Thermodynamics: An Engineering Approach

8th Edition

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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

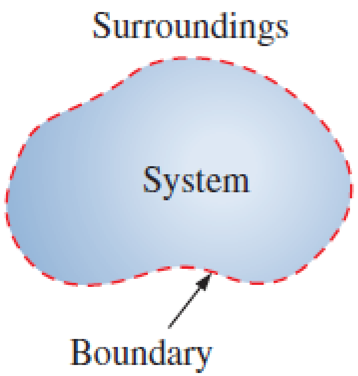


FIGURE 1–18
System, surroundings, and boundary.

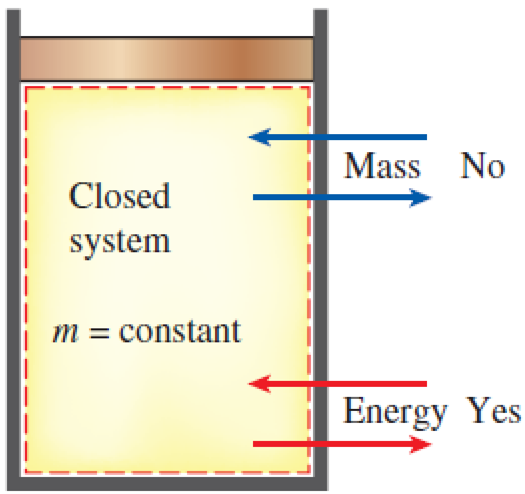


FIGURE 1–19
Mass cannot cross the boundaries of a closed system, but energy can.

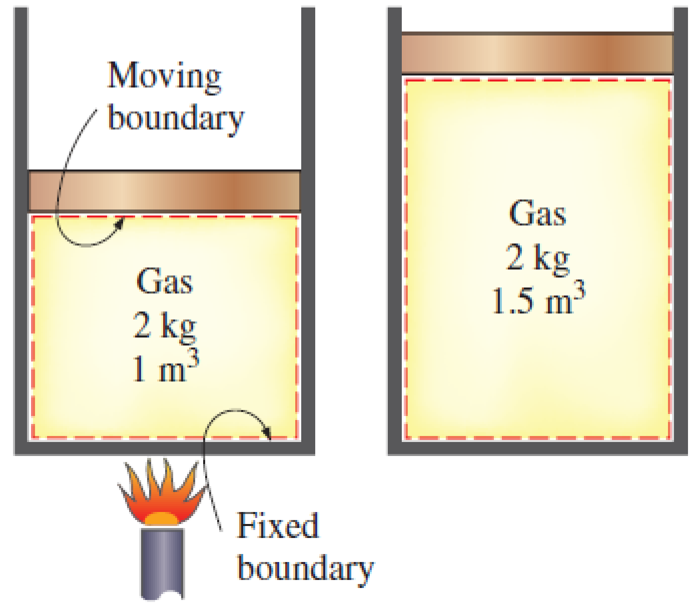
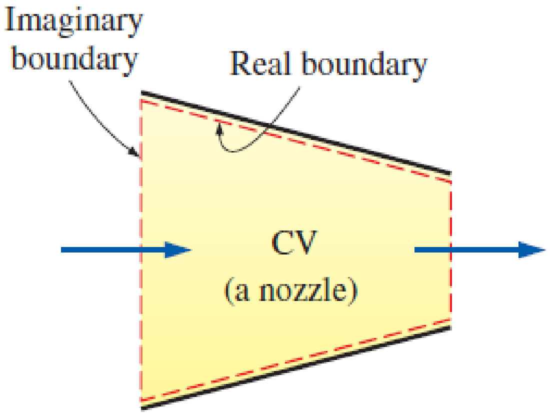


FIGURE 1–20
A closed system with a moving boundary.

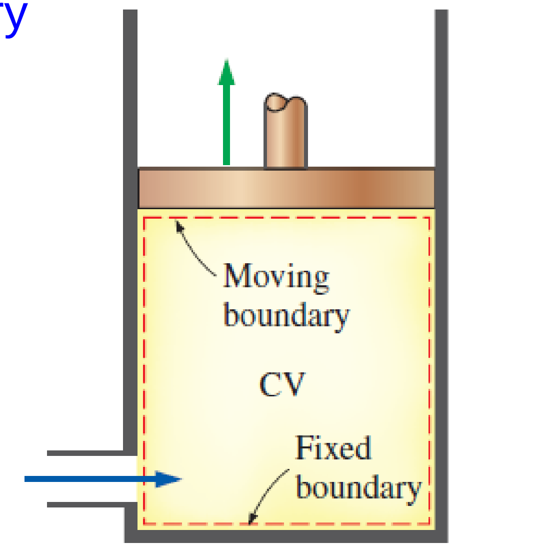
- **Open system (control volume)**: A properly selected region in space.
- It usually encloses a device that involves mass flow such as a compressor, turbine, or nozzle.
- Both mass and energy can cross the boundary of a control volume.
- **Control surface**: The boundaries of a control volume. It can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

FIGURE 1–22
An open system (a control volume) with one inlet and one exit.

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



(*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.

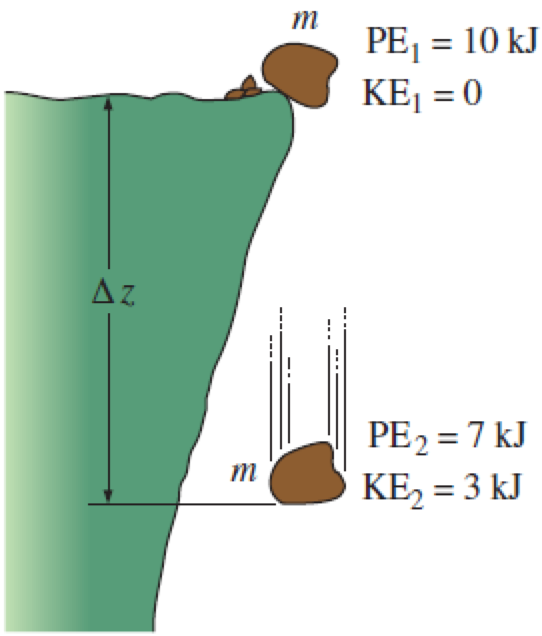


FIGURE 2–39
Energy cannot be created or destroyed; it can only change forms.

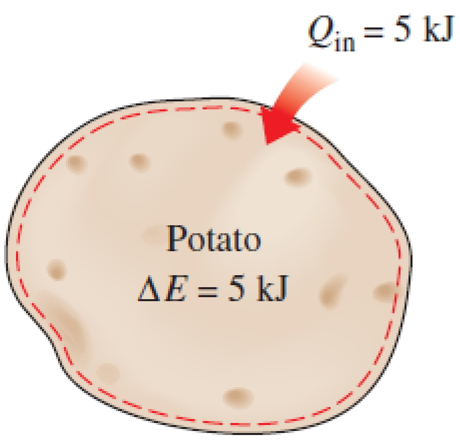


FIGURE 2–40
The increase in the energy of a potato in an oven is equal to the amount of heat transferred to it.

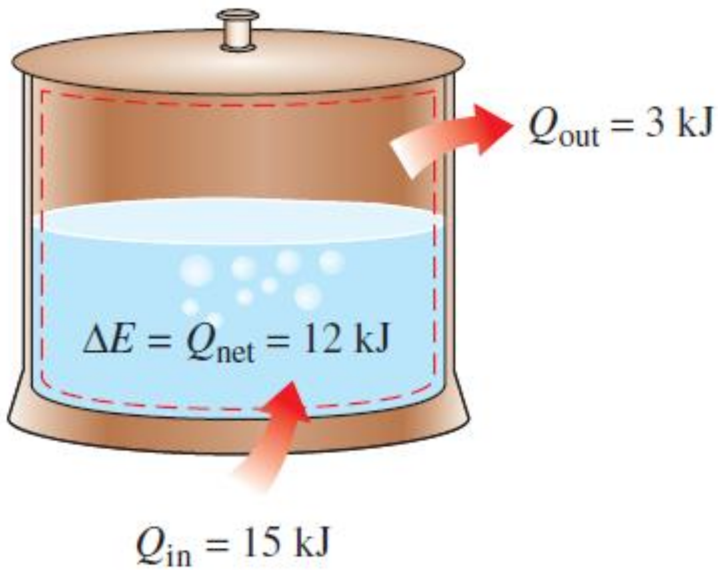


FIGURE 2–41
In the absence of any work interactions, the energy change of a system is equal to the net heat transfer.

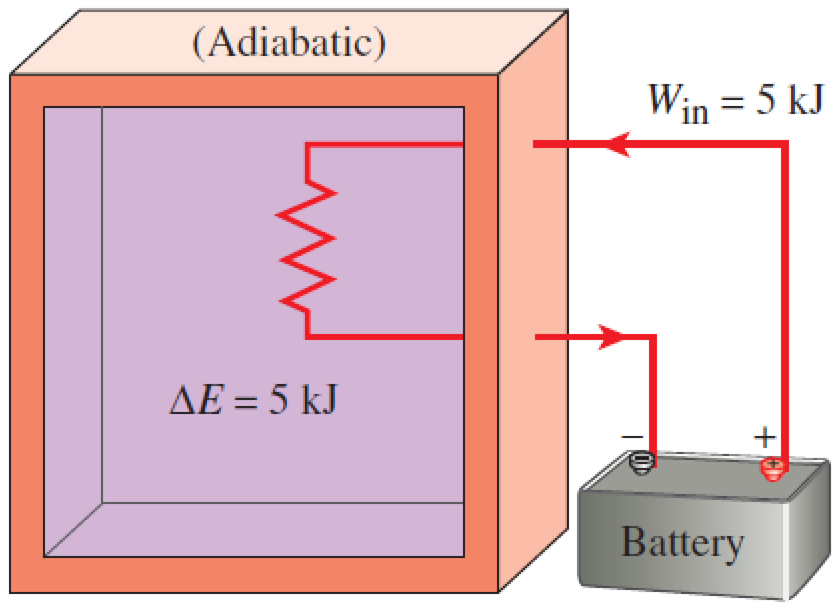


FIGURE 2–42
The work (electrical) done on an adiabatic system is equal to the increase in the energy of the system.

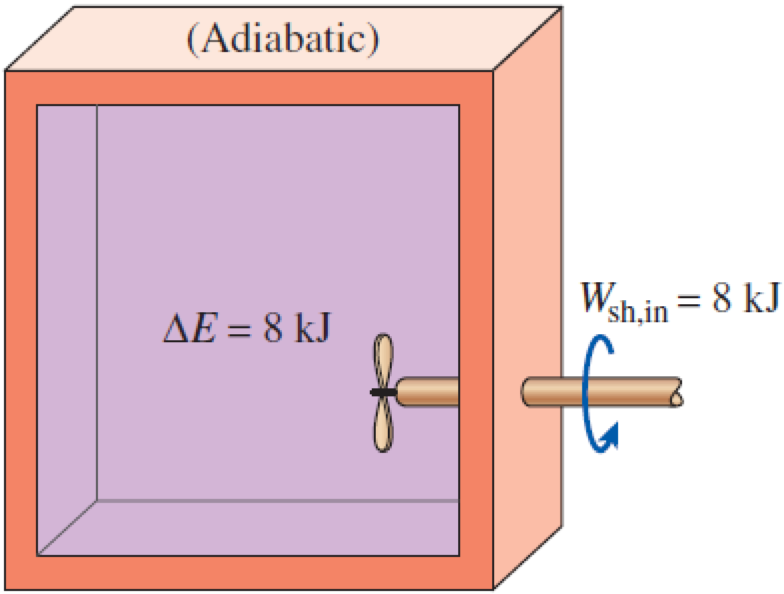


FIGURE 2–43
The work (shaft) done on an adiabatic system is equal to the increase in the energy of the system.

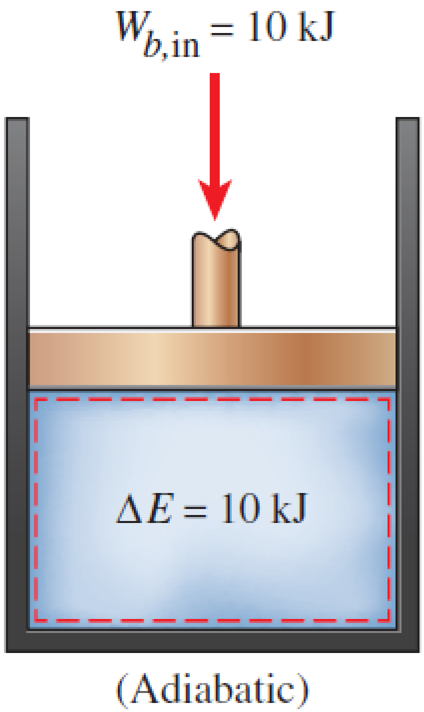


FIGURE 2–44
The work (boundary) done on an adiabatic system is equal to the increase in the energy of the system.

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.

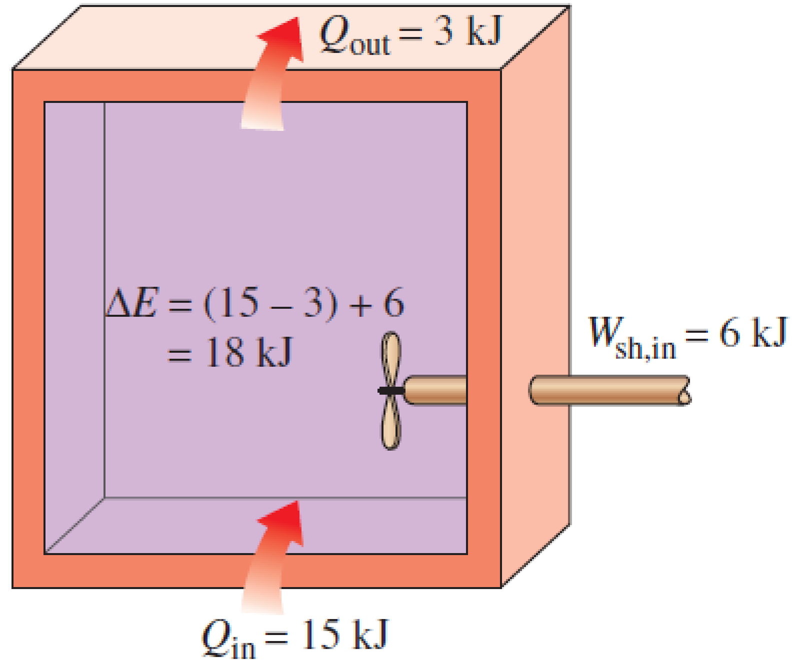


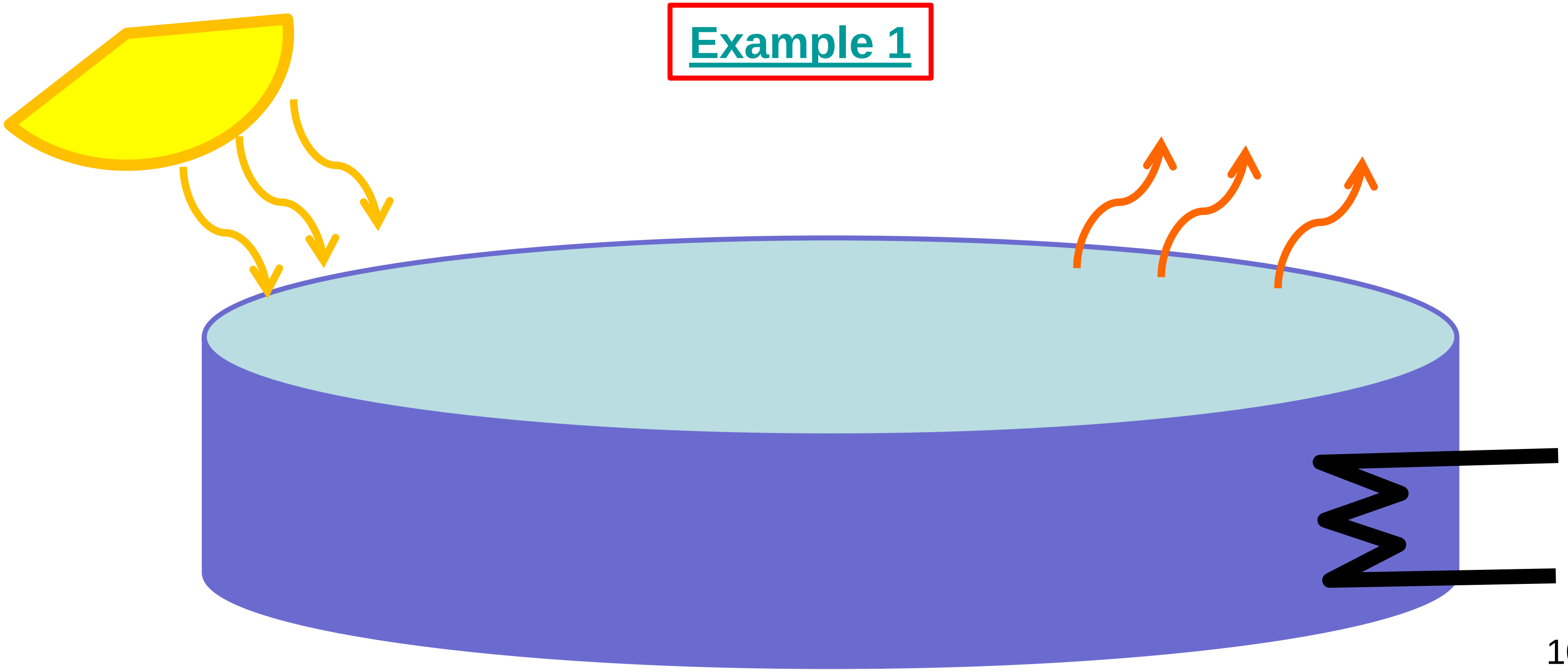
FIGURE 2–45

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

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

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

Internal, kinetic, and potential energy changes

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

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

$$\Delta \text{PE} = mg(z_2 - z_1)$$

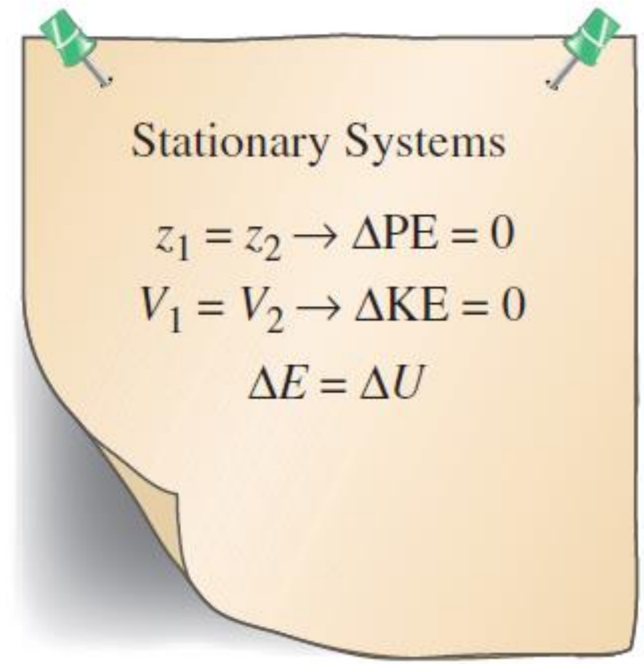


FIGURE 2–46

For stationary systems, $\Delta \text{KE} = \Delta \text{PE} = 0$; 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

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

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

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

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.*

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

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

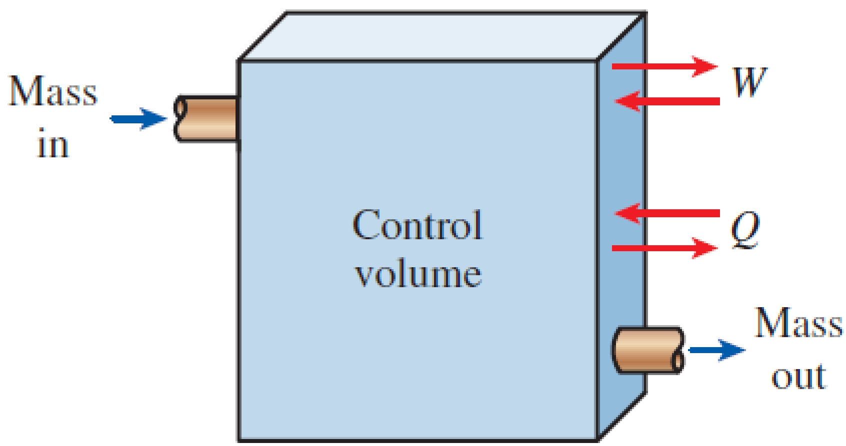


FIGURE 2–47

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

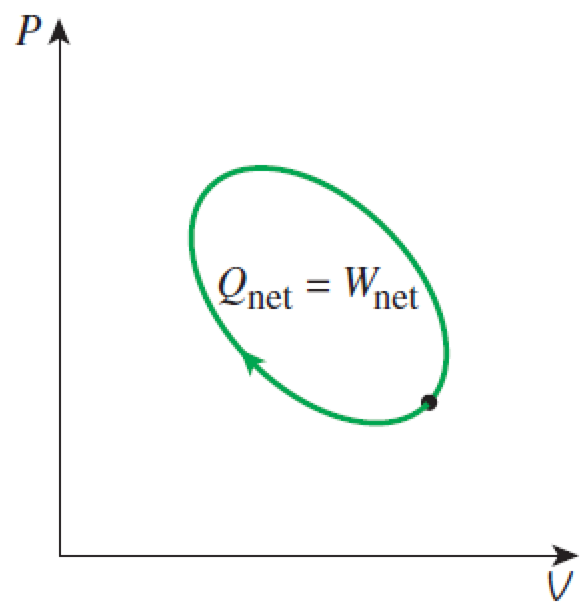


FIGURE 2–48

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

PROCESSES AND CYCLES

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.

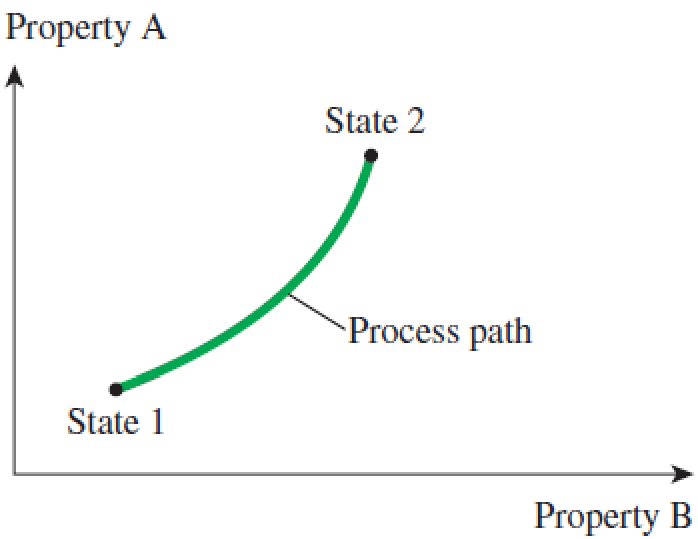


FIGURE 1–29
A process between states 1 and 2 and the process path.

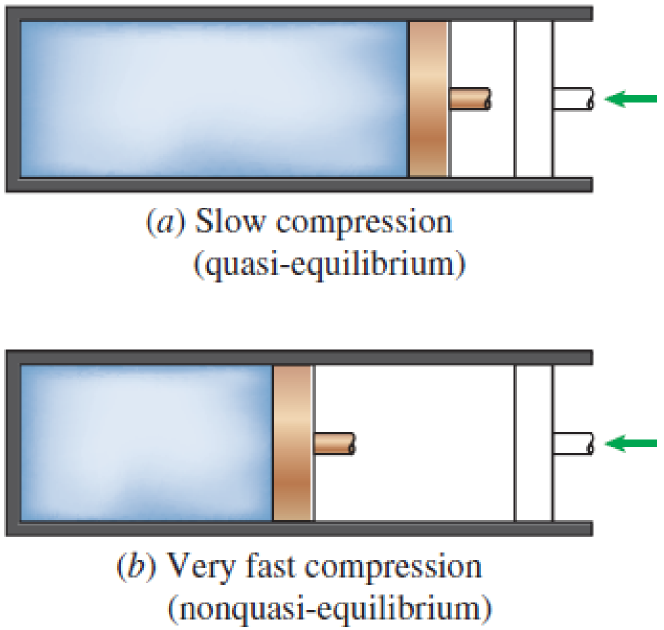


FIGURE 1–30
Quasi-equilibrium and nonquasi-equilibrium compression processes.

- 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.

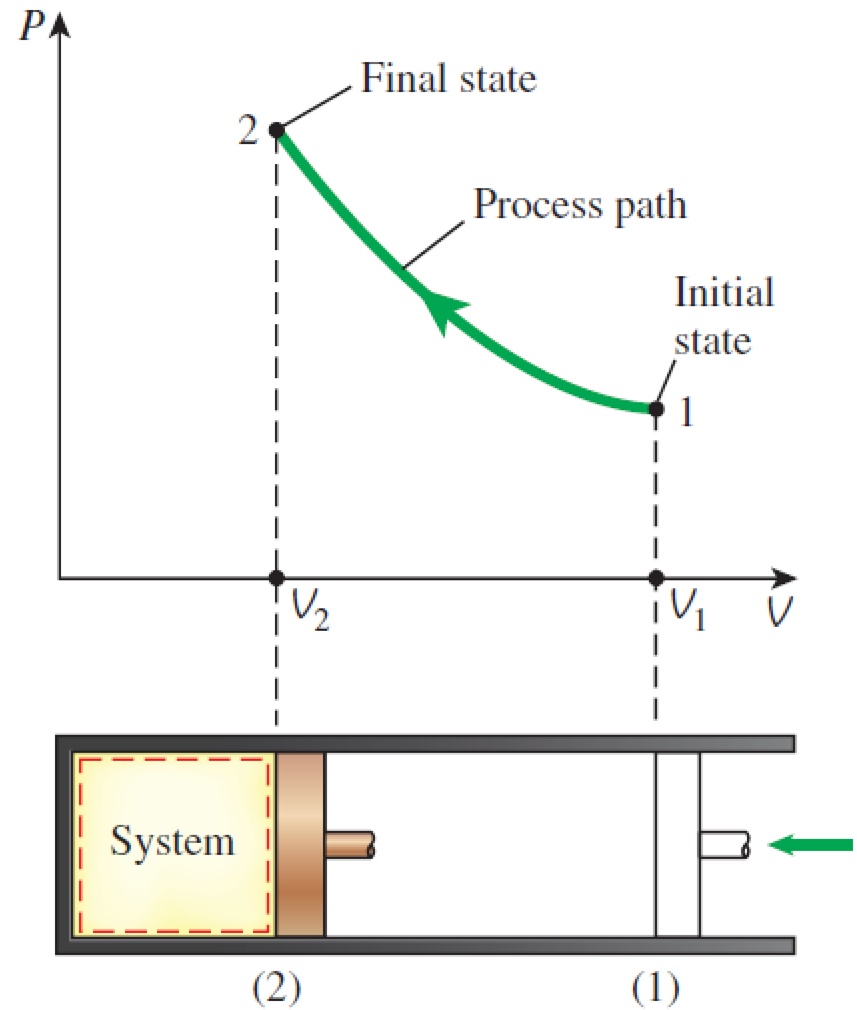


FIGURE 1–31

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

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.

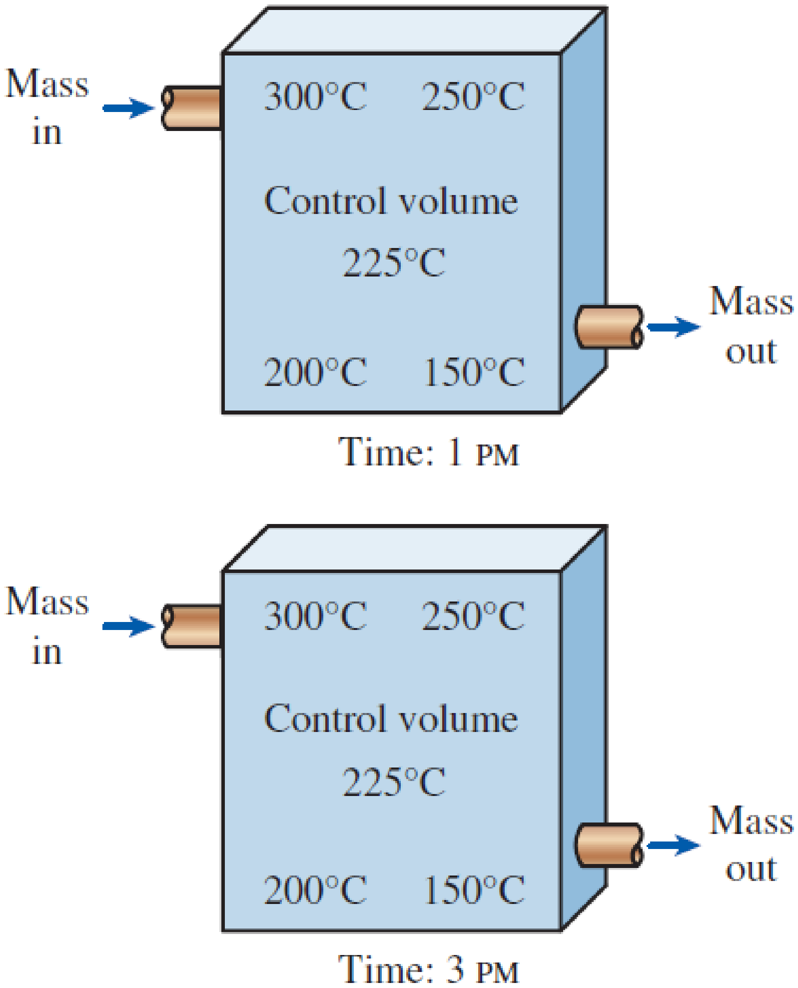


FIGURE 1–32
During a steady-flow process, fluid properties within the control volume may change with position but not with time.

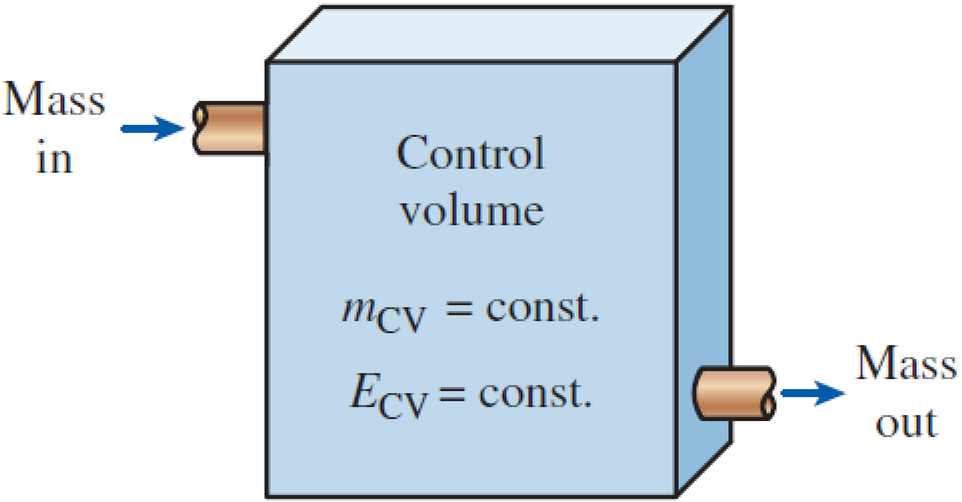


FIGURE 1–33
Under steady-flow conditions, the mass and energy contents of a control volume remain constant.

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.

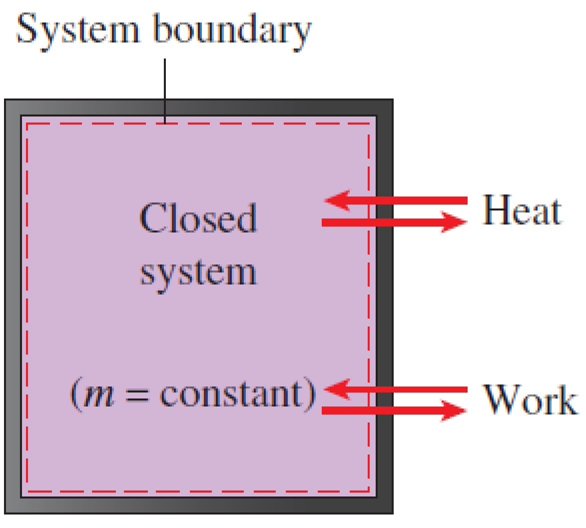


FIGURE 2–14
Energy can cross the boundaries of a closed system in the form of heat and work.

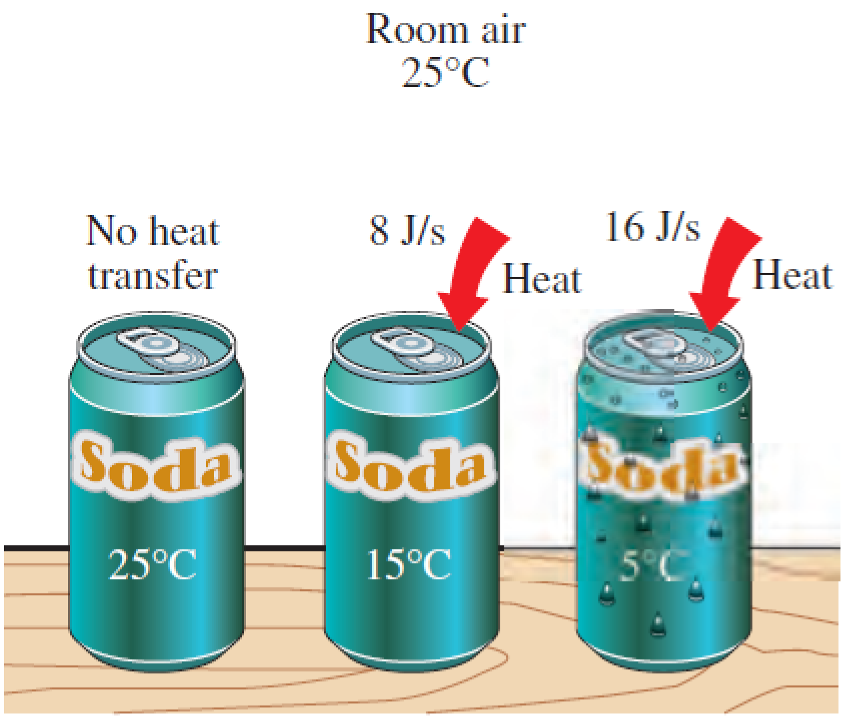


FIGURE 2–15
Temperature difference is the driving force for heat transfer. The larger the temperature difference, the higher is the rate of heat transfer.

$$q = \frac{Q}{m} \qquad (\mathrm{kJ/kg})$$ Heat transfer per unit mass

$$Q = \dot{Q}\,\Delta t \qquad (\mathrm{kJ})$$ Amount of heat transfer when heat transfer rate is constant

$$Q = \int_{t_1}^{t_2} \dot{Q}\,dt \qquad (\mathrm{kJ})$$ Amount of heat transfer when heat transfer rate changes with time

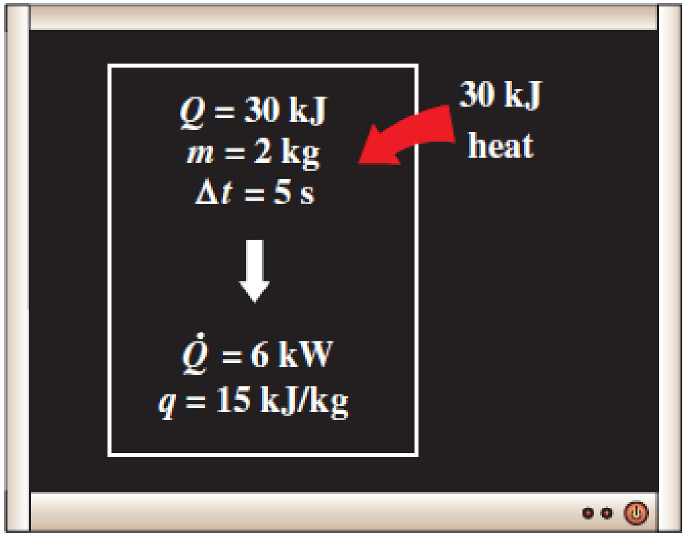


FIGURE 2–18

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

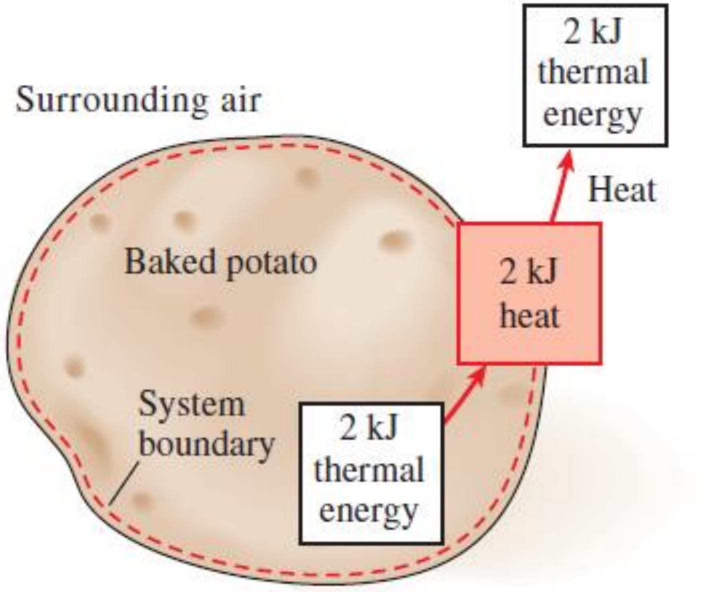


FIGURE 2–16

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

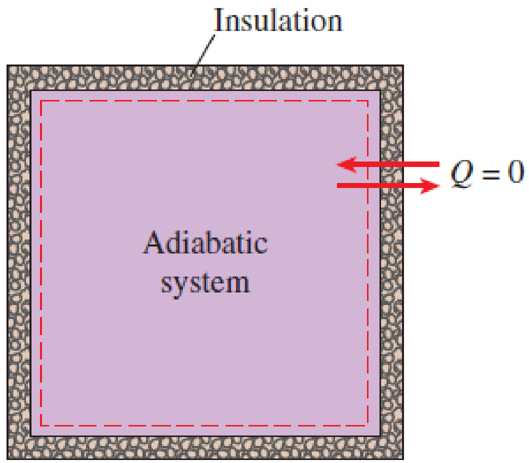


FIGURE 2–17

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).

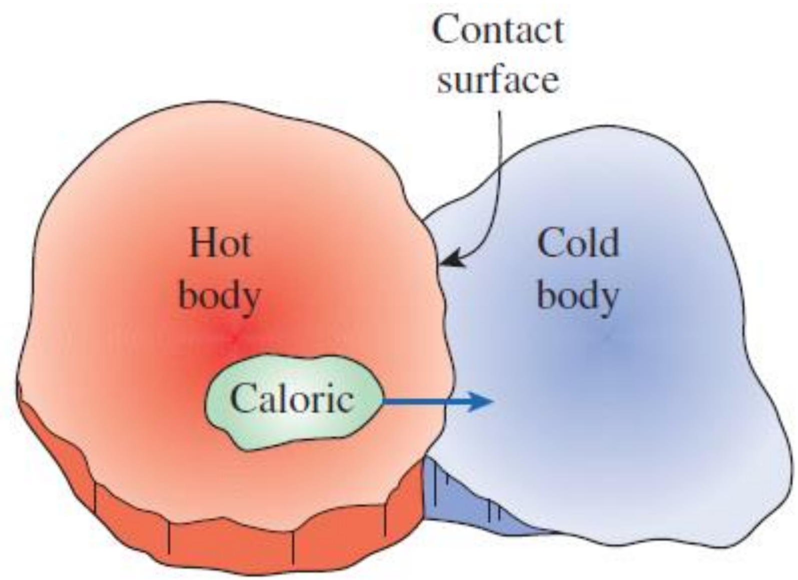


FIGURE 2–19

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

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

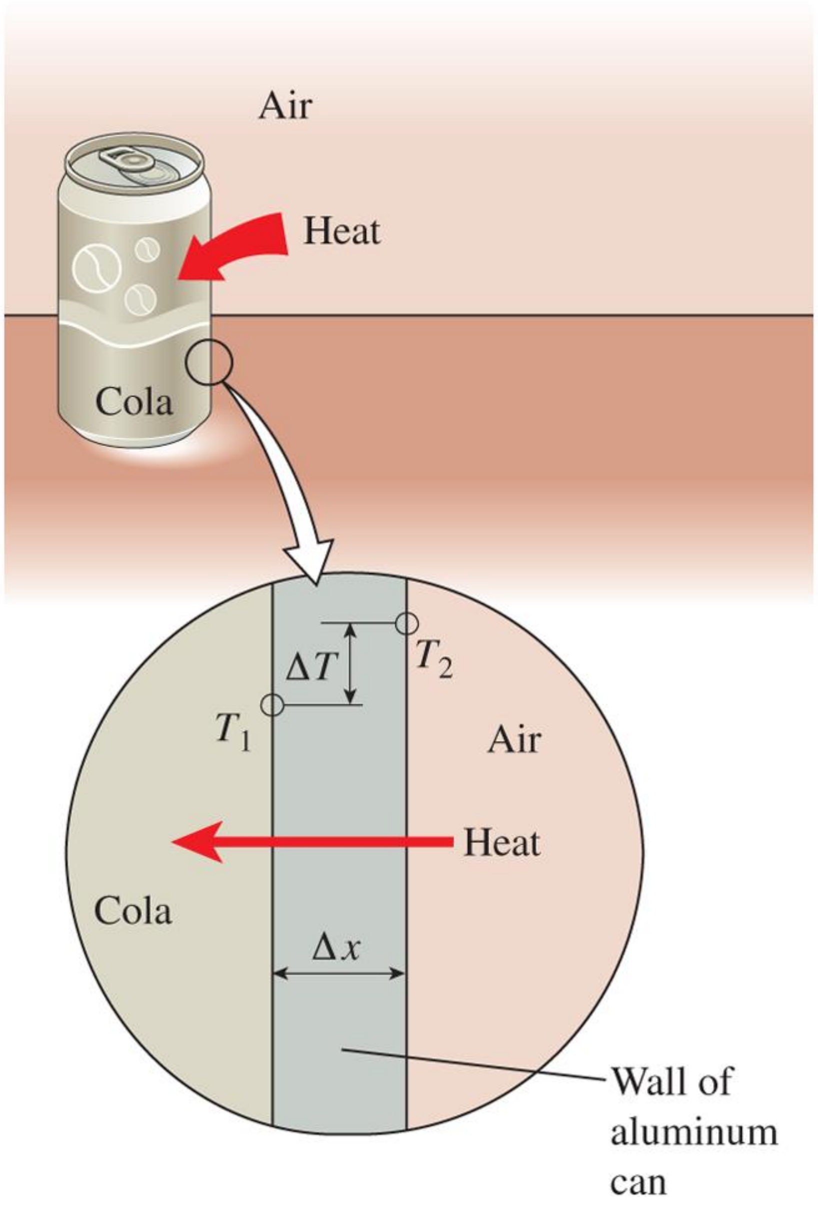
Conduction

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

- 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 $\dot{Q}_{cond} = -k_t A \frac{dT}{dx}$
  - 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?

$$a = 900℃ \qquad b = -300\,\frac{℃}{m} \qquad c = -50\,\frac{℃}{m^2}$$

Example 2

Convection

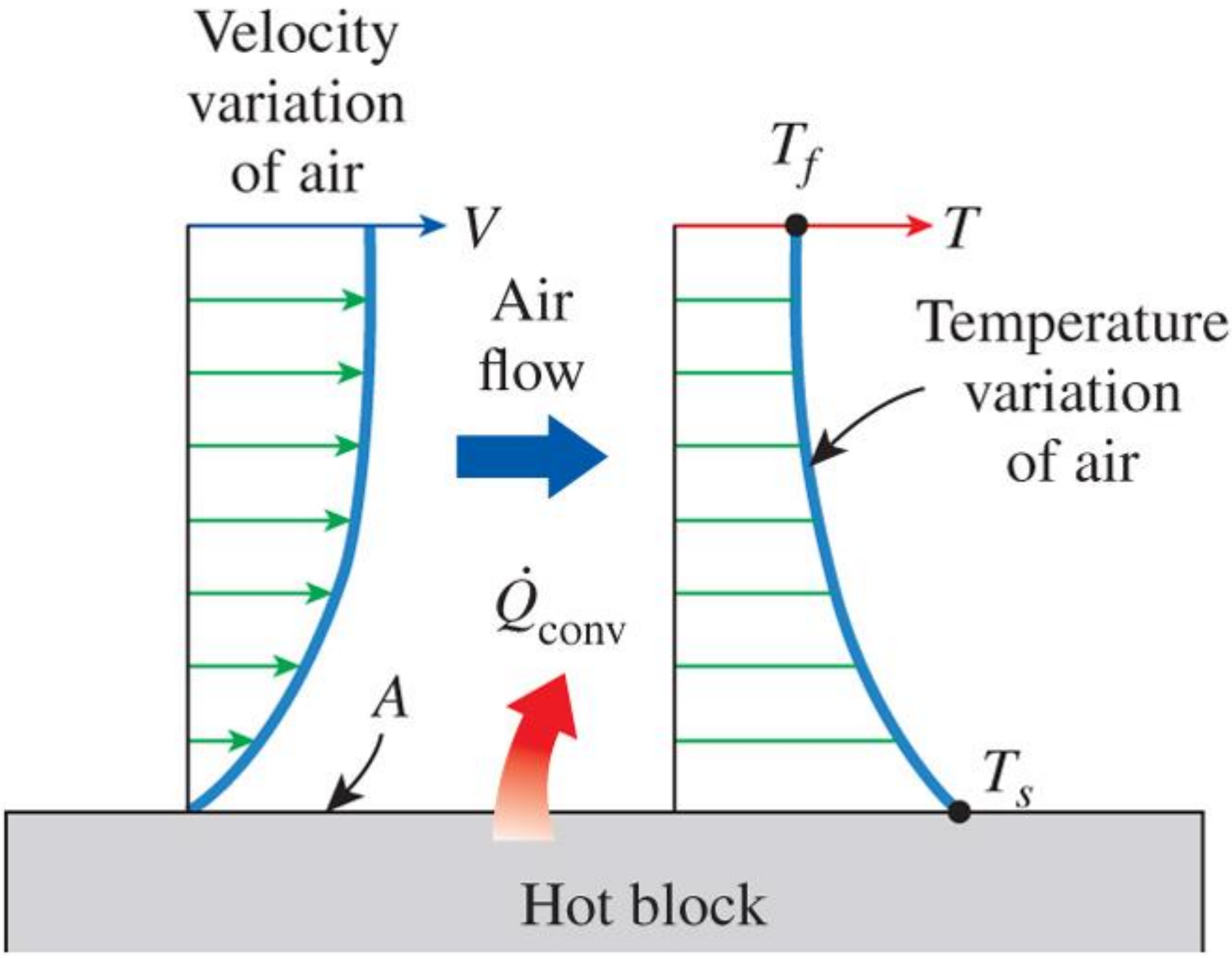
- Transfer of energy to/from a solid surface from/to an adjacent moving fluid (liquid or gas)
- Combination of conduction and fluid motion
- Faster fluid motion results in more heat transfer
- If fluid is motionless then pure conduction occurs
- Forced convection: fluid is *forced* over surface by external 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

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



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

Radiation

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

- 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

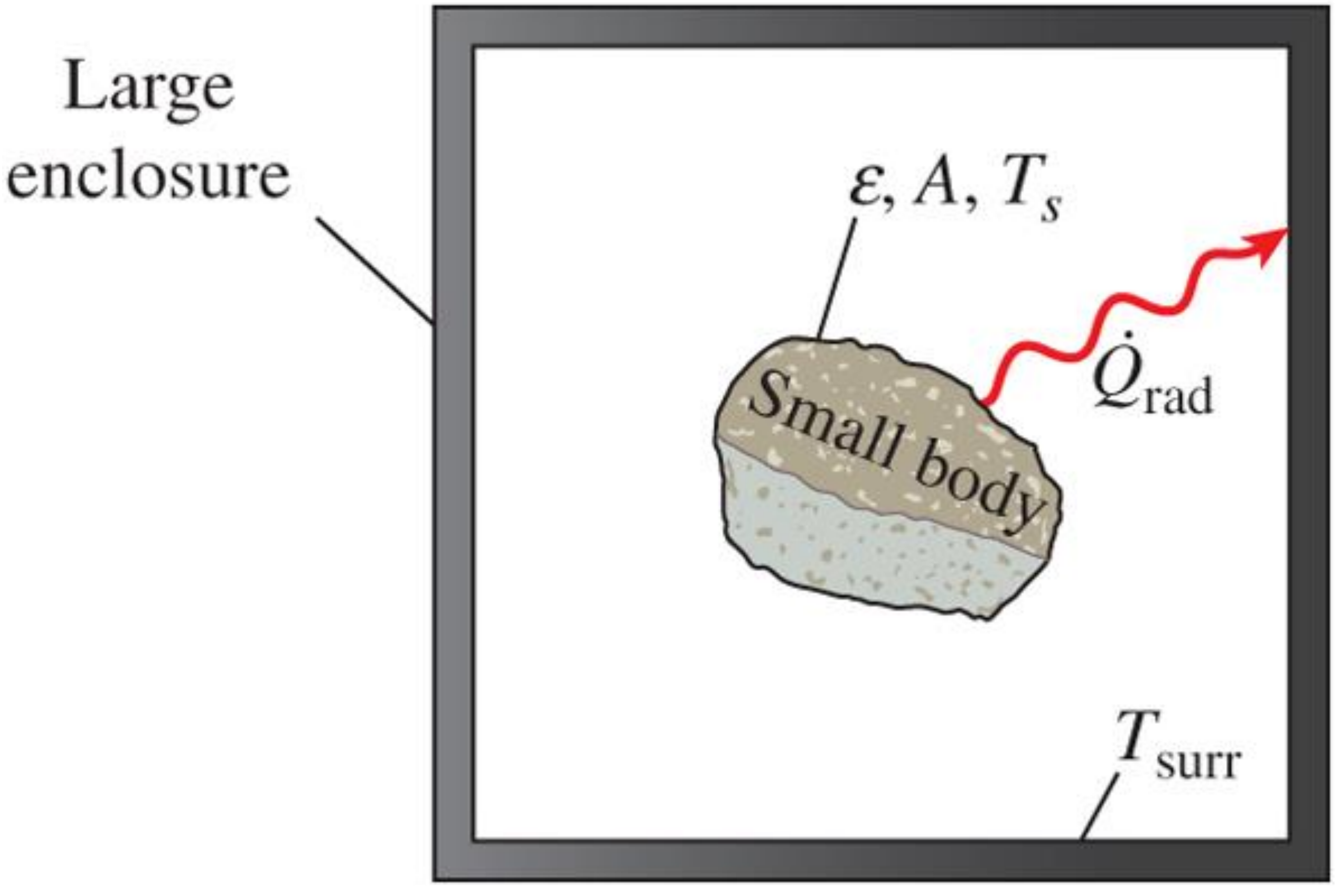
$$\dot{Q}_{emit,max} = \varepsilon \sigma A T_s^4$$

- 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

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



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.

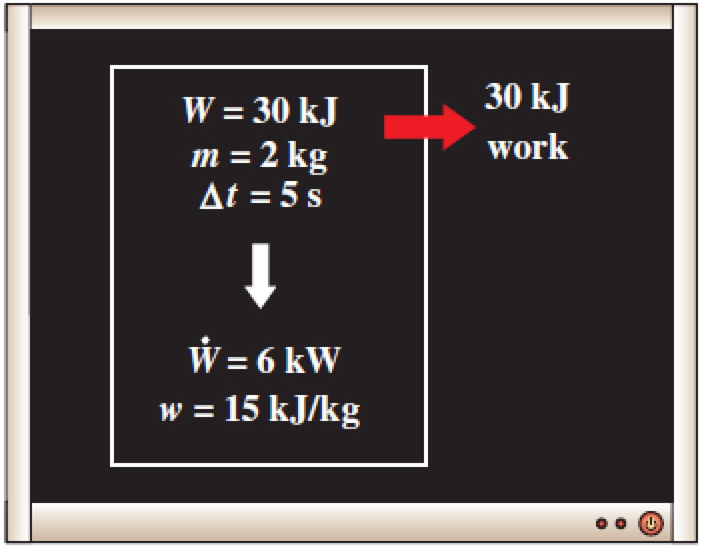


FIGURE 2–20
The relationships among w, W, and $\dot{W}$.

Work done per unit mass

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

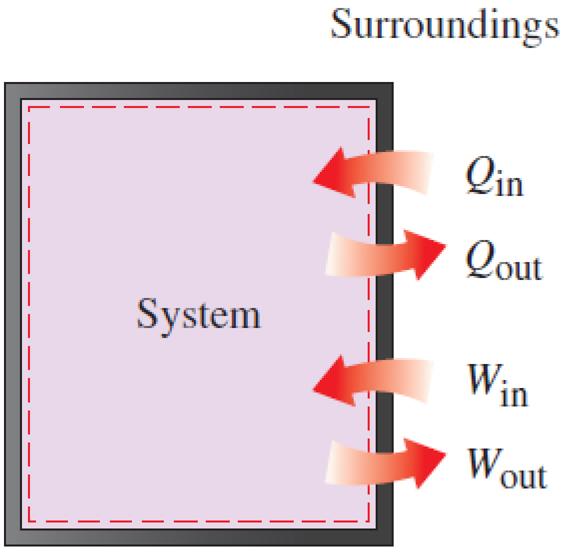


FIGURE 2–21
Specifying the directions of heat and work.

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).

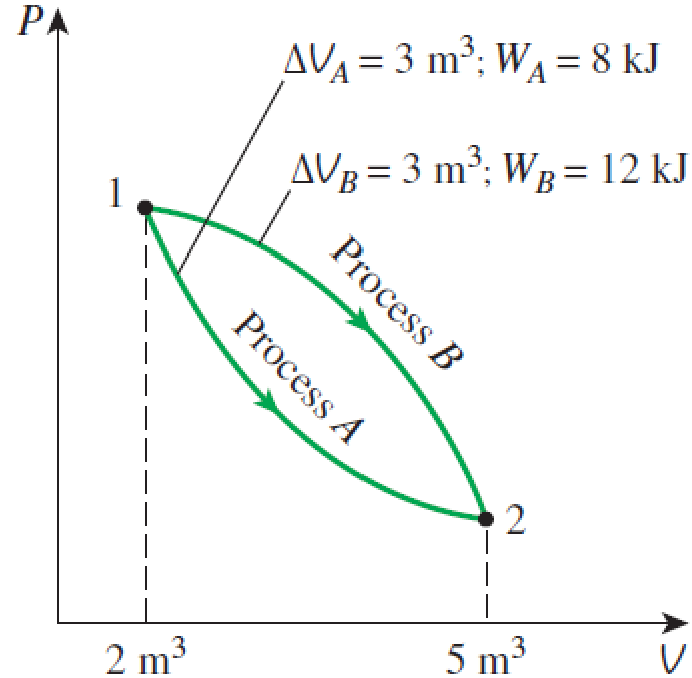


FIGURE 2–22
Properties are point functions; but heat and work are path functions (their magnitudes depend on the path followed).

Properties are point functions have exact differentials (d).

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

Path functions have inexact differentials (δ)

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

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

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

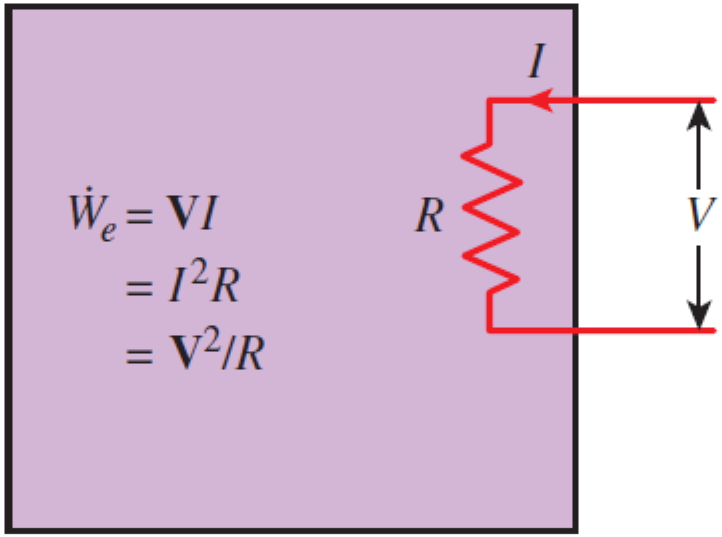


FIGURE 2–27
Electrical power in terms of resistance R, current I, and potential difference $\mathbf{V}$.

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

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

When force is not constant

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

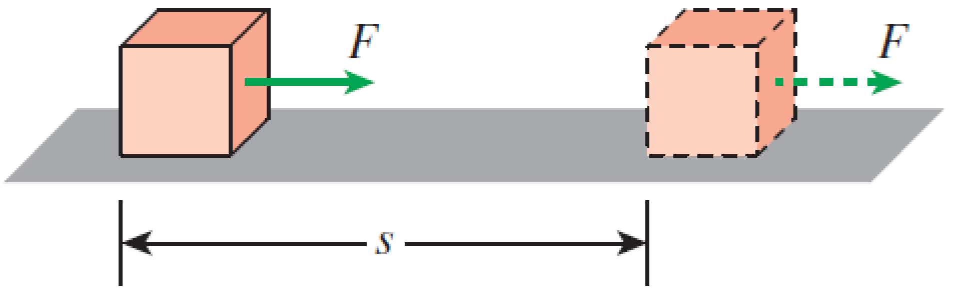


FIGURE 2–28
The work done is proportional to the force applied (F) and the distance traveled (s).

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

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

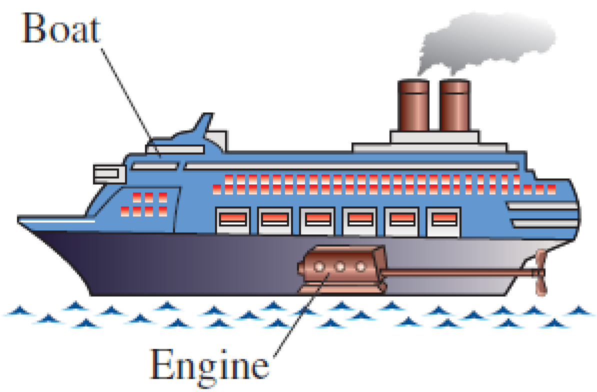


FIGURE 2–29
Energy transmission through rotating shafts is commonly encountered in practice.

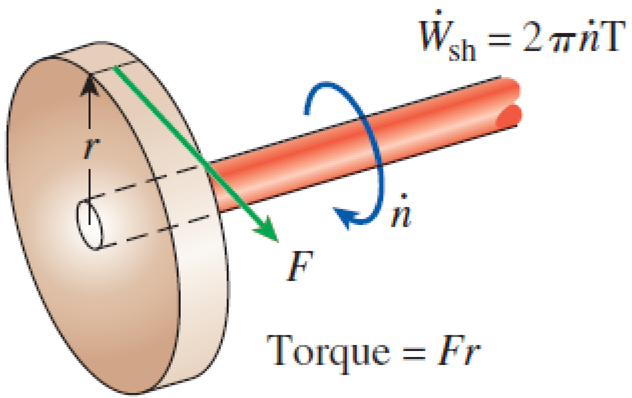


FIGURE 2–30
Shaft work is proportional to the torque applied and the number of revolutions of the shaft.

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

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

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

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

k: spring constant (kN/m)

Substituting and integrating yield

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

x_1 and x_2: the initial and the final displacements

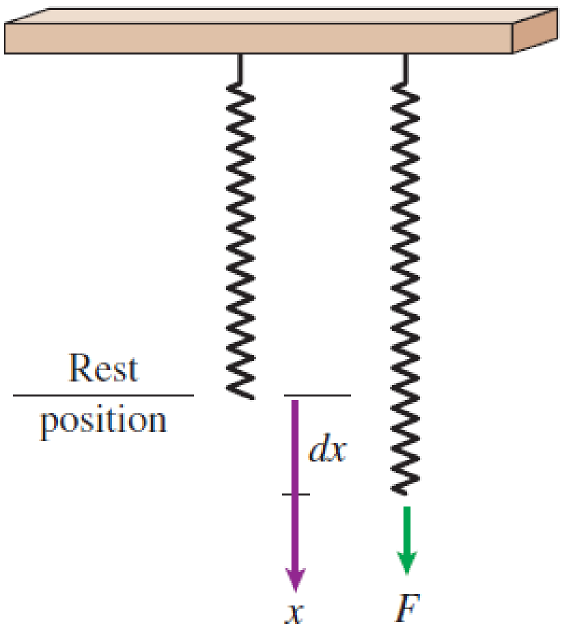


FIGURE 2–32
Elongation of a spring under the influence of a force.

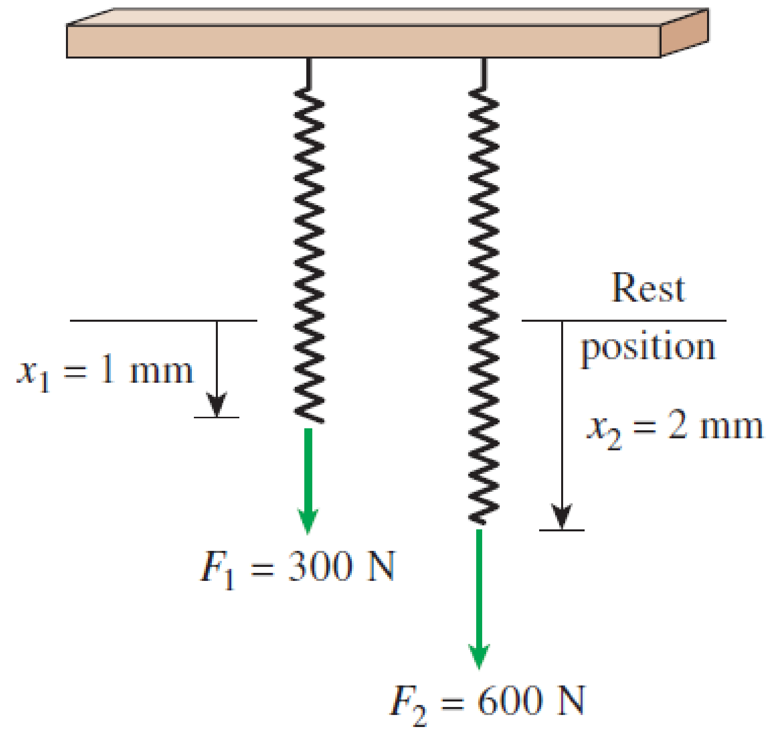


FIGURE 2–33
The displacement of a linear spring doubles when the force is doubled.

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

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

Work Done on Elastic Solid Bars

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

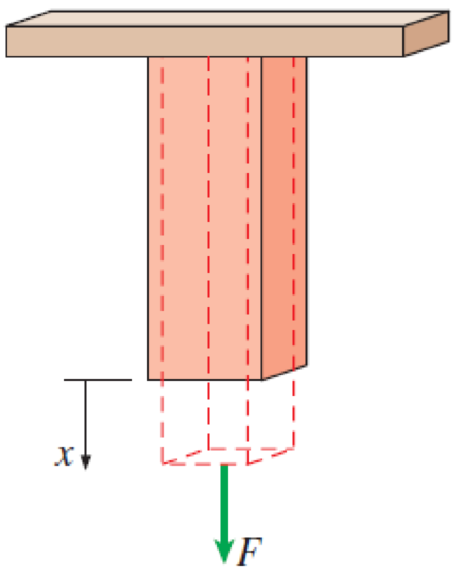


FIGURE 2–34
Solid bars behave as springs under the influence of a force.

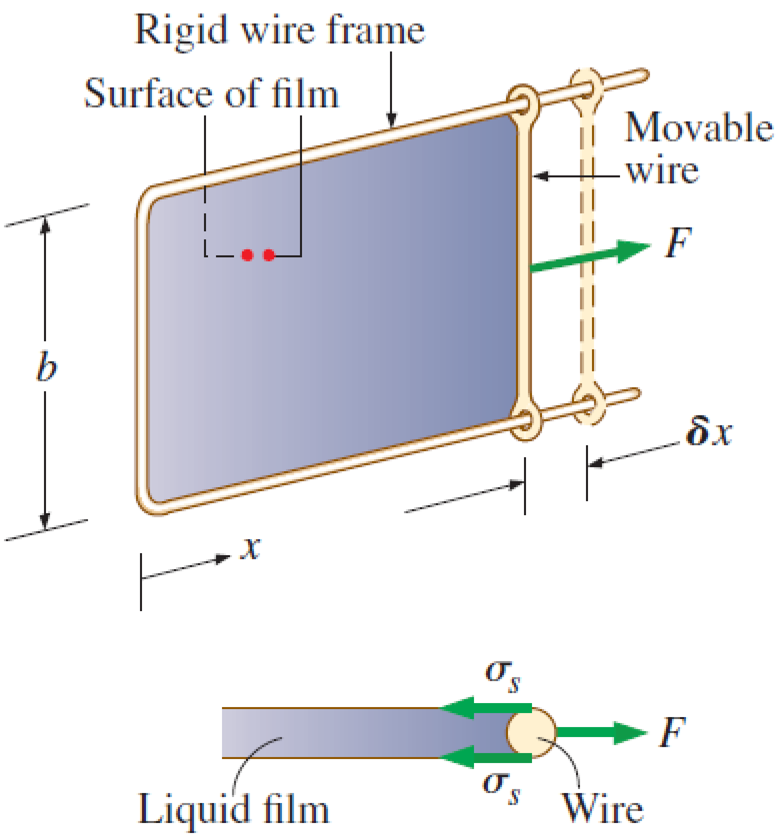


FIGURE 2–35
Stretching a liquid film with a U-shaped wire, and the forces acting on the movable wire of length b.

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.*

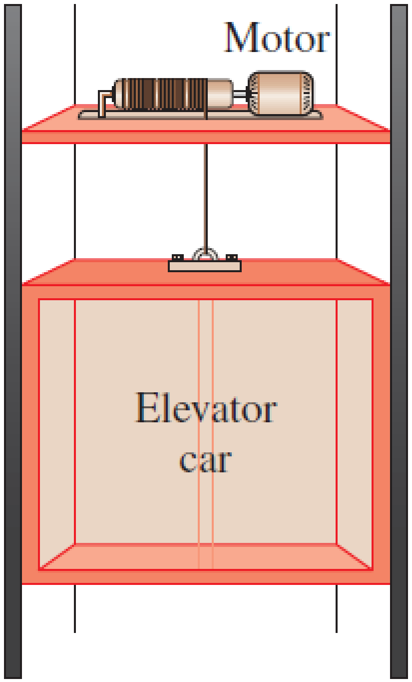


FIGURE 2–36
The energy transferred to a body while being raised is equal to the change in its potential energy.

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)