Topic 5
First Law of Thermodynamics

Objectives

- Explain the basic concepts of thermodynamics such as system, process, and cycle.

- Define the concept of heat and the terminology associated with energy transfer by heat.

- Discuss the three mechanisms of heat transfer: conduction, convection, and radiation.

- Define the concept of work, including electrical work and several forms of mechanical work.

- Introduce the first law of thermodynamics, energy balances, and mechanisms of energy transfer to or from a system.

- Determine that a fluid flowing across a control surface of a control volume carries energy across the control surface in addition to any energy transfer across the control surface that may be in the form of heat and/or work.

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**: 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.*

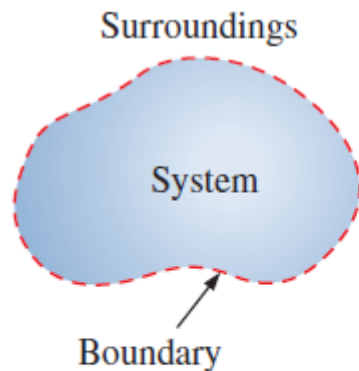- **Closed system (Control mass):** A fixed amount of mass, and no mass can cross its boundary

Surroundings

System

Boundary

FIGURE 1–18
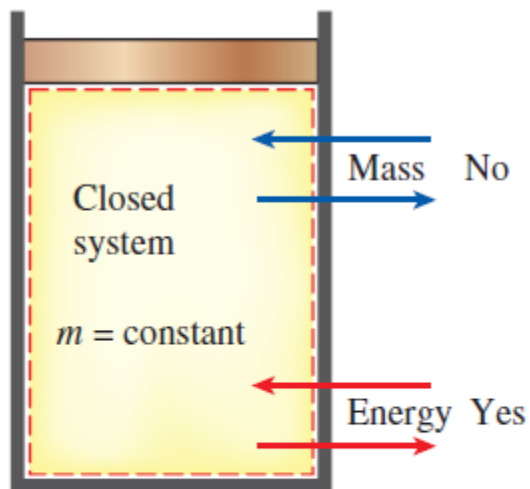
System, surroundings, and boundary.

Moving boundary

Gas
2 kg
1 m³

Gas
2 kg
1.5 m³

Fixed boundary

FIGURE 1–20

A closed system with a moving boundary.

Mass   No

Closed system

m = constant

Energy Yes

FIGURE 1–19

Mass cannot cross the boundaries of a closed system, but energy can.

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- **Open system** (**control volume**): A properly selected region in space.
- It usually encloses a device that involves mass flow such as a compressor, turbine, or nozzle.
- Both mass and energy can cross the boundary of a control volume.
- **Control surface**: The boundaries of a control volume. It can be real or imaginary.

A control volume can involve fixed, moving, real, and imaginary boundaries.

FIGURE 1–22

An open system (a control volume) with one inlet and one exit.
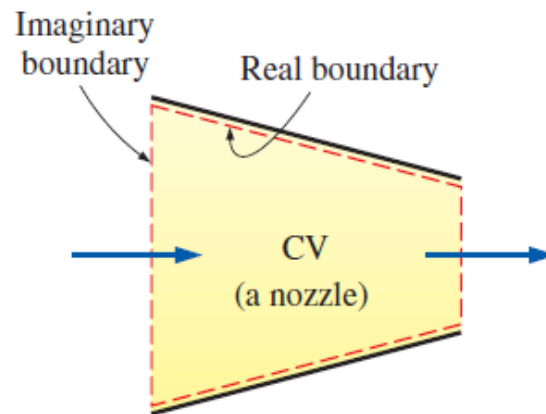
(a) A control volume (CV) with real and imaginary boundaries
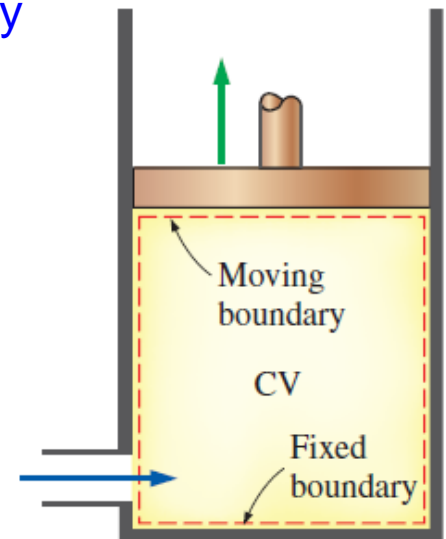
(b) A control volume (CV) with fixed and moving boundaries as well as real and imaginary boundaries

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.
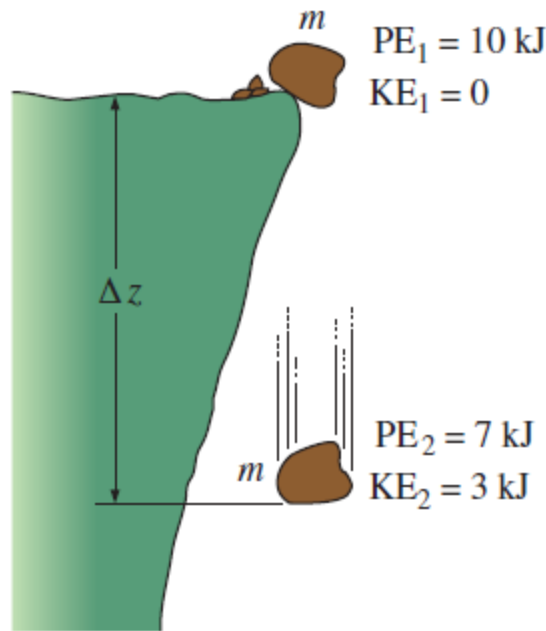

m
$PE_1 = 10 \text{ kJ}$
$KE_1 = 0$

Δz

$PE_2 = 7 \text{ kJ}$
m
$KE_2 = 3 \text{ kJ}$

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

$Q_{in} = 5 \text{ kJ}$
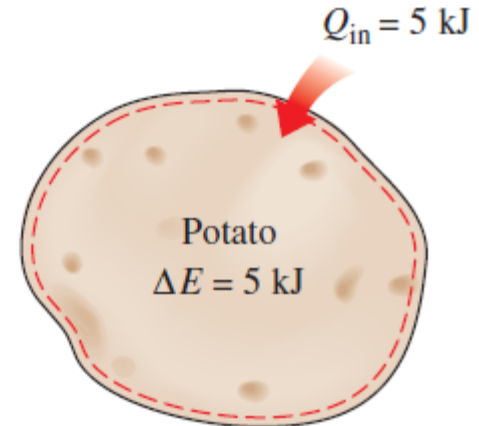
Potato
$\Delta E = 5 \text{ kJ}$

FIGURE 2–40
The increase in the energy of a potato in an oven is equal to the amount of heat transferred to it.

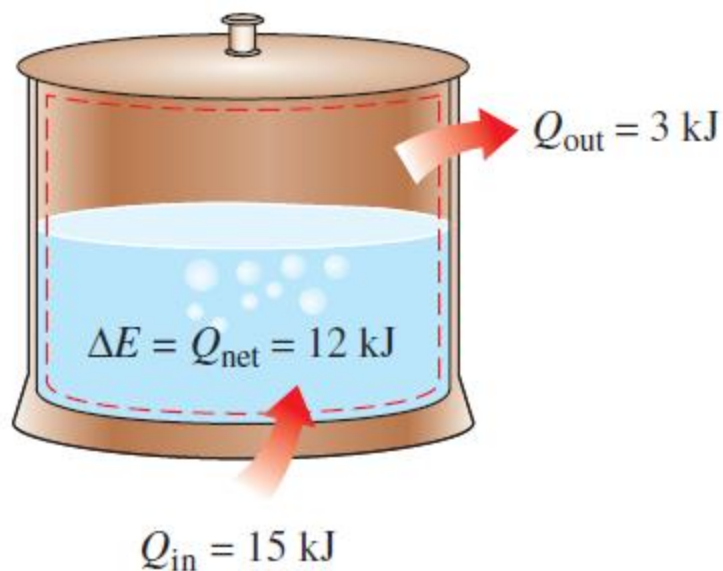$Q_{out} = 3 \text{ kJ}$

$\Delta E = Q_{net} = 12 \text{ kJ}$

$Q_{in} = 15 \text{ kJ}$

FIGURE 2–41

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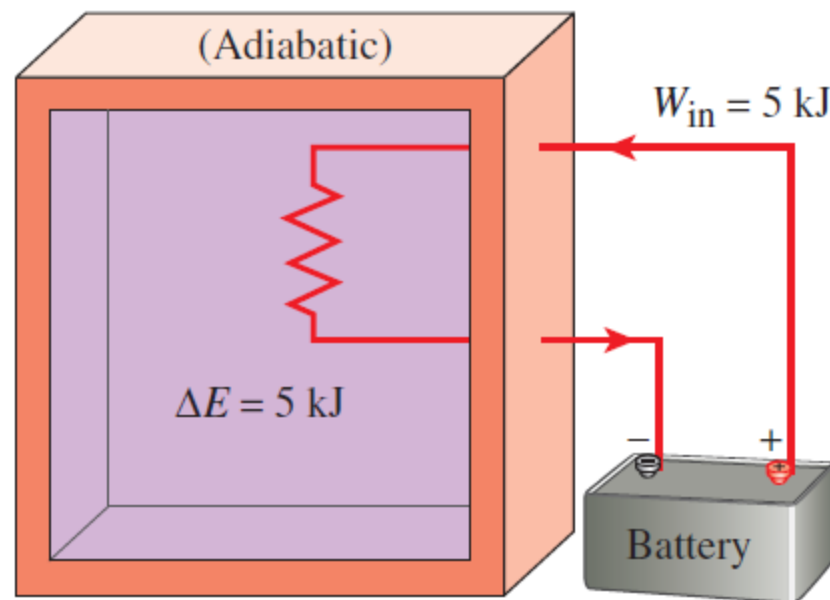

(Adiabatic)

$W_{in} = 5 \text{ kJ}$

$\Delta E = 5 \text{ kJ}$

Battery

FIGURE 2–42

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

(Adiabatic)

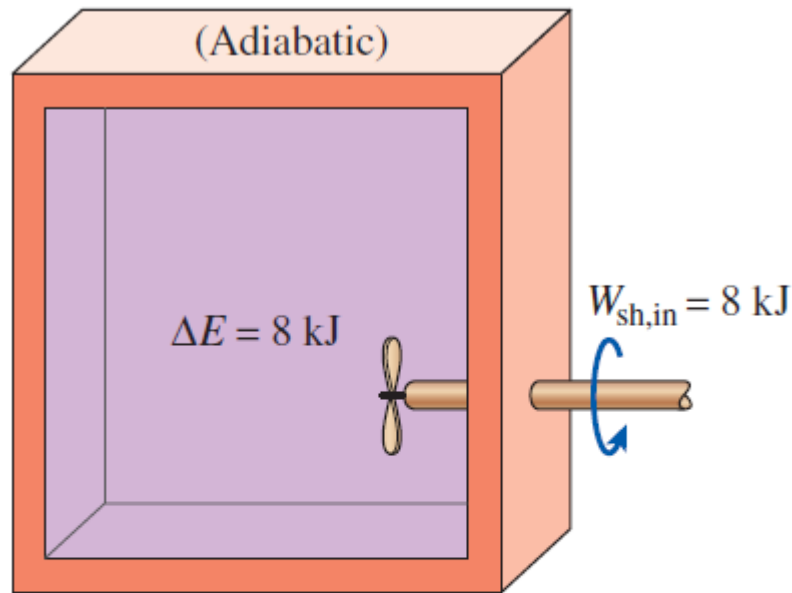$\Delta E = 8$ kJ

$W_{sh,in} = 8$ kJ

FIGURE 2–43

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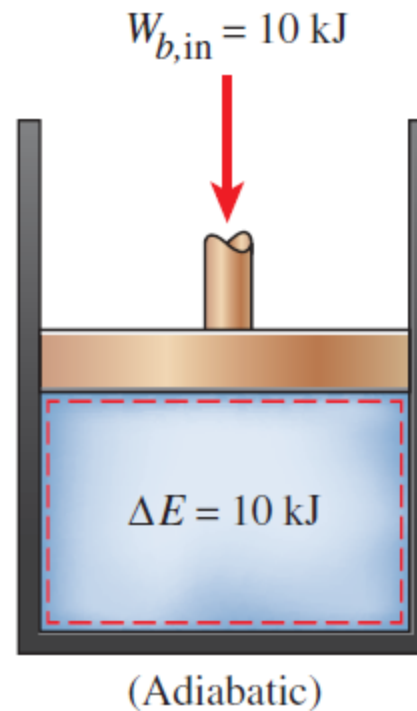

$W_{b,in} = 10$ kJ

$\Delta E = 10$ kJ

(Adiabatic)

FIGURE 2–44

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

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Energy Balance

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

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

The 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.

$Q_{out} = 3 \text{ kJ}$

$\Delta E = (15 - 3) + 6$
$= 18 \text{ kJ}$

$W_{sh,in} = 6 \text{ kJ}$
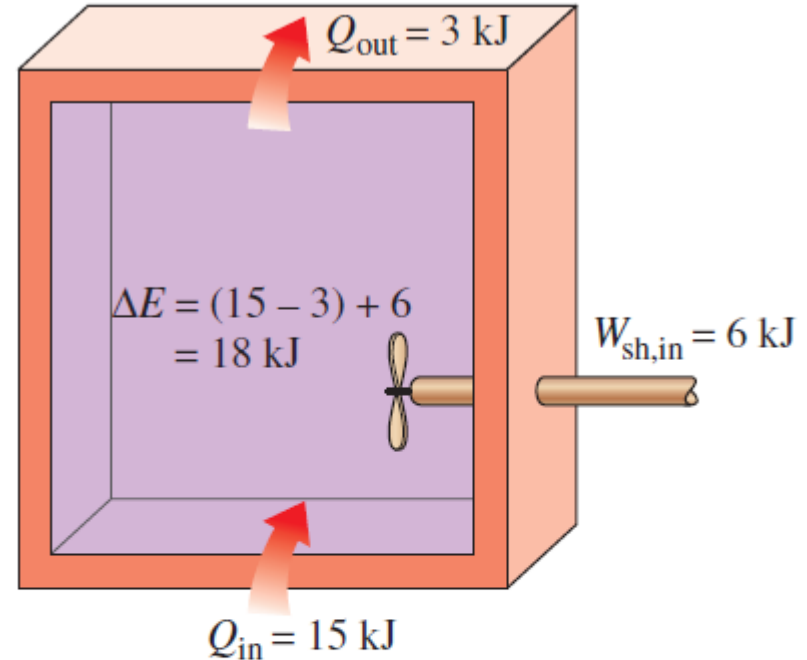
$Q_{in} = 15 \text{ kJ}$

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.

Example

A heater running off 120 V and 5 A with an efficiency of 70% is used to heat a pool. The pool loses heat at a constant rate of 120 W. Over the course of the day, the sun provides 500 kJ of heat over a 6 hour period. Determine the rate of heating (or cooling) in the pool. What is the net energy gain (or lost) by the pool after the 6 hour sunny period?

Example 1
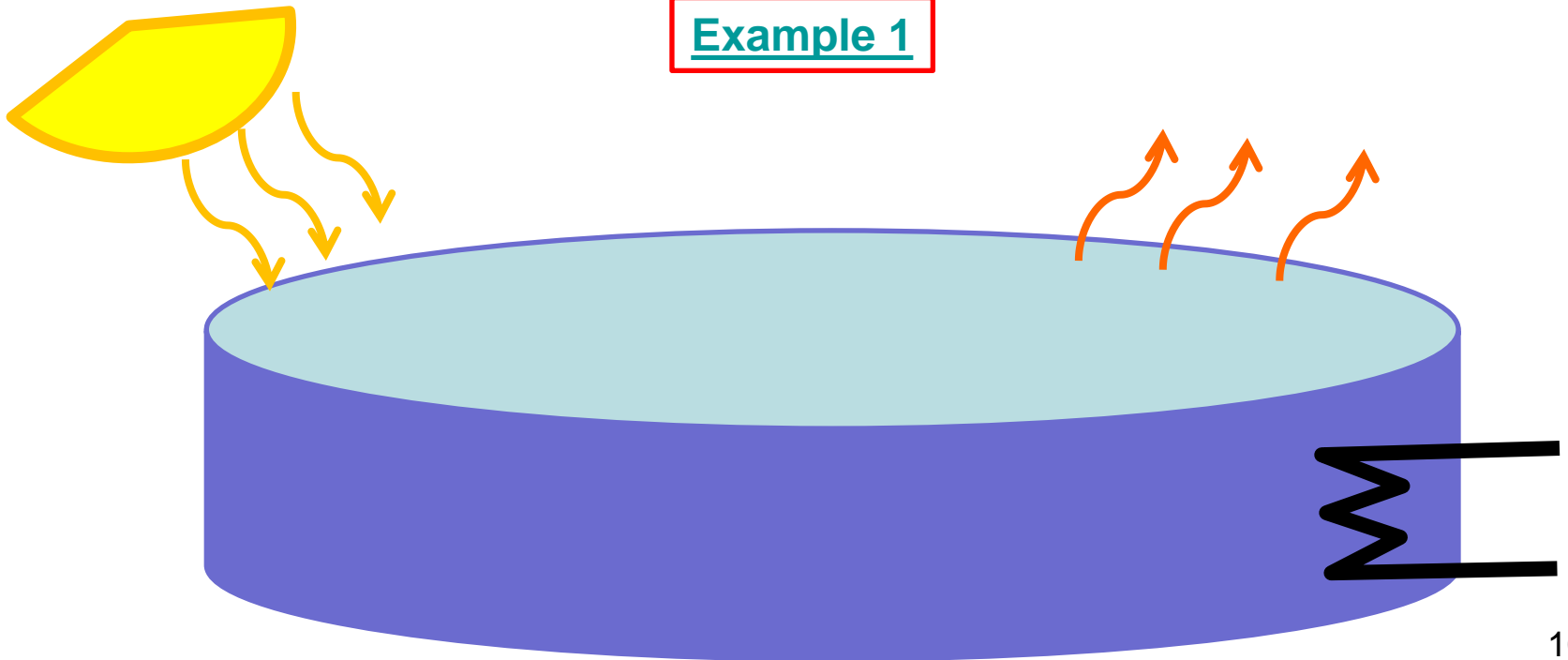
Energy Change of a System, ΔE_{system}

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

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

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

Internal, kinetic, and potential energy changes

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

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

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

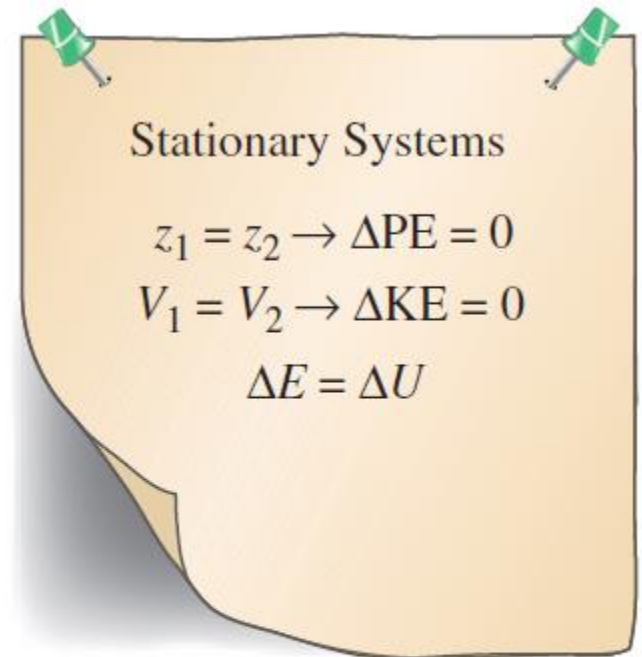Stationary Systems

$$z_1 = z_2 \rightarrow \Delta PE = 0$$
$$V_1 = V_2 \rightarrow \Delta KE = 0$$
$$\Delta E = \Delta U$$

FIGURE 2–46

For stationary systems, $\Delta KE = \Delta PE = 0$; thus $\Delta E = \Delta U$.

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

Energy balance for any system undergoing any kind of process can be expressed more compactly as

$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc., energies}}} \quad \text{(kJ)} \tag{2-35}$$

or, in the **rate form**, as

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{system}/dt}_{\substack{\text{Rate of change in internal,} \\ \text{kinetic, potential, etc., energies}}} \quad \text{(kW)} \tag{2-36}$$

For constant rates, the total quantities during a time interval Δt are related to the quantities per unit time as

$$Q = \dot{Q}\,\Delta t, \quad W = \dot{W}\,\Delta t, \quad \text{and} \quad \Delta E = (dE/dt)\,\Delta t \quad \text{(kJ)} \tag{2-37}$$

The energy balance can be expressed on a **per unit mass** basis as

$$e_{in} - e_{out} = \Delta e_{system} \quad \text{(kJ/kg)} \tag{2-38}$$

which is obtained by dividing all the quantities in Eq. 2–35 by the mass m of the system. Energy balance can also be expressed in the differential form as

$$\delta E_{in} - \delta E_{out} = dE_{system} \quad \text{or} \quad \delta e_{in} - \delta e_{out} = de_{system} \tag{2-39}$$

Mechanisms of energy transfer:

- Heat transfer
- Work transfer
- Mass flow

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

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

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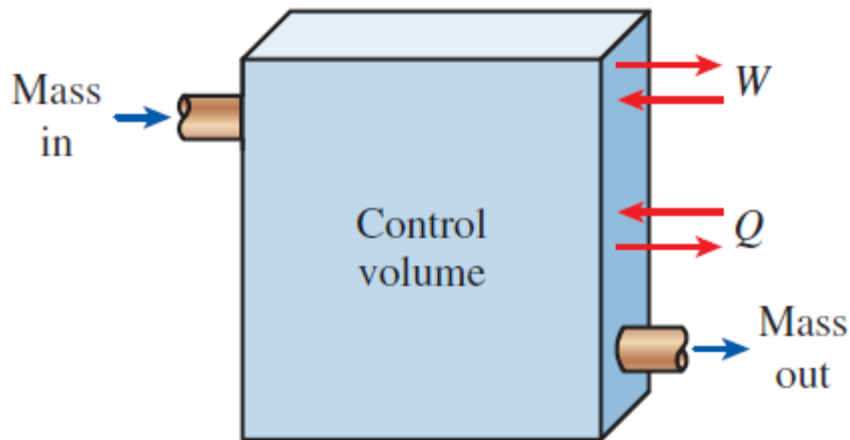

FIGURE 2–47

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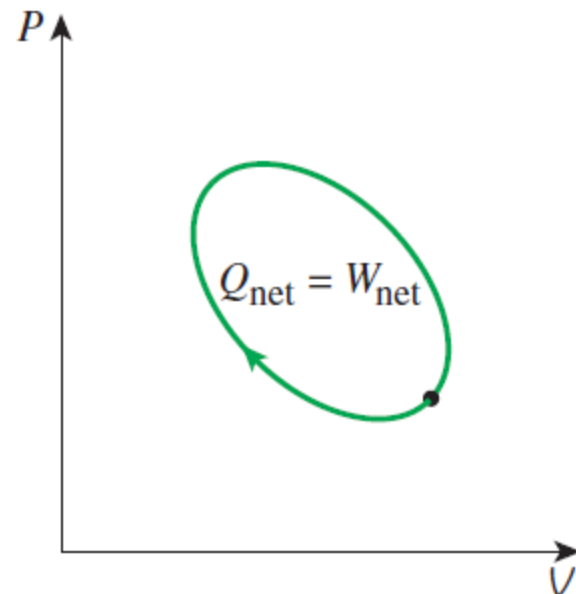

FIGURE 2–48

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

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.

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

Property A

State 2

Process path
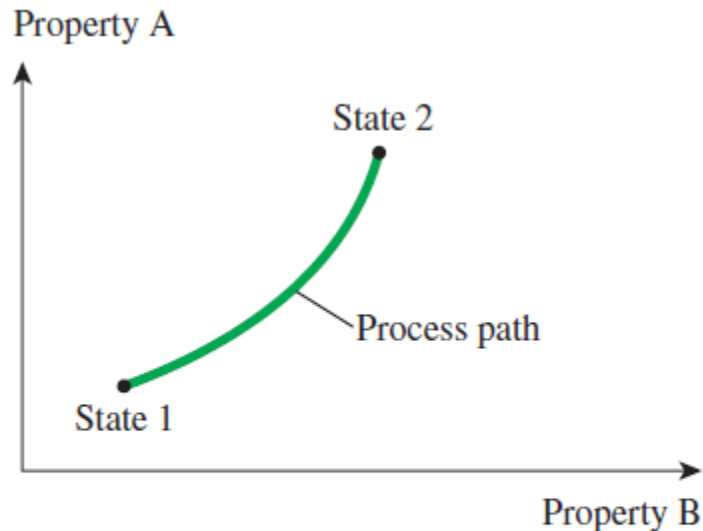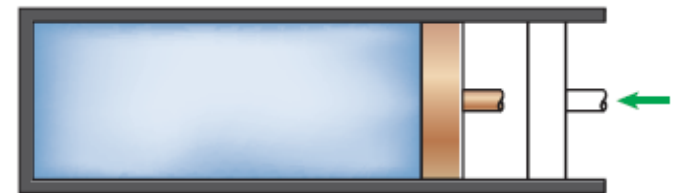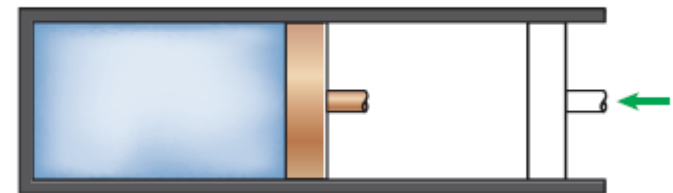
State 1

Property B

FIGURE 1–29

A process between states 1 and 2 and the process path.

(a) Slow compression (quasi-equilibrium)

(b) Very fast compression (nonquasi-equilibrium)

FIGURE 1–30

Quasi-equilibrium and nonquasi-equilibrium compression processes.

- 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 particularproperty 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.

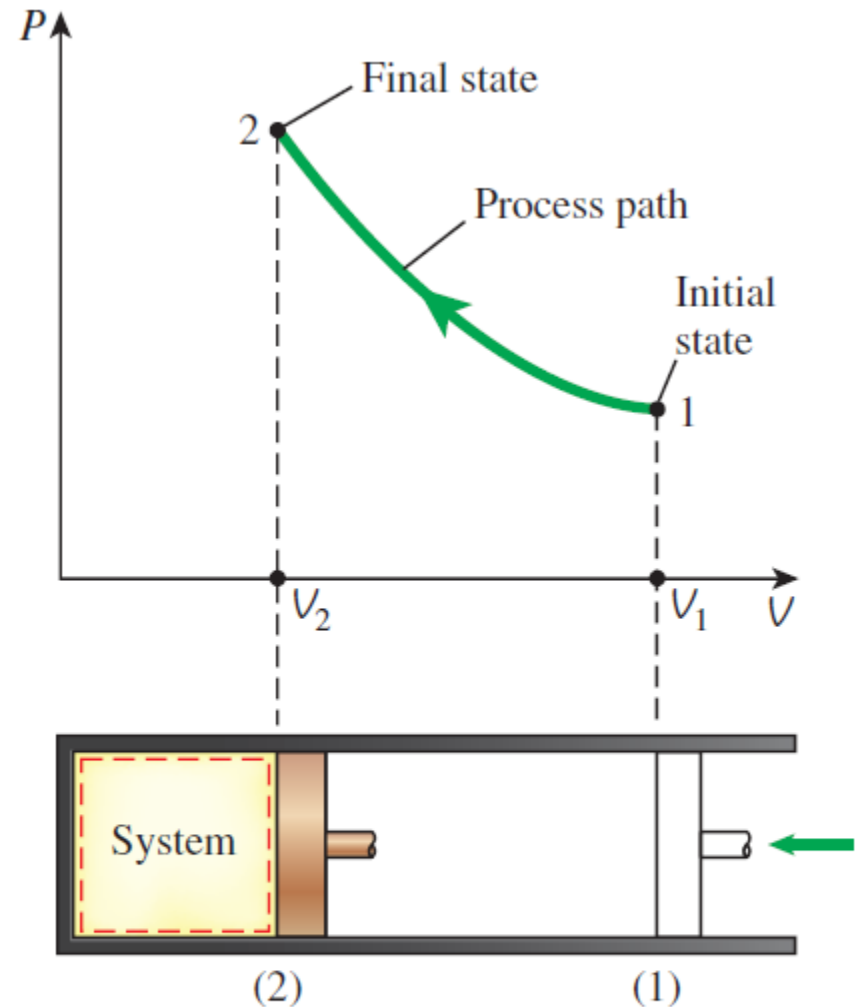- **Cycle**: A process during which the initial and final states are identical.

FIGURE 1–31

The P-V diagram of a compression process.

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The Steady-Flow Process

- 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.

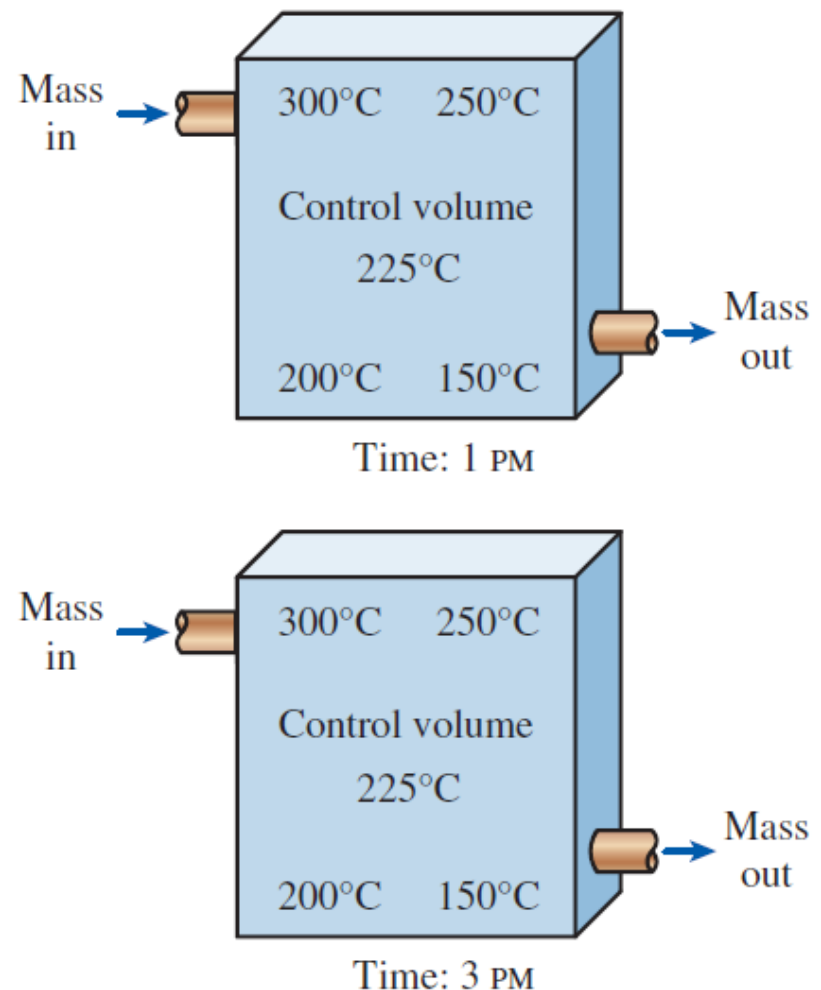**FIGURE 1–32**

During a steady-flow process, fluid properties within the control volume may change with position but not with time.
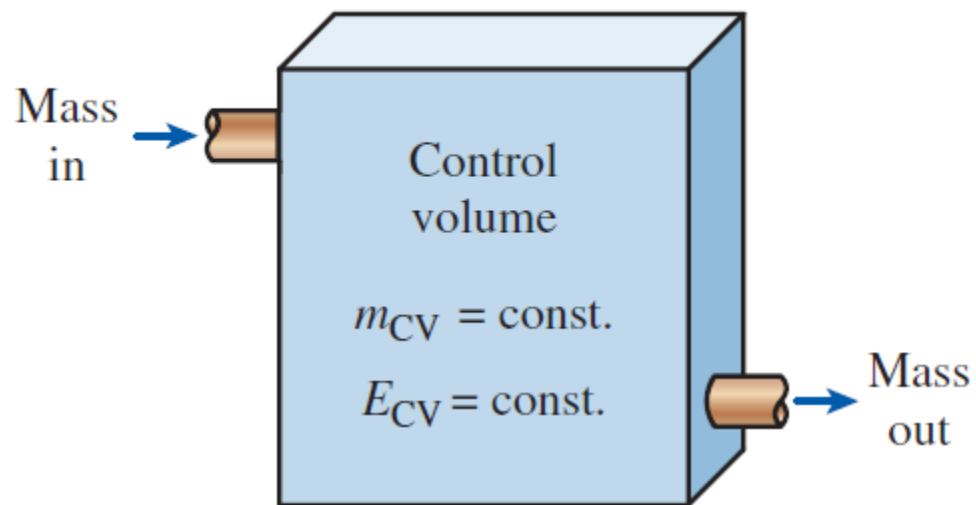
FIGURE 1–33

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

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.

System boundary

Closed system

(m = constant)
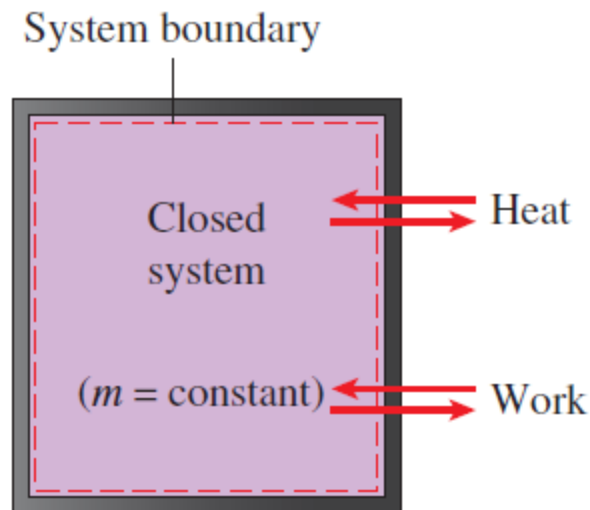
← Heat

← Work

FIGURE 2–14

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

Room air
25°C

No heat transfer

8 J/s   Heat

16 J/s   Heat

Soda   25°C
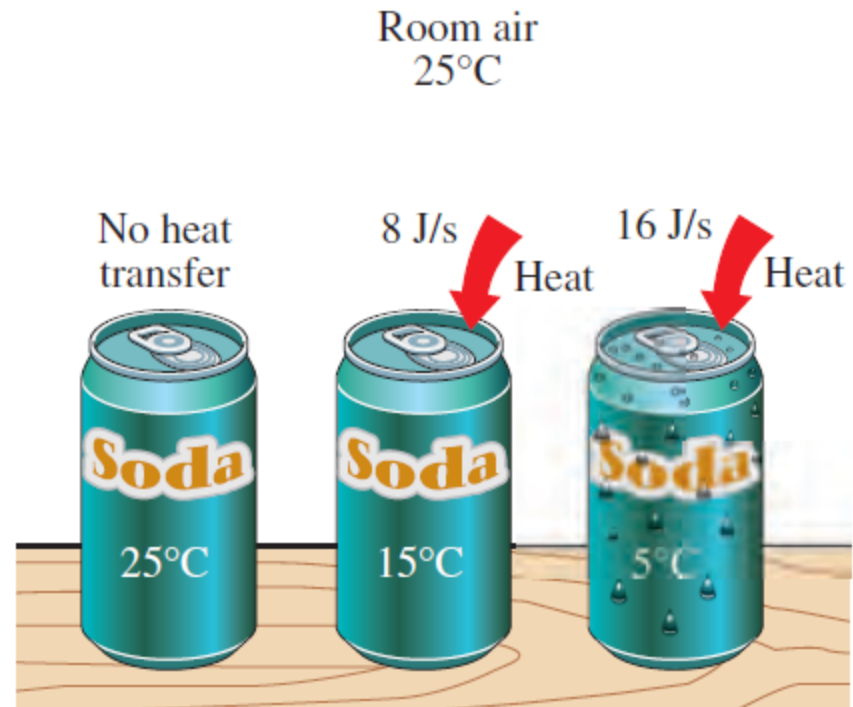
Soda   15°C

Soda   5°C

FIGURE 2–15

Temperature difference is the driving force for heat transfer. The larger the temperature difference, the higher is the rate of heat transfer.

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

Heat transfer per unit mass

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

Amount of heat transfer when heat transfer rate is constant

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

Amount of heat transfer when heat transfer rate changes with time

$Q = 30 \text{ kJ}$
$m = 2 \text{ kg}$
$\Delta t = 5 \text{ s}$

30 kJ heat

$\dot{Q} = 6 \text{ kW}$
$q = 15 \text{ kJ/kg}$

FIGURE 2–18

The relationships among q, Q, and $\dot{Q}$.

Surrounding air

Baked potato

2 kJ thermal energy

Heat

2 kJ heat

System boundary

2 kJ thermal energy

FIGURE 2–16

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

Insulation

$Q = 0$

Adiabatic system

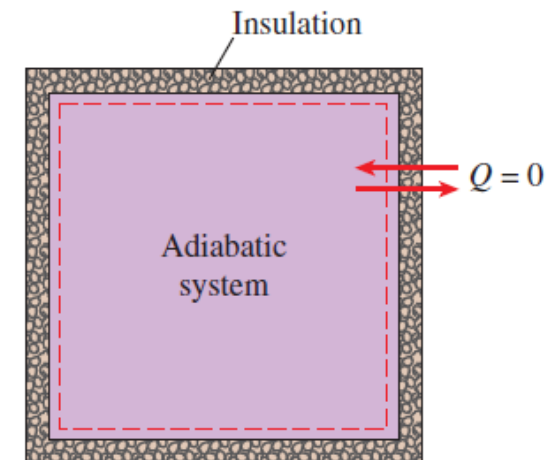**FIGURE 2–17**

During an adiabatic process, a system exchanges no 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:

- **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.
- **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.
- **Radiation:** The transfer of energy due to the emission of electromagnetic waves (or photons).

FIGURE 2–19
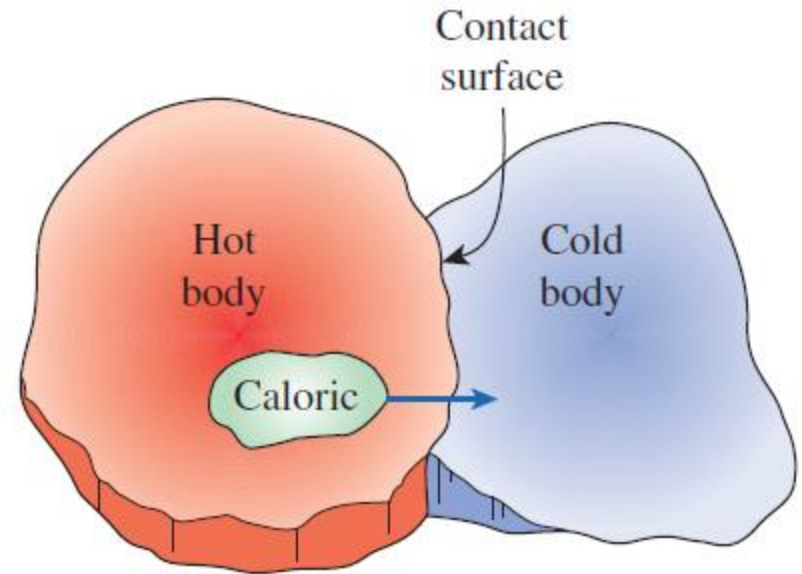
In the early nineteenth century, heat was thought to be an invisible fluid called the *caloric* that flowed from warmer bodies to the cooler ones.

Mechanisms of Heat Transfer

- There are 3 modes of heat transfer:
  - Conduction
  - Convection
  - Radiation

- All modes require temperature difference between source and sink

- Heat transfers from high temperature to low temperature

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Conduction

- Transfer of more energetic particles to less energetic particles

- Occurs in solids, liquids, and gasses
  - Liquids and gasses: collision of molecules during random motion (Brownian motion)
  - Solids: combination of crystal lattice vibrations and energy transport by free electrons

Conduction

$$\dot{Q}_{cond} = -k_t A \frac{\Delta T}{\Delta x}$$

- Heat of conduction is proportional to temperature difference (ΔT) and area normal to heat transfer

- Thermal conductivity, k_t: proportionality constant measures material's ability to conduct heat

- Conductors (e.g. most metals) have high k_t

- Insulators (e.g. wood, styrofoam) have low k_t

- Fourier's law of heat conduction $\quad \dot{Q}_{cond} = -k_t A \frac{dT}{dx}$

  - Negative sign is used due to negative temperature gradient

Conduction

$$\dot{Q}_{cond} = -k_t A \frac{\Delta T}{\Delta x}$$
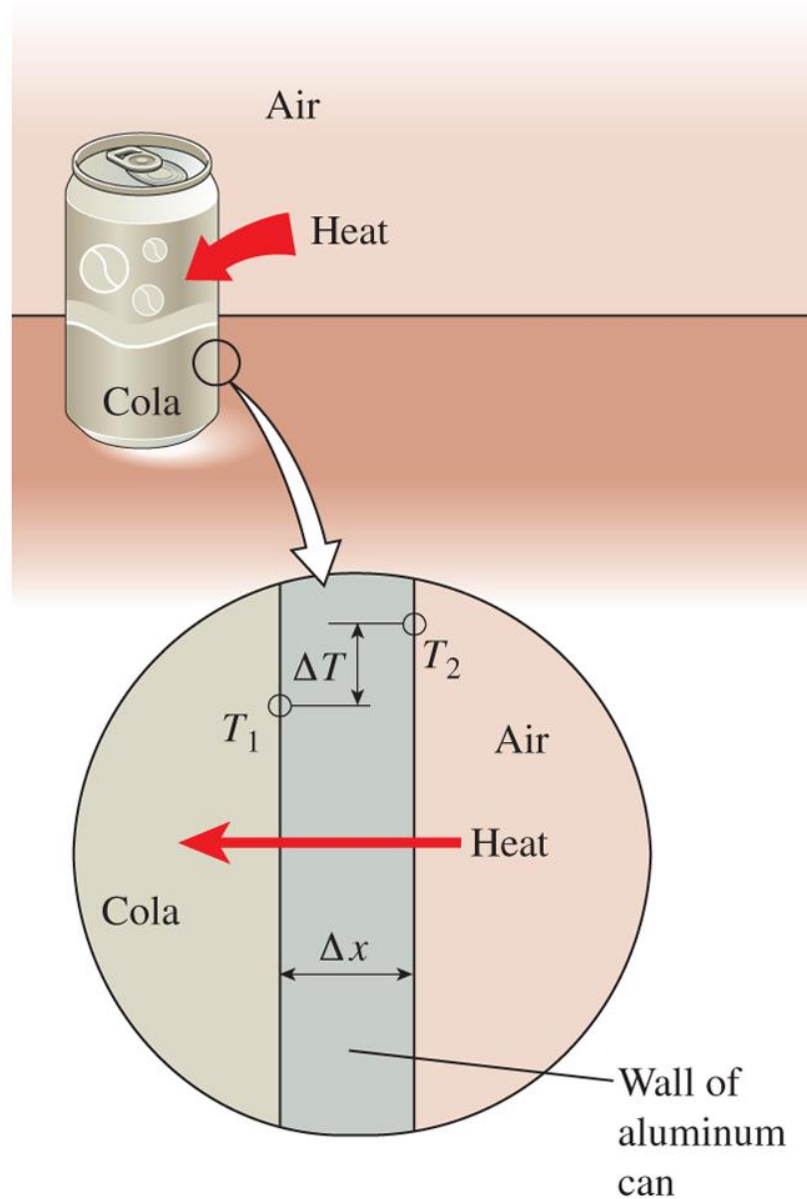
Example

The temperature distribution across a wall 1 m thick at a certain instant of time is given as

$$T(x) = a + bx + cx^2$$

where T is in degrees Celsius and x is in meters, while a, b, and c are listed below. The wall has an area of $10 \ m^2$ and a thermal conductivity of $40 \frac{W}{mK}$. Determine the rate of heat transfer entering the wall and leaving the wall. Is the wall gaining or losing energy?

$$a = 900°\text{C} \qquad b = -300 \frac{°\text{C}}{m} \qquad c = -50 \frac{°\text{C}}{m^2}$$

Example 2

Convection

- Transfer of energy to/from a solid surface from/to an adjacent moving fluid (liquid or gas)

- Combination of conduction and fluid motion

- Faster fluid motion results in more heat transfer

- If fluid is motionless then pure conduction occurs

- Forced convection: fluid is *forced* over surface by external means (fan, pump, wind, etc.)

- Free (or natural) convection: fluid motion is caused by buoyancy force due to changes in density (e.g. warmer air rises because it is less dense)

Convection

- Heat transfer in processes that involve phase changes in fluids are consider to be convection
    - Movement of vapor bubbles through a liquid (evaporation)
    - Falling of liquid droplets (condensation)
- Newton's Law of Cooling $\dot{Q}_{conv} = hA(T_s - T_f)$
- Convective heat transfer coefficient, *h*
    - not a property of the fluid
    - Determined experimentally; affected by surface geometry, fluid properties, fluid velocity
- T_s – surface temperature; T_f – bulk fluid temperature
    - Note: the temperature of fluid at the surface is T_s not T_f (continuum)

Convection

$$\dot{Q}_{conv} = hA(T_s - T_f)$$

Velocity variation of air

Air flow

$\dot{Q}_{conv}$

A

T_f

Temperature variation of air

T_s

Hot block
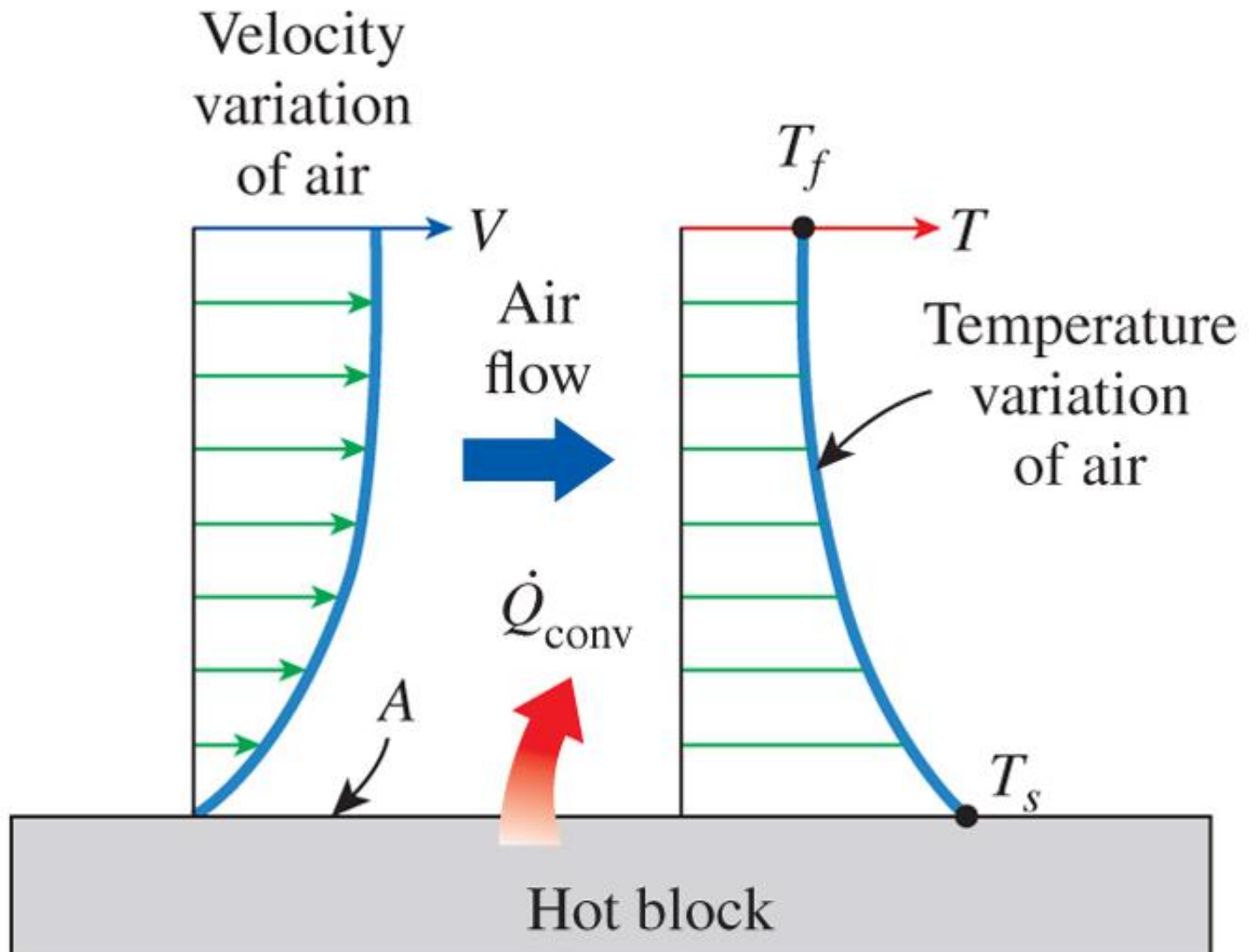
Radiation

- Energy is emitted by matter in the form of electromagnetic waves (or photons)

- Results from the change of electronic configurations of atoms or molecules

- Does not require presence of medium between source and sink; can work in a vacuum

- All bodies at a temperature above absolute zero emit thermal radiation

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Radiation

$$\sigma = 5.67 \times 10^{-8} \frac{W}{m^2 K^4}$$

- Maximum radiation from a surface: Stefan-Boltzman's Law $\dot{Q}_{emit,max} = \sigma A T_s^4$

- Surface that emits maximum radiation is called a blackbody

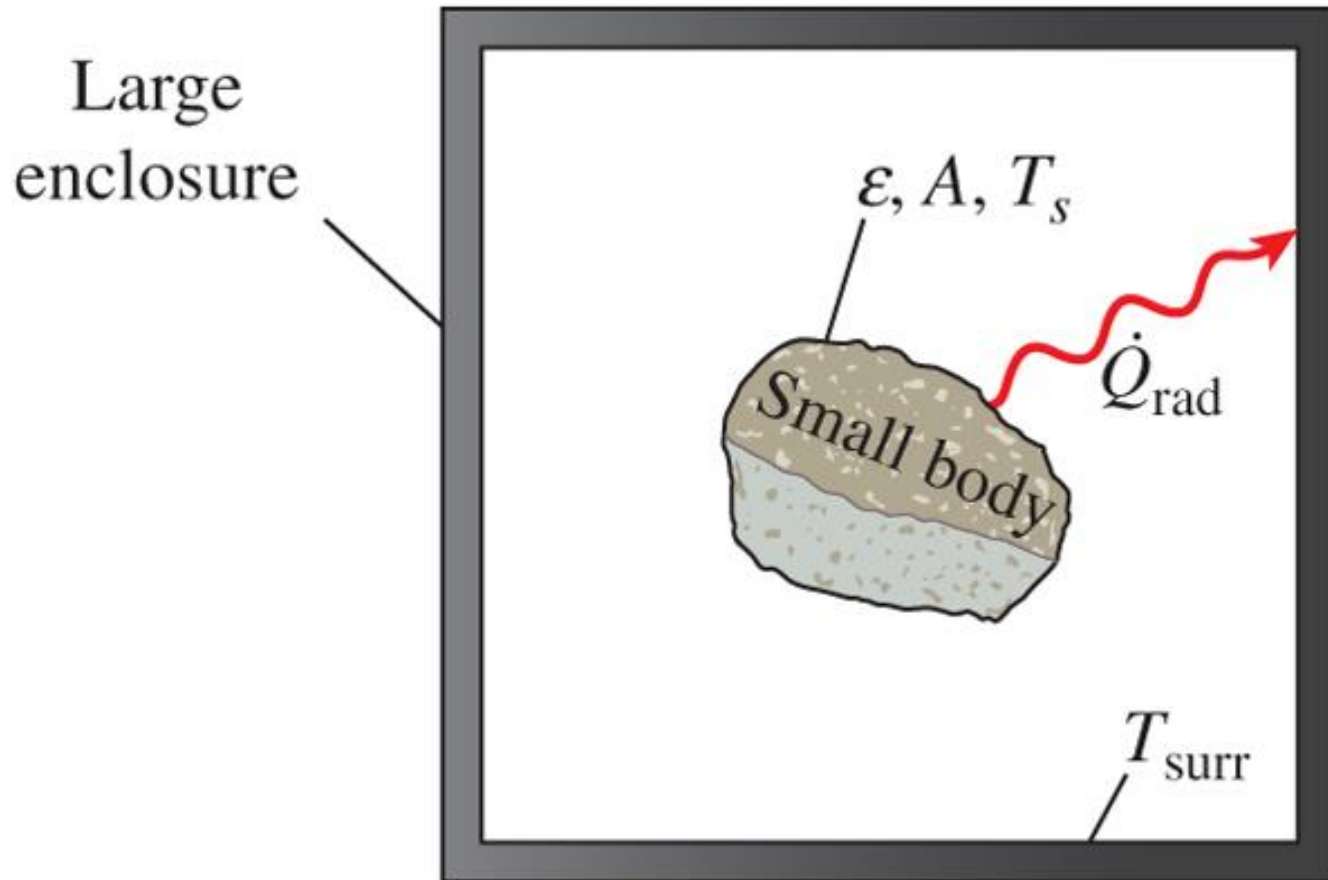- *Real* surfaces emit less than the maximum

$$\dot{Q}_{emit,max} = \varepsilon \sigma A T_s^4$$

- Emissivity, ε: material property between 0 and 1 (for blackbodies $\varepsilon = 1$)

- For a large surface surrounding a radiation source:

$$\dot{Q}_{rad} = \varepsilon \sigma A (T_s^4 - T_{surr}^4)$$

Radiation

$$\dot{Q}_{rad} = \varepsilon\sigma A(T_s^4 - T_{surr}^4)$$

Large enclosure

ε, A, T_s

Small body

$\dot{Q}_{rad}$

T_{surr}

Example

Humans can control their heat production rate and heat loss rate to maintain a nearly constant core temperature under a wide range of environmental conditions. The process is called thermoregulation. From the perspective of calculating heat transfer between a human body and its surroundings, we focus on a layer of skin and fat, with its outer surface exposed to the environment and its inner surface at a temperature slightly less than the core temperature of $308\ K$. Consider a person with a skin/fat layer of thickness of $3\ mm$ and effective thermal conductivity of $0.3\ \frac{W}{m\ K}$. The person has surface area of $1.8\ m^2$ and is dressed in a bathing suit. The emissivity of the skin is 0.95. When the person is in still air at $297\ K$, what is the skin surface temperature and rate of heat loss to the environment? Assume the convection coefficient of the air is $2\ \frac{W}{m^2 K}$. How are the surface temperature and rate of heat loss affected when the person is in water with a convection coefficient of $200\ \frac{W}{m^2 K}$?

Example 3

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.
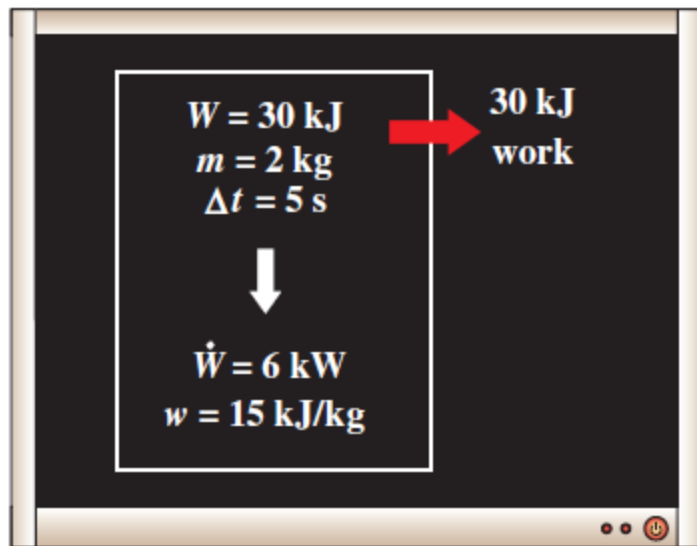
Work done per unit mass

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

$W = 30 \text{ kJ}$
$m = 2 \text{ kg}$
$\Delta t = 5 \text{ s}$

30 kJ work

$\dot{W} = 6 \text{ kW}$
$w = 15 \text{ kJ/kg}$

FIGURE 2–20
The relationships among w, W, and $\dot{W}$.

Surroundings

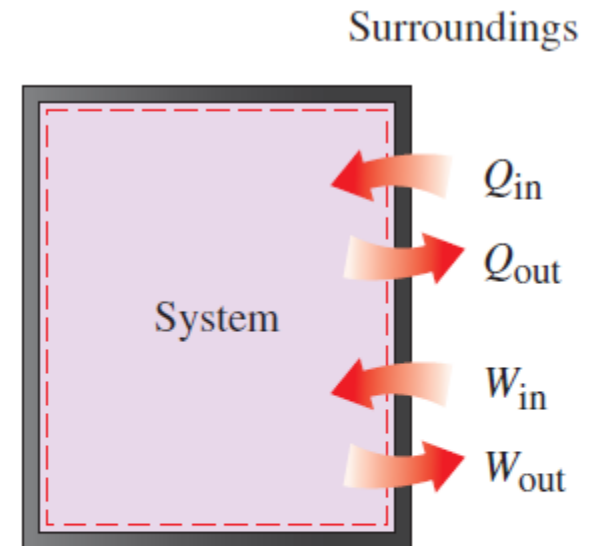Q_{in}
Q_{out}

System

W_{in}
W_{out}

FIGURE 2–21
Specifying the directions of heat and work.

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 have exact differentials (d).

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

Path functions have inexact differentials (δ)

P

$\Delta V_A = 3 \text{ m}^3; W_A = 8 \text{ kJ}$

$\Delta V_B = 3 \text{ m}^3; W_B = 12 \text{ kJ}$

1

Process B

Process A

2

2 m^3 5 m^3 V

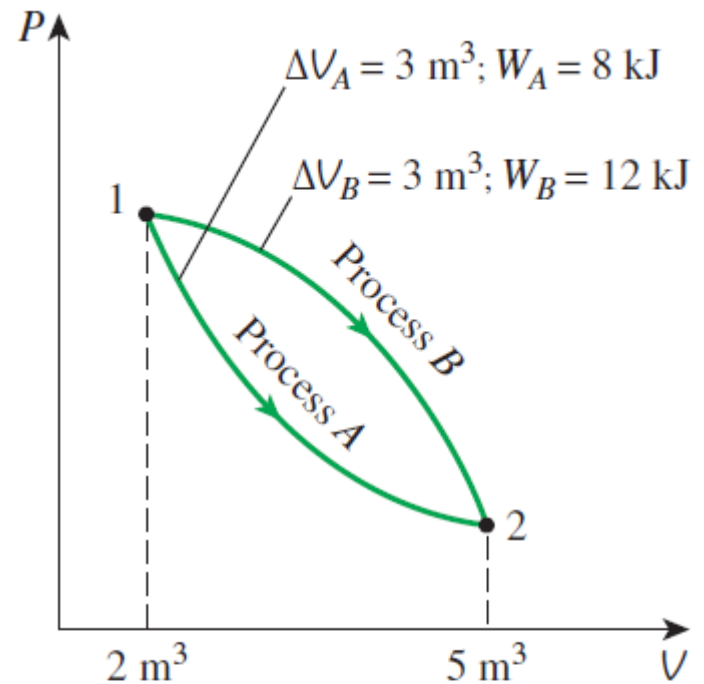**FIGURE 2–22**

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

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

Electrical Work

Electrical work

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

Electrical power

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

When potential difference and current change with time

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

When potential difference and current remain constant
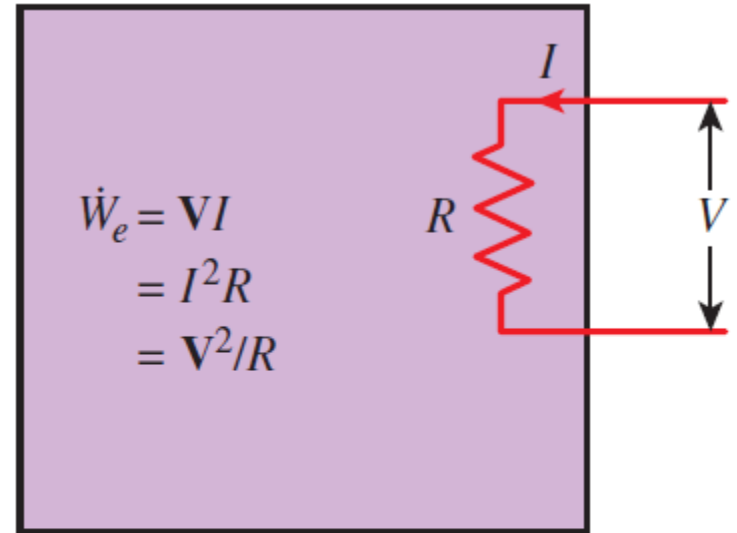
$$W_e = \mathbf{V}I \, \Delta t \qquad (\text{kJ})$$

$$\dot{W}_e = \mathbf{V}I$$
$$= I^2 R$$
$$= \mathbf{V}^2/R$$

FIGURE 2–27

Electrical power in terms of resistance R, current I, and potential difference $\mathbf{V}$.

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

$$W = Fs \qquad (kJ)$$

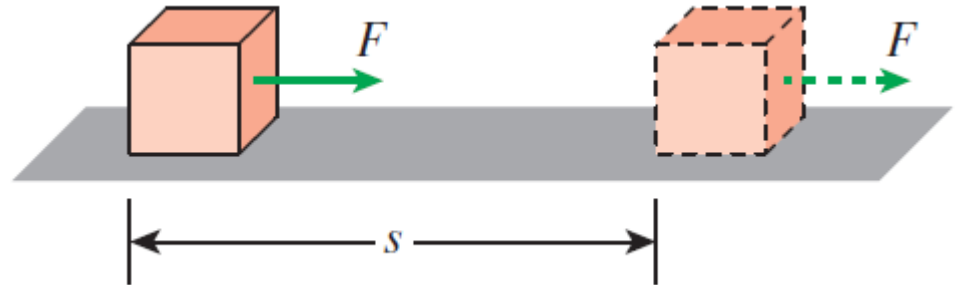When force is not constant

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

FIGURE 2–28

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

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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

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

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

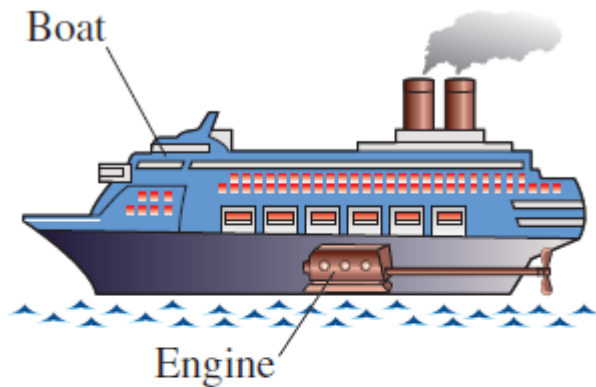$$\dot{W}_{sh} = 2\pi \dot{n}T \qquad (\text{kW})$$

Boat

Engine

FIGURE 2–29

Energy transmission through rotating shafts is commonly encountered in practice.

$\dot{W}_{sh} = 2\pi \dot{n}\text{T}$

r

$\dot{n}$

F
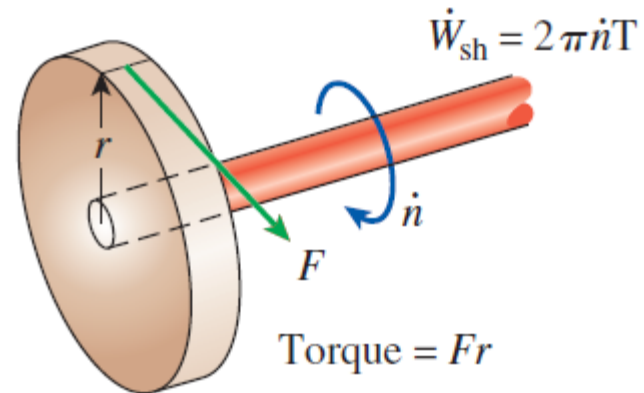
Torque $= Fr$

FIGURE 2–30

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

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

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

For linear elastic springs, the displacement x is proportional to the force applied

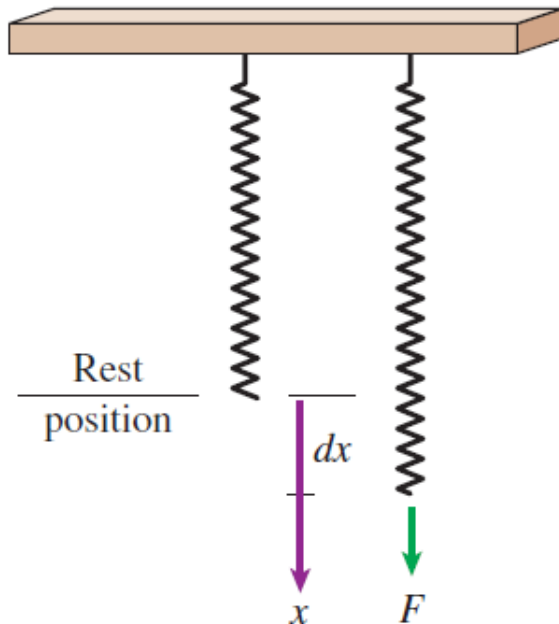$$F = kx \qquad (\text{kN}) \quad k\text{: spring constant (kN/m)}$$

Substituting and integrating yield

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

x_1 and x_2: the initial and the final displacements

FIGURE 2–32
Elongation of a spring under the influence of a force.
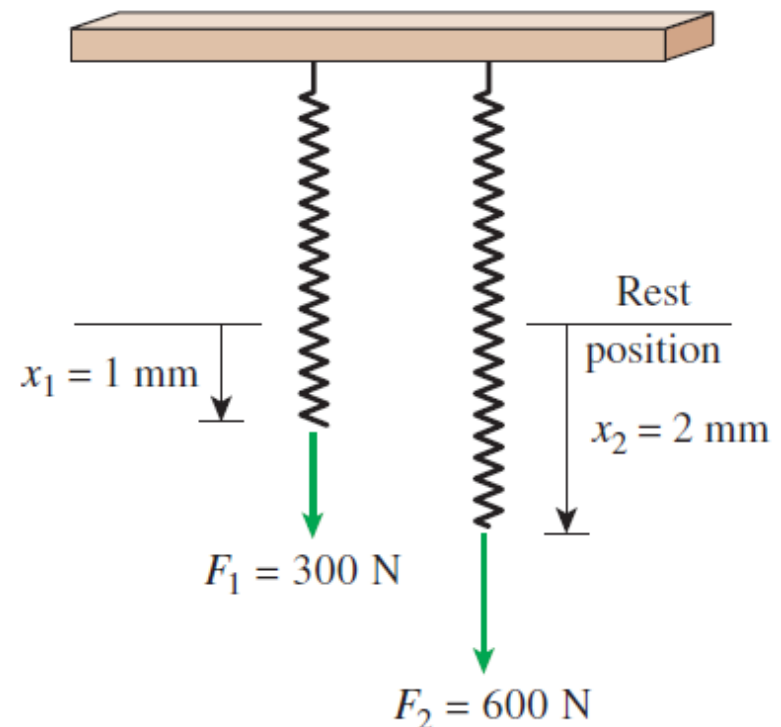

FIGURE 2–33
The displacement of a linear spring doubles when the force is doubled.

Example

Determine the energy necessary to stretch a spring (with a spring constant of 200 lbf/in) 4 inches. Express your answer in Btu.

Useful Information: 1 Btu = 778.169 lbf · ft

Example 4

Work Associated with the Stretching of a Liquid Film

$$W_{surface} = \int_1^2 \sigma_s \, dA \qquad (kJ)$$

Work Done on Elastic Solid Bars

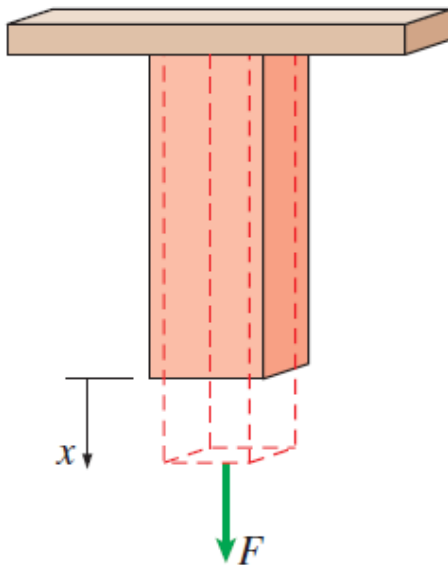$$W_{elastic} = \int_1^2 F \, dx = \int_1^2 \sigma_n A \, dx \qquad (kJ)$$

FIGURE 2–34

Solid bars behave as springs under the influence of a force.

Rigid wire frame

Surface of film

Movable wire

F

b

δx

x
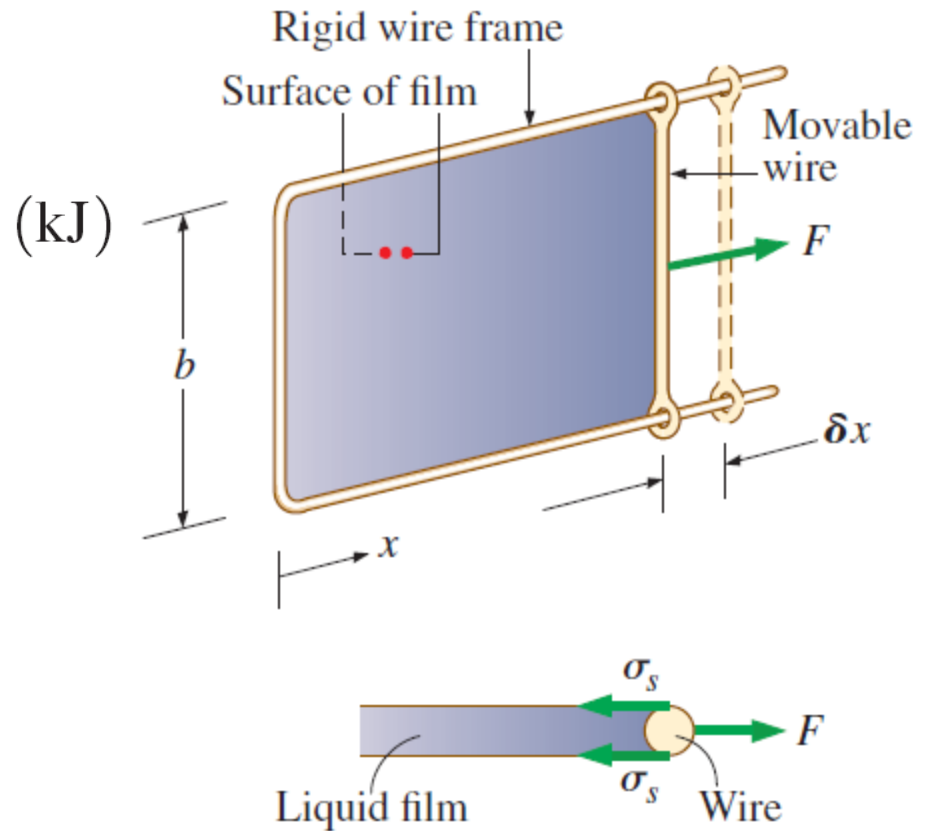
σ_s

F

σ_s

Liquid film

Wire

FIGURE 2–35

Stretching a liquid film with a U-shaped wire, and the forces acting on the movable wire of length b.

Work Done to Raise or to Accelerate a Body

1. The work transfer needed to raise a body is equal to the change in the potential energy of the body.

2. The work transfer needed to accelerate a body is equal to the change in the kinetic energy of the body.

Nonmechanical Forms of Work

Electrical work: The generalized force is the *voltage* (the electrical potential) and the generalized displacement is the *electrical charge*.

Magnetic work: The generalized force is the *magnetic field strength* and the generalized displacement is the total *magnetic dipole moment*.

Electrical polarization work: The generalized force is the *electric field strength* and the generalized displacement is the *polarization of the medium.*
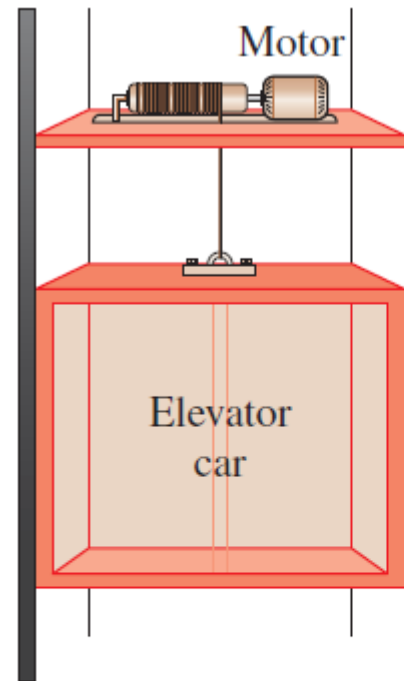

FIGURE 2-36
The energy transferred to a body while being raised is equal to the change in its potential energy.

Summary

- Systems and control volumes
- Processes and cycles
  - The steady-flow process
- Energy transfer by heat
- Energy transfer by work
- Mechanical forms of work
- The first law of thermodynamics
  - Energy balance
  - Energy change of a system
  - Mechanisms of energy transfer (heat, work, mass flow)