer*

- To perform the integration, it would be necessary to know how the rate of heat transfer varies with time.

When $\dot{Q}$ remains constant during a process,

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

where $\Delta t = t_2 - t_1$ is the time interval during which the process takes place.

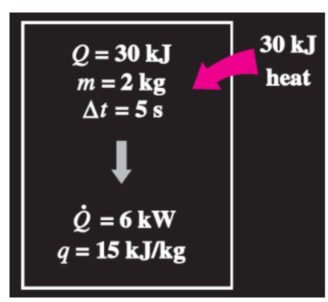
- Heat transfer *into* a system is taken to be *positive*, and heat transfer *from* a system is taken as *negative*.

  $Q > 0$: heat transfer *to* the system $Q < 0$: heat transfer *from* the system

Energy Transfer by Heat

- The value of a heat transfer depends on the details of a process and not just the end states.
- Thus, like work, ***heat is not a property,*** and its differential is written as ∂Q, i.e. **Path Functions** have **inexact differentials.**
- The amount of energy transfer by heat for a process is given by the integral

$$Q = \int_1^2 \delta Q$$



- In some cases it is convenient to use the *heat flux,* $\dot{q}$ which is the heat transfer rate per unit of system surface area,

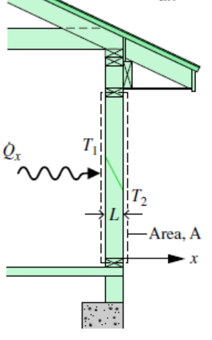
$$\dot{Q} = \int_A \dot{q}\, dA$$

where A represents the area on the boundary of the system where heat transfer occurs.

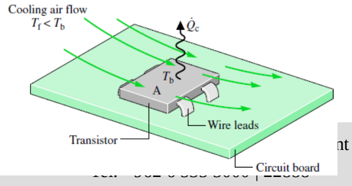
Energy Transfer by Heat

- Heat is transferred by three mechanisms: conduction, convection, and radiation.
- **Conduction** is 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.
- **Convection** is 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.
- **Radiation** is the transfer of energy due to the emission of electromagnetic waves (or photons). $\dot{Q}_e = \varepsilon\sigma A T_b^4$

$$\dot{Q}_x = -\kappa A \frac{dT}{dx}$$



$$\dot{Q}_x = -\kappa A\left[\frac{T_2 - T_1}{L}\right]$$



$$\dot{Q}_c = hA(T_b - T_f)$$

Energy Transfer by Work

- Work, like heat, is an energy interaction between a system and its surroundings.
- Then we can simply say that an energy interaction that is not caused by a temperature difference between a system and its surroundings is work.
- Therefore, *if the energy crossing the boundary of a closed system is not heat, it must be work.*
- More specifically, *work is the energy transfer associated with a force acting through a distance.*
- Examples are : A rising piston, a rotating shaft, and an electric wire crossing the system boundaries are all associated with work interactions.
- The work done during a process between states 1 and 2 is denoted by W_{12}, or simply W.
- The work done *per unit mass* of a system is denoted by w and is expressed as

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

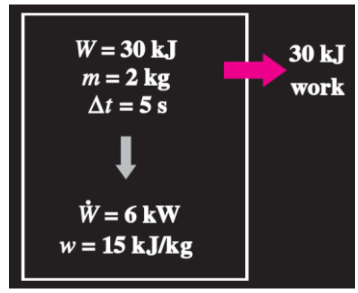
The work done *per unit time* is called **power** and is denoted $\dot{W}$ kJ/s, or kW.

Energy Transfer by Work

$$W = \int_{t_1}^{t_2} \dot{W}\, dt = \int_{t_1}^{t_2} \mathbf{F} \cdot \mathbf{V}\, dt$$

$W < 0$: work done *on* the system

$W > 0$: work done *by* the system



Heat and work are *directional quantities*, and thus the complete description of a heat or work interaction requires the specification of both the *magnitude* and *direction*

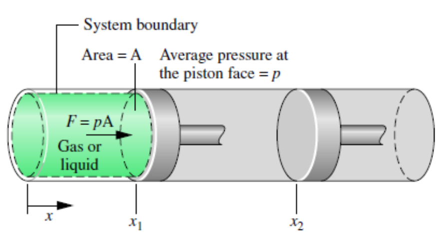
- **Work is also Path functions** have **inexact differentials,** δW,

$$\int_1^2 \delta W = W_{12} \qquad (not\ \Delta W) \qquad \text{and} \qquad \delta W \text{ is not } W_2 - W_1$$

Energy Transfer by Work

Expansion or Compression Work

- As the gas expands its pressure exerts a normal force on the piston.
- *p* denote the pressure acting at the interface between the gas and the piston., A is the area of the piston face.
- The force exerted by the gas on the piston is simply the product *p*A,
- The work done by the system as he piston is displaced a distance *dx* is

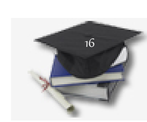


For a compression, dV is negative.

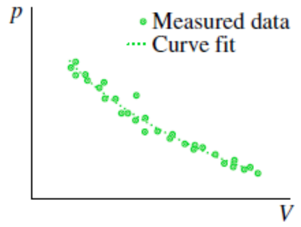
dV is positive when volume increases,

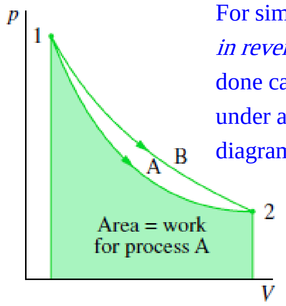
$$\delta W = pA\, dx \quad \Rightarrow \quad \delta W = p\, dV$$

$$\Rightarrow \quad W = \int_{V_1}^{V_2} p\, dV$$

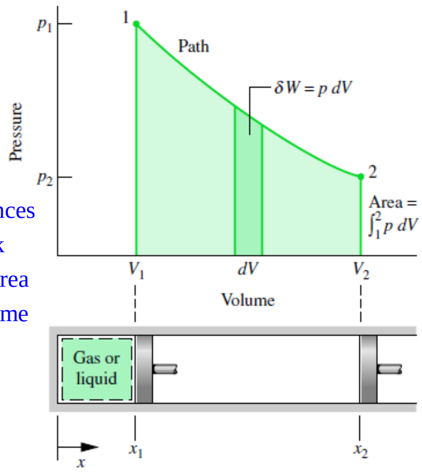


Energy Transfer by Work





For simple compressible substances *in reversible processes*, the work done can be represented as the area under a curve in a pressure-volume diagram



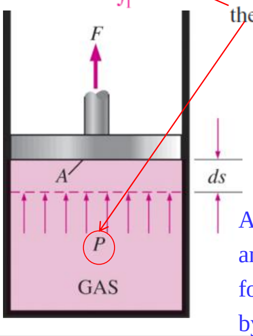
Moving Boundary Work

- **Moving boundary work ($P\,dV$ work)**: The expansion and compression work in a piston-cylinder device.

$$\delta W_b = F\,ds = PA\,ds = P\,dV$$

$$W_b = \int_1^2 P\,dV \quad \text{(kJ)}$$

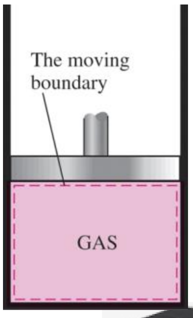
the pressure at the inner face of the piston.

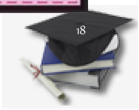


- **Quasi-equilibrium process**: A process during which the system remains nearly in equilibrium at all times.
- W_b is positive → for expansion
- W_b is negative → for compression

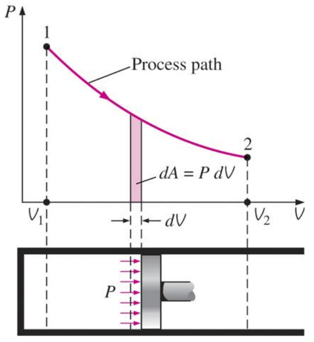
The work associated with a moving boundary is called *boundary work.*

A gas does a differential amount of work δW_b as it forces the piston to move by a differential amount *ds*.





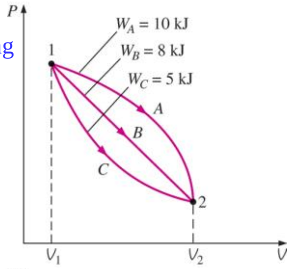
Moving Boundary Work



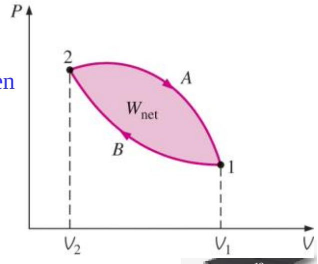
The area under the process curve on a *P*-*V* diagram represents the boundary

$$\text{Area} = A = \int_1^2 dA = \int_1^2 P\,dV$$

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

$P = CV^{-n}$ Polytropic process: *C*, *n* (polytropic exponent) constants

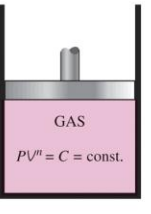
$$W_b = \int_1^2 P\,dV = \int_1^2 CV^{-n}\,dV = C\frac{V_2^{-n+1} - V_1^{-n+1}}{-n+1} = \frac{P_2V_2 - P_1V_1}{1-n}$$ Polytropic process

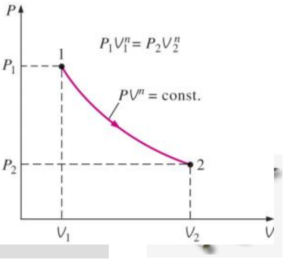
$$W_b = \frac{mR(T_2 - T_1)}{1-n}$$ Polytropic and for ideal gas $n \neq 1$

$$W_b = \int_1^2 P\,dV = \int_1^2 CV^{-1}\,dV = PV\ln\left(\frac{V_2}{V_1}\right)$$ When $n = 1$ (isothermal process)

$$W_b = \int_1^2 P\,dV = P_0\int_1^2 dV = P_0(V_2 - V_1)$$ Constant pressure process

What is the boundary work for a constant-volume process?





Schematic and *P*-*V* diagram for a polytropic process.

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Example

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.

Example

A frictionless piston–cylinder device contains 10 lbm of steam at 60 psia and 320F. Heat is now transferred to the steam until the temperature reaches 400F. If the piston is not attached to a shaft and its mass is constant, determine the work done by the steam during this process.

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Example

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.

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Example

A gas in a piston–cylinder assembly undergoes an expansion process for which the relationship between pressure and volume is given by

$$pV^n = constant$$

The initial pressure is 3 bar, the initial volume is 0.1 m^3, and the final volume is 0.2 m^3. Determine the work for the process, in kJ, if (a) $n = 1.5$, (b) $n = 1.0$, and (c) $n = 0$.

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Example Cont.

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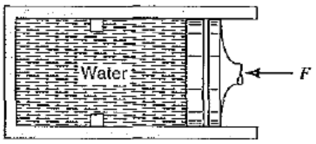
Example

The piston/cylinder setup shown contains 0.1 kg of water **at 1000 kPa, 500°C**. The water is now cooled with a constant force on the piston until it reaches half the initial volume. After this it cools to 25°C while the piston is against the stops. Find the final water pressure and the work in the overall process, and show the process in a *P*-*v* diagram



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Example Cont.

Summary

For a closed system:

$$PV^n = \text{constant}$$

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^n$$

Expansion/Compression (Moving Boundary) Work (Ideal Gas OR liquid):

$$\int_1^2 P \cdot dV = \frac{P_2V_2 - P_1V_1}{1-n}, (n \neq 1)$$

$$\int_1^2 P \cdot dV = P_1V_1 \ln\left(\frac{V_2}{V_1}\right), (n = 1)$$

Ideal Gases ONLY:

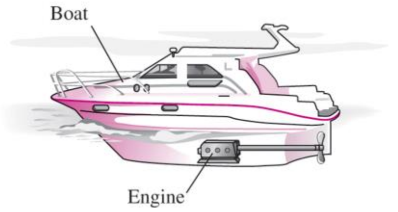
$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(n-1)/n} = \left(\frac{V_1}{V_2}\right)^{(n-1)}$$

$$\int_1^2 P \cdot dV = \frac{mR(T_2 - T_1)}{1-n}, (n \neq 1)$$

$$\int_1^2 P \cdot dV = mRT \ln\left(\frac{V_2}{V_1}\right)$$

Energy Transfer by Work

Shaft Work



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

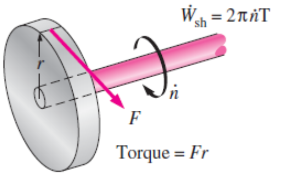
$$\mathrm{T} = Fr \quad \rightarrow \quad F = \frac{\mathrm{T}}{r}$$

This force acts through a distance s,

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

- For a specified constant torque, the work done during n revolutions :

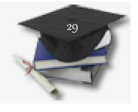
$$W_{sh} = Fs = \left(\frac{\mathrm{T}}{r}\right)(2\pi rn) = 2\pi n\mathrm{T}$$



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

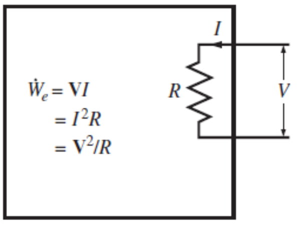
$$\dot{W}_{sh} = 2\pi\dot{n}\mathrm{T} \qquad \mathrm{(kW)}$$

where $\dot{n}$ is the number of revolutions per unit time.



Energy Transfer by Work

Electrical Work



$$\dot{W}_e = \mathbf{V}I$$

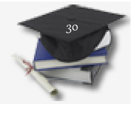
where $\dot{W}_e$ is the **electrical power** and I is the *current*

the electrical work done during a time interval Δt is

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

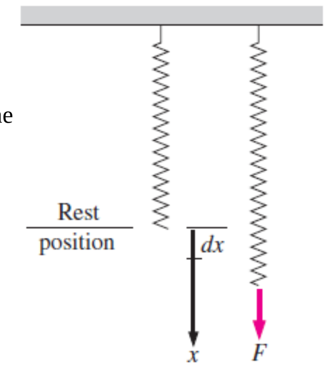
When both **V** and I remain constant during the time interval Δt,

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



Energy Transfer by Work

Spring Work



- When the length of the spring changes by a differential amount *dx* under the influence of a force *F*, the work done is

$$\delta W_{\text{spring}} = F\,dx$$

For linear elastic springs,

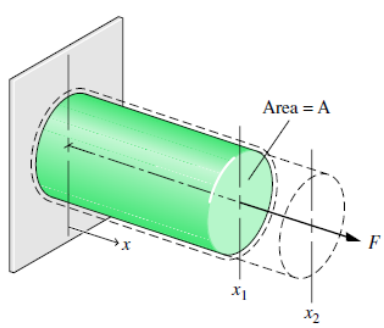
$$F = kx \qquad \text{(kN)}$$

$$\Rightarrow \quad W_{\text{spring}} = \tfrac{1}{2}k(x_2^2 - x_1^2)$$

where x_1 and x_2 are the initial and the final displacements of the spring,

Energy Transfer by Work

Work Done on Elastic Solid Bars



- For solid bar under tension.
- The bar is fixed at $x = 0$,
- The force F is applied at the other end.

$$F = \sigma_n A,$$

Where A is the cross-sectional area of the bar and σ is the *normal stress acting at the end* of the bar.

- The work done as the end of the bar moves a distance *dx* is given by

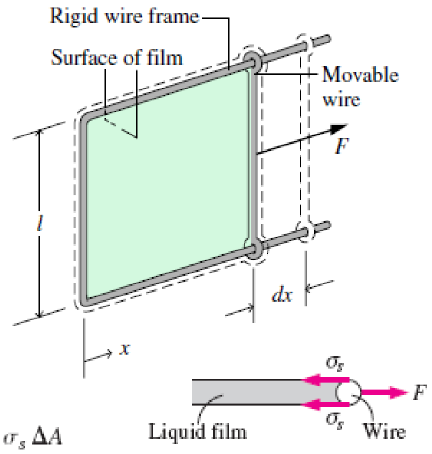
$$W_{\text{elastic}} = \int_1^2 F\,dx = \int_1^2 \sigma_n A\,dx$$

Energy Transfer by Work

Work Associated with the Stretching of a Liquid Film

- A force *F needs to* be applied on the movable wire in the opposite direction to balance this pulling effect.
- The thin film in the device has two surfaces (the top and bottom surfaces) exposed to air. The length along which the tension acts in this case is 2*b*.

$$F = 2b\sigma_s,$$



$$W_{\text{surface}} = \int_1^2 \sigma_s \, dA$$

$$W = \text{Force} \times \text{Distance} = F\,\Delta x = 2b\sigma_s\,\Delta x = \sigma_s\,\Delta A$$

where $dA = 2b\,dx$ is the change in the surface area of the film.

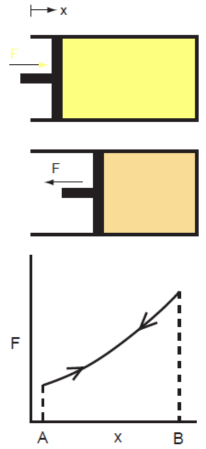
Energy Transfer by Work

- Work is said to be reversible if and only if the work done in moving dx is exactly recovered if the motion is reversed.

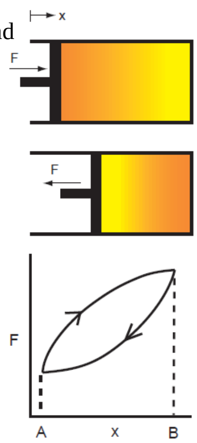
$$\text{Forward:} \quad đW_{forward} = \mathbf{F}(\mathbf{x}, \mathbf{v}) \cdot d\mathbf{x}$$

$$\text{Reverse:} \quad đW_{reverse} = -\,đW_{forward} = \mathbf{F}(\mathbf{x}, -\mathbf{v}) \cdot (-d\mathbf{x}).$$

Quasi-static



Rapid compression and expansion of a gas



- An important feature of a reversible process is that, depending on the process, it represents the maximum work that can be extracted in going from one state to another, or the minimum work that is needed to create the state change.

Summary

- Both are recognized at the boundaries of a system as they cross the boundaries. That is, both heat and work are *boundary* phenomena.
- Systems possess energy, but not heat or work.
- Both are associated with a *process,* not a state. Unlike properties, heat or work has no meaning at a state.
- 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 have exact differentials (d).

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

Path functions have inexact differentials (δ)

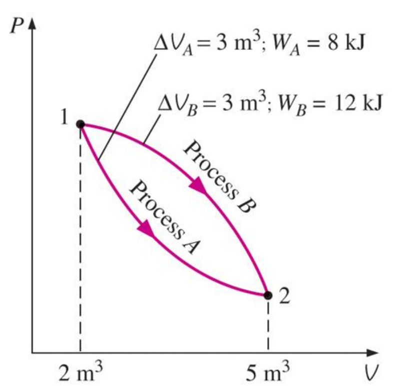
$$\int_1^2 \delta W = W_{12} \qquad (not\ \Delta W)$$

$$\int_1^2 \delta Q = Q_{12} \qquad (not\ \Delta Q)$$

Summary

Heat vs. Work

- ✓ Both are recognized at the boundaries of a system as they cross the boundaries. That is, both heat and work are *boundary* phenomena.
- ✓ Systems possess energy, but not heat or work.
- ✓ Both are associated with a *process*, not a state.
- ✓ Unlike properties, heat or work has no meaning at a state.
- ✓ 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).

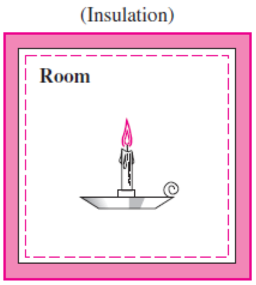
Examples

A candle is burning in a well-insulated room. Taking the room (the air plus the candle) as the system, determine

(*a*) if there is any heat transfer during this burning process and

- Heat is recognized as it crosses the boundaries.
- Since the room is well insulated, we have an adiabatic system and no heat will pass through the boundaries

$Q = 0$ for this process.

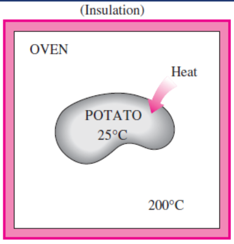


(*b*) if there is any change in the internal energy of the system.

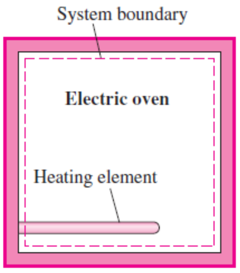
During the process just described, part of the chemical energy is converted to sensible energy. Since there is no increase or decrease in the total internal energy of the system

$$\Delta U = 0$$

Examples



- Energy transfer is a temperature difference, this is a **heat transfer process**.
  - If the entire oven, including the heating element, is taken to be the system



This energy transfer to the oven is not caused by a temperature difference between the oven and the surrounding air. Instead, it is caused by *electrons* crossing the system boundary and thus **doing work**.

- If the system is taken as only the air in the oven without the heating element.
- No electrons will be crossing the system boundary at any point. Instead, the energy generated in the interior of the heating element will be transferred to the air around it as a result of the temperature difference between the heating element and the air in the oven (**heat transfer**).