3. How is it possible for the temperature of air trapped in a balloon to increase? To decrease?

4. Why is it incorrect to say that a system *contains* heat?

5. What examples of heat transfer by conduction, radiation, and convection do you encounter when using a charcoal grill?

6. After running 5 miles on a treadmill at her campus rec center, Ashley observes that the treadmill belt is warm to the touch. Why is the belt warm?

7. When microwaves are beamed onto a tumor during cancer therapy to increase the tumor's temperature, this interaction is considered work and not heat transfer. Why?

8. For good acceleration, what is more important for an automobile engine, horsepower or torque?

9. Experimental molecular motors are reported to exhibit movement upon the absorption of light, thereby achieving a conversion of electromagnetic radiation into motion. Should the incident light be considered work or heat transfer?

10. Referring to Fig. 2.8, which process, A or B, has the greater heat transfer?

11. In the *differential* form of the closed system energy balance, $dE = \delta Q - \delta W$, why is d and not δ used for the differential on the left?

12. When two amusement park bumper cars collide head-on and come to a stop, how do you account for the kinetic energy the pair had just before the collision?

13. What form does the energy balance take for an *isolated* system?

14. What forms of energy and energy transfer are present in the life cycle of a thunderstorm?

15. How would you define an *efficiency* for the motor of Example 2.6?

16. How much kinetic energy per unit of mass does a human sneeze develop?

17. How many tons of CO_2 are produced annually by a conventional automobile?

▶ PROBLEMS: DEVELOPING ENGINEERING SKILLS

Exploring Energy Concepts

2.1 A baseball has a mass of 0.3 lb. What is the kinetic energy relative to home plate of a 94 mile per hour fastball, in Btu?

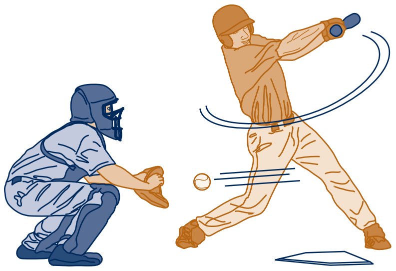


Fig. P2.1

2.2 An object whose mass is 400 kg is located at an elevation of 25 m above the surface of the earth. For $g = 9.78$ m/s^2, determine the gravitational potential energy of the object, in kJ, relative to the surface of the earth.

2.3 An object whose weight is 100 lbf experiences a decrease in kinetic energy of 500 ft · lbf and an increase in potential energy of 1500 ft · lbf. The initial velocity and elevation of the object, each relative to the surface of the earth, are 40 ft/s and 30 ft, respectively. If $g = 32.2$ ft/s^2, determine

(a) the final velocity, in ft/s.
(b) the final elevation, in ft.

2.4 A 2.5 × 3.5 × 6 in. brick whose density is 120 lb/ft^3 slips off the top of a building under construction and falls 69 ft. For $g = 32.0$ ft/s^2, determine the change in gravitational potential energy of the brick, in ft · lbf.

2.5 What is the overall change in potential energy, in ft · lbf and Btu, of an automobile weighing 2500 lbf in a drive from San Diego, CA to Santa Fe, NM? Take g constant.

2.6 An object of mass 1000 kg, initially having a velocity of 100 m/s, decelerates to a final velocity of 20 m/s. What is the change in kinetic energy of the object, in kJ?

2.7 A 30-seat turboprop airliner whose mass is 14,000 kg takes off from an airport and eventually achieves its cruising speed of 620 km/h at an altitude of 10,000 m. For $g = 9.78$ m/s^2, determine the change in kinetic energy and the change in gravitational potential energy of the airliner, each in kJ.

2.8 An automobile having a mass of 900 kg initially moves along a level highway at 100 km/h relative to the highway. It then climbs a hill whose crest is 50 m above the level highway and parks at a rest area located there. For the automobile, determine its changes in kinetic and potential energy, each in kJ. For each quantity, kinetic energy and potential energy, specify your choice of datum and reference value at that datum. Let $g = 9.81$ m/s^2.

2.9 Vehicle crumple zones are designed to absorb energy during an impact by deforming to reduce transfer of energy to occupants. How much kinetic energy, in Btu, must a crumple zone absorb to fully protect occupants in a 3000-lb vehicle that suddenly decelerates from 10 mph to 0 mph?

2.10 An object whose mass is 300 lb experiences changes in its kinetic and potential energies owing to the action of a resultant force **R**. The work done on the object by the resultant force is 140 Btu. There are no other interactions between the object and its surroundings. If the object's elevation increases by 100 ft and its final velocity is 200 ft/s, what is its initial velocity, in ft/s? Let $g = 32.2$ ft/s^2.

2.11 A disk-shaped flywheel, of uniform density ρ, outer radius R, and thickness w, rotates with an angular velocity ω, in rad/s.

(a) Show that the moment of inertia, $I = \int_{\text{vol}} \rho r^2 dV$, can be expressed as $I = \pi \rho w R^4/2$ and the kinetic energy can be expressed as $\text{KE} = I\omega^2/2$.
(b) For a steel flywheel rotating at 3000 RPM, determine the kinetic energy, in $\text{N} \cdot \text{m}$, and the mass, in kg, if $R = 0.38$ m and $w = 0.025$ m.
(c) Determine the radius, in m, and the mass, in kg, of an aluminum flywheel having the same width, angular velocity, and kinetic energy as in part (b).

2.12 Using $\text{KE} = I\omega^2/2$ from Problem 2.11a, how fast would a flywheel whose moment of inertia is $200 \text{ lb} \cdot \text{ft}^2$ have to spin, in RPM, to store an amount of kinetic energy equivalent to the potential energy of a 100 lb mass raised to an elevation of 30 ft above the surface of the earth? Let $g = 32.2 \text{ ft/s}^2$.

2.13 Two objects having different masses fall freely under the influence of gravity from rest and the same initial elevation. Ignoring the effect of air resistance, show that the magnitudes of the velocities of the objects are equal at the moment just before they strike the earth.

2.14 An object whose mass is 50 lb is projected upward from the surface of the earth with an initial velocity of 200 ft/s. The only force acting on the object is the force of gravity. Plot the velocity of the object versus elevation. Determine the elevation of the object, in ft, when its velocity reaches zero. The acceleration of gravity is $g = 31.5 \text{ ft/s}^2$.

2.15 During the packaging process, a can of soda of mass 0.4 kg moves down a surface inclined 20° relative to the horizontal, as shown in Fig. P2.15. The can is acted upon by a constant force **R** parallel to the incline and by the force of gravity. The magnitude of the constant force **R** is 0.05 N. Ignoring friction between the can and the inclined surface, determine the can's change in kinetic energy, in J, and whether it is *increasing* or *decreasing*. If friction between the can and the inclined surface were significant, what effect would that have on the value of the change in kinetic energy? Let $g = 9.8 \text{ m/s}^2$.

2.16 Beginning from rest, an object of mass 200 kg slides down a 10-m-long ramp. The ramp is inclined at an angle of 40° from the horizontal. If air resistance and friction between the object and the ramp are negligible, determine the velocity of the object, in m/s, at the bottom of the ramp. Let $g = 9.81 \text{ m/s}^2$.

2.17 Jack, who weighs 150 lbf, runs 5 miles in 43 minutes on a treadmill set at a one-degree incline. The treadmill display shows he has *burned* 620 kcal. For Jack to break even calorie-wise, how much vanilla ice cream, in cups, may he have after his workout?

Fig. P2.17

Evaluating Work

2.18 A system with a mass of 8 kg, initially moving horizontally with a velocity of 30 m/s, experiences a constant horizontal deceleration of 3 m/s^2 due to the action of a resultant force. As a result, the system comes to rest. Determine the magnitude of the resultant force, in N, the amount of energy transfer by work, in kJ, and the total distance, in m, that the system travels.

2.19 An object initially at rest experiences a constant horizontal acceleration due to the action of a resultant force applied for 10 s. The work of the resultant force is 10 Btu. The mass of the object is 55 lb. Determine the constant horizontal acceleration in ft/s^2.

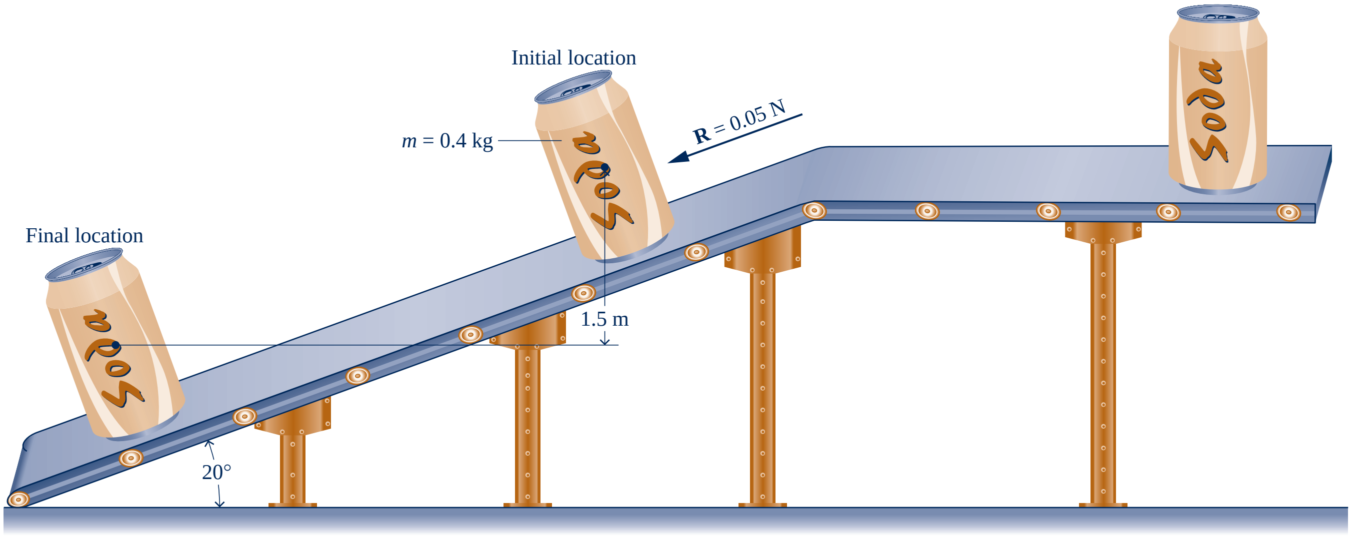


Fig. P2.15

2.20 The drag force, F_d, imposed by the surrounding air on a vehicle moving with velocity V is given by

$$F_d = C_d A \tfrac{1}{2} \rho V^2$$

where C_d is a constant called the drag coefficient, A is the projected frontal area of the vehicle, and ρ is the air density. Determine the power, in hp, required to overcome aerodynamic drag for an automobile moving at (a) 25 miles per hour, (b) 70 miles per hour. Assume $C_d = 0.28$, $A = 25$ ft^2, and $\rho = 0.075$ lb/ft^2.

2.21 A major force opposing the motion of a vehicle is the rolling resistance of the tires, F_r, given by

$$F_r = f \mathscr{W}$$

where f is a constant called the rolling resistance coefficient and $\mathscr{W}$ is the vehicle weight. Determine the power, in kW, required to overcome rolling resistance for a truck weighing 322.5 kN that is moving at 110 km/h. Let $f = 0.0069$.

2.22 The two major forces opposing the motion of a vehicle moving on a level road are the rolling resistance of the tires, F_r, and the aerodynamic drag force of the air flowing around the vehicle, F_d, given respectively by

$$F_r = f \mathscr{W}, \qquad F_d = C_d A \tfrac{1}{2} \rho V^2$$

where f and C_d are constants known as the rolling resistance coefficient and drag coefficient, respectively, $\mathscr{W}$ and A are the vehicle weight and projected frontal area, respectively, V is the vehicle velocity, and ρ is the air density. For a passenger car with $\mathscr{W} = 3550$ lbf, $A = 23.3$ ft^2, and $C_d = 0.34$, and when $f = 0.02$ and $\rho = 0.08$ lb/ft^3

(a) determine the power required, in hp, to overcome rolling resistance and aerodynamic drag when V is 55 mi/h.
(b) plot versus vehicle velocity ranging from 0 to 75 mi/h (i) the power to overcome rolling resistance, (ii) the power to overcome aerodynamic drag, and (iii) the total power, all in hp.

What implication for vehicle fuel economy can be deduced from the results of part (b)?

2.23 Measured data for pressure versus volume during the compression of a refrigerant within the cylinder of a refrigeration compressor are given in the table below. Using data from the table, complete the following:

(a) Determine a value of n such that the data are fit by an equation of the form $pV^n = constant$.
(b) Evaluate analytically the work done on the refrigerant, in Btu, using Eq. 2.17 along with the result of part (a).
(c) Using graphical or numerical integration of the data, evaluate the work done on the refrigerant, in Btu.
(d) Compare the different methods for estimating the work used in parts (b) and (c). Why are they estimates?

Data Point	p (lbf/in.^{2})	V (in.^{3})
1	112	13.0
2	131	11.0
3	157	9.0
4	197	7.0
5	270	5.0
6	424	3.0

2.24 Measured data for pressure versus volume during the expansion of gases within the cylinder of an internal combustion engine are given in the table below. Using data from the table, complete the following:

(a) Determine a value of n such that the data are fit by an equation of the form, $pV^n = constant$.
(b) Evaluate analytically the work done by the gases, in kJ, using Eq. 2.17 along with the result of part (a).
(c) Using graphical or numerical integration of the data, evaluate the work done by the gases, in kJ.
(d) Compare the different methods for estimating the work used in parts (b) and (c). Why are they estimates?

Data Point	p (bar)	V (cm^3)
1	15	300
2	12	361
3	9	459
4	6	644
5	4	903
6	2	1608

2.25 A gas in a piston–cylinder assembly undergoes a process for which the relationship between pressure and volume is $pV^2 = constant$. The initial pressure is 1 bar, the initial volume is 0.1 m^3, and the final pressure is 9 bar. Determine (a) the final volume, in m^3, and (b) the work for the process, in kJ.

2.26 Carbon dioxide (CO_2) gas within a piston–cylinder assembly undergoes an expansion from a state where $p_1 = 20$ lbf/in.^{2}, $V_1 = 0.5$ ft^3 to a state where $p_2 = 5$ lbf/in.^{2}, $V_2 = 2.5$ ft^3. The relationship between pressure and volume during the process is $p = A + BV$, where A and B are constants. (a) For the CO_2, evaluate the work, in ft · lbf and Btu. (b) Evaluate A, in lbf/in.^{2}, and B, in (lbf/in.^{2})/ft^3.

2.27 A gas in a piston–cylinder assembly undergoes a compression process for which the relation between pressure and volume is given by $pV^n = constant$. The initial volume is 0.1 m^3, the final volume is 0.04 m^3, and the final pressure is 2 bar. Determine the initial pressure, in bar, and the work for the process, in kJ, if (a) $n = 0$, (b) $n = 1$, (c) $n = 1.3$.

2.28 Nitrogen (N_2) gas within a piston–cylinder assembly undergoes a compression from $p_1 = 0.2$ MPa, $V_1 = 2.75$ m^3 to a state where $p_2 = 2$ MPa. The relationship between pressure and volume during the process is $pV^{1.35} = constant$. For the N_2, determine (a) the volume at state 2, in m^3, and (b) the work, in kJ.

2.29 Oxygen (O_2) gas within a piston–cylinder assembly undergoes an expansion from a volume $V_1 = 0.01$ m^3 to a volume $V_2 = 0.03$ m^3. The relationship between pressure and volume during the process is $p = AV^{-1} + B$, where $A = 0.06$ bar · m^3 and $B = 3.0$ bar. For the O_2, determine (a) the initial and final pressures, each in bar, and (b) the work, in kJ.

2.30 A closed system consisting of 14.5 lb of air undergoes a *polytropic* process from $p_1 = 80$ lbf/in.^{2}, $v_1 = 4$ ft^3/lb to a final state where $p_2 = 20$ lbf/in.^{2}, $v_2 = 11$ ft^3/lb. Determine the amount of energy transfer by work, in Btu, for the process.

2.31 Air contained within a piston–cylinder assembly is slowly heated. As shown in Fig. P2.31, during this process the pressure first varies linearly with volume and then remains constant. Determine the total work, in kJ.

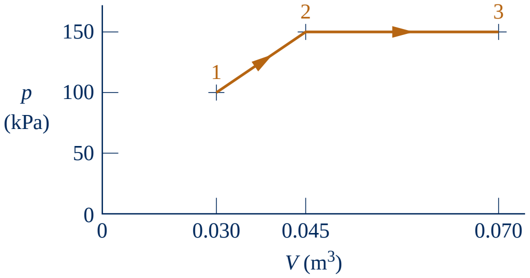


Fig. P2.31

2.32 A gas contained within a piston–cylinder assembly undergoes three processes in series:

Process 1–2: Constant volume from $p_1 = 1$ bar, $V_1 = 4$ m^3 to state 2, where $p_2 = 2$ bar.

Process 2–3: Compression to $V_3 = 2$ m^3, during which the pressure–volume relationship is $pV = constant$.

Process 3–4: Constant pressure to state 4, where $V_4 = 1$ m^3.

Sketch the processes in series on p–V coordinates and evaluate the work for each process, in kJ.

2.33 Carbon monoxide gas (CO) contained within a piston–cylinder assembly undergoes three processes in series:

Process 1–2: Expansion from $p_1 = 5$ bar, $V_1 = 0.2$ m^3 to $V_2 = 1$ m^3, during which the pressure-volume relationship is $pV = constant$.

Process 2–3: Constant-volume heating from state 2 to state 3, where $p_3 = 5$ bar.

Process 3–1: Constant-pressure compression to the initial state.

Sketch the processes in series on p–V coordinates and evaluate the work for each process, in kJ.

2.34 Air contained within a piston–cylinder assembly undergoes three processes in series:

Process 1–2: Compression at constant pressure from $p_1 = 10$ lbf/in.^{2}, $V_1 = 4$ ft^3 to state 2.

Process 2–3: Constant-volume heating to state 3, where $p_3 = 50$ bf/in.^{2}

Process 3–1: Expansion to the initial state, during which the pressure-volume relationship is $pV = constant$.

Sketch the processes in series on p–V coordinates. Evaluate (a) the volume at state 2, in ft^3, and (b) the work for each process, in Btu.

2.35 The belt sander shown in Fig. P2.35 has a belt speed of 1500 ft/min. The coefficient of friction between the sander and a plywood surface being finished is 0.2. If the downward (normal) force on the sander is 15 lbf, determine (a) the power transmitted by the belt, in Btu/s and hp, and (b) the work done in one minute of sanding, in Btu.

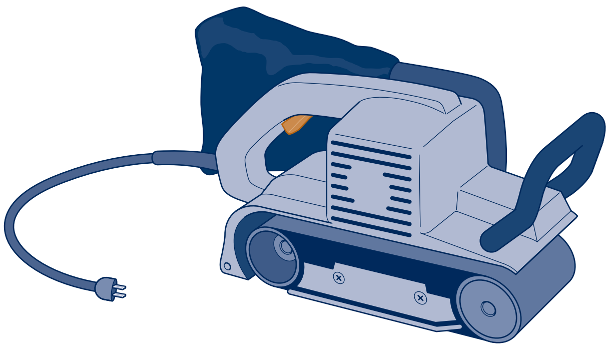


Fig. P2.35

2.36 A 0.15-m-diameter pulley turns a belt rotating the driveshaft of a power plant pump. The torque applied by the belt on the pulley is 200 N · m, and the power transmitted is 7 kW. Determine the net force applied by the belt on the pulley, in kN, and the rotational speed of the driveshaft, in RPM.

2.37 A 10-V battery supplies a constant current of 0.5 amp to a resistance for 30 min. (a) Determine the resistance, in ohms. (b) For the battery, determine the amount of energy transfer by work, in kJ.

2.38 A car magazine article states that the power $\dot{W}$ delivered by an automobile engine, in hp, is calculated by multiplying the torque $\mathcal{T}$, in ft · lbf, by the rotational speed of the driveshaft ω, in RPM, and dividing by a constant:

$$\dot{W} = \frac{\mathcal{T}\omega}{C}$$

What is the value and units of the constant C?

2.39 The pistons of a V-6 automobile engine develop 226 hp. If the engine driveshaft rotational speed is 4700 RPM and the torque is 248 ft · lbf, what percentage of the developed power is transferred to the driveshaft? What accounts for the difference in power? Does an engine this size meet your transportation needs? Comment.

2.40 As shown in Fig. P2.40, a steel wire suspended vertically having a cross-section area A and an initial length x_0 is

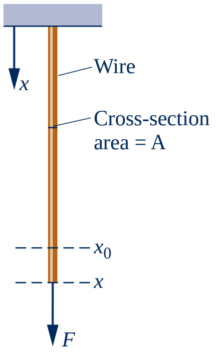


Fig. P2.40

stretched by a downward force F applied to the end of the wire. The normal stress in the wire varies linearly according to $\sigma = C\varepsilon$, where ε is the *strain*, given by $\varepsilon = (x - x_0)/x_0$, and x is the stretched length of the wire. C is a material constant (Young's modulus). Assuming the cross-sectional area remains constant,

(a) obtain an expression for the work done on the wire.
(b) evaluate the work done on the wire, in ft · lbf, and the magnitude of the downward force, in lbf, if $x_0 = 10$ ft, $x = 10.01$ ft, $A = 0.1$ in.^{2}, and $C = 2.5 \times 10^7$ lbf/in.^{2}

2.41 A soap film is suspended on a wire frame, as shown in Fig. 2.10. The movable wire is displaced by an applied force F. If the surface tension remains constant,

(a) obtain an expression for the work done in stretching the film in terms of the surface tension τ, length ℓ, and a finite displacement Δx.
(b) evaluate the work done, in J, if $\ell = 5$ cm, $\Delta x = 0.5$ cm, and $\tau = 25 \times 10^{-5}$ N/cm.

2.42 As shown in Fig. P2.42, a spring having an initial unstretched length of ℓ_0 is stretched by a force F applied at its end. The stretched length is ℓ. By *Hooke's law,* the force is linearly related to the spring extension by $F = k(\ell - \ell_0)$ where k is the *stiffness.* If stiffness is constant,

(a) obtain an expression for the work done in changing the spring's length from ℓ_1 to ℓ_2.
(b) evaluate the work done, in J, if $\ell_0 = 3$ cm, $\ell_1 = 6$ cm, $\ell_2 = 10$ cm, and the stiffness is $k = 10^4$ N/m.

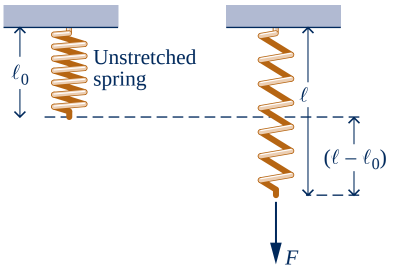


Fig. P2.42

Evaluating Heat Transfer

2.43 A fan forces air over a computer circuit board with surface area of 70 cm^2 to avoid overheating. The air temperature is 300 K while the circuit board surface temperature is 340 K. Using data from Table 2.1, determine the largest and smallest heat transfer rates, in W, that might be encountered for this forced convection.

2.44 As shown in Fig. P2.44, the 6-in.-thick exterior wall of a building has an average thermal conductivity of 0.32 Btu/h · ft · °R. At steady state, the temperature of the wall decreases linearly from $T_1 = 70$°F on the inner surface to T_2 on the outer surface. The outside ambient air temperature is $T_0 = 25$°F and the convective heat transfer coefficient is 5.1 Btu/h · ft^2 · °R. Determine (a) the temperature T_2 in °F, and (b) the rate of heat transfer through the wall, in Btu/h per ft^2 of surface area.

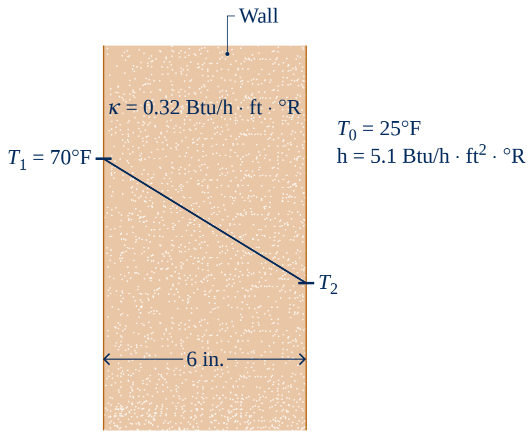


Fig. P2.44

2.45 As shown in Fig. P2.45, an oven wall consists of a 0.25-in.-thick layer of steel ($\kappa_s = 8.7$ Btu/h · ft · °R) and a layer of brick ($\kappa_b = 0.42$ Btu/h · ft · °R). At steady state, a temperature decrease of 1.2°F occurs over the steel layer. The inner temperature of the steel layer is 540°F If the temperature of the outer surface of the brick must be no greater than 105°F determine the minimum thickness of brick, in in., that ensures this limit is met.

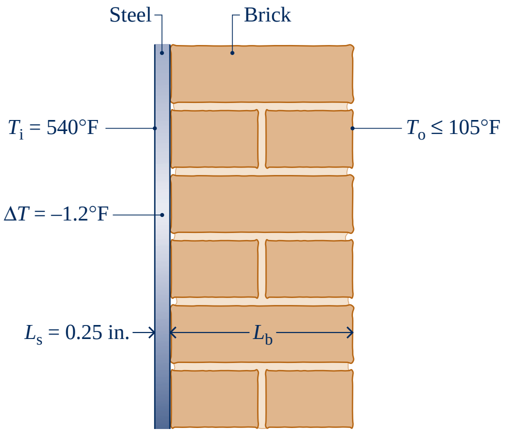


Fig. P2.45

2.46 A composite plane wall consists of a 12-in.-thick layer of insulating concrete block ($\kappa_c = 0.27$ Btu/h · ft · °R) and a 0.625-in.-thick layer of gypsum board ($\kappa_b = 1.11$ Btu/h · ft · °R). The outer surface temperature of the concrete block and gypsum board are 460°R and 560°R, respectively, and there is perfect contact at the interface between the two layers. Determine at steady state the instantaneous rate of heat transfer, in Btu/h per ft^2 of surface area, and the temperature, in °R, at the interface between the concrete block and gypsum board.

2.47 A composite plane wall consists of a 75-mm-thick layer of insulation ($\kappa_i = 0.05$ W/m · K) and a 25-mm-thick layer of siding ($\kappa = 0.10$ W/m · K). The inner temperature of the insulation is 20°C. The outer temperature of the siding is −13°C. Determine at steady state (a) the temperature at the interface of the two layers, in °C, and (b) the rate of heat transfer through the wall, in W per m^2 of surface area.

2.48 An insulated frame wall of a house has an average thermal conductivity of 0.04 Btu/h · ft · °R. The thickness of the wall is 6 in. The inside air temperature is 70°F, and the heat transfer coefficient for convection between the inside air and the wall is 2 Btu/h · ft^2 · °R. On the outside, the ambient air temperature is 32°F and the heat transfer coefficient for convection between the wall and the outside air is 5 Btu/h · ft^2 · °R. Determine at steady state the rate of heat transfer through the wall, in Btu/h per ft^2 of surface area.

2.49 Complete the following exercise using heat transfer relations:

(a) Referring to Fig. 2.13, determine the net rate of radiant exchange, in W, for $\varepsilon = 0.8$, $A = 0.125\ m^2$, $T_b = 475$ K, $T_s = 298$ K.
(b) Referring to Fig. 2.14, determine the rate of convection heat transfer from the surface to the air, in W, for $h = 10\ W/m^2 \cdot K$, $A = 0.125\ m^2$, $T_b = 305$ K, $T_f = 298$ K.

2.50 At steady state, a spherical interplanetary electronics-laden probe having a diameter of 0.5 m transfers energy by radiation from its outer surface at a rate of 150 W. If the probe does not receive radiation from the sun or deep space, what is the surface temperature, in K? Let $\varepsilon = 0.8$.

2.51 A body whose surface area is 0.5 m^2, emissivity is 0.8, and temperature is 150°C is placed in a large, evacuated chamber whose walls are at 25°C. What is the rate at which radiation is *emitted* by the surface, in W? What is the *net* rate at which radiation is *exchanged* between the surface and the chamber walls, in W?

2.52 The outer surface of the grill hood shown in Fig. P2.52 is at 47°C and the emissivity is 0.93. The heat transfer coefficient for convection between the hood and the surroundings at 27°C is 10 W/m^2 · K. Determine the net rate of heat transfer between the grill hood and the surroundings by convection and radiation, in kW per m^2 of surface area.

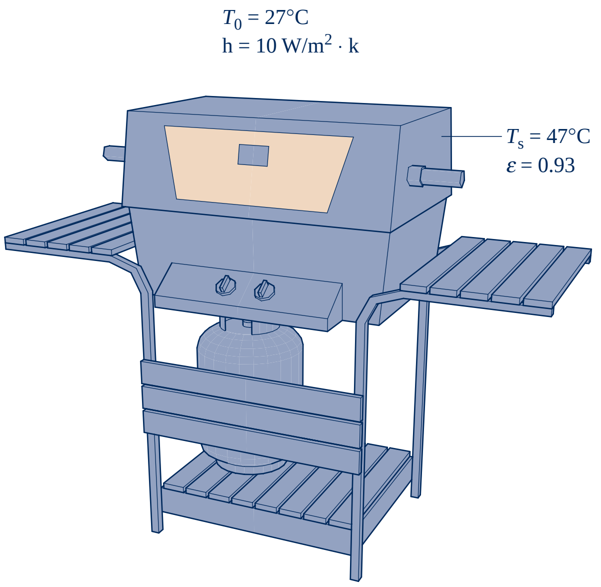


Fig. P2.52

Using the Energy Balance

2.53 Each line of the following table gives data for a process of a closed system. Each entry has the same energy units. Determine the missing entries.

Process	Q	W	E_1	E_2	ΔE
a		−20		+50	+70
b	+50		+20	+50	
c		−60		+60	+20
d		−90		+50	0
e	+50	+150	+20		

2.54 Each line of the following table gives data, in Btu, for a process of a closed system. Determine the missing table entries, in Btu.

Process	Q	W	E_1	E_2	ΔE
a	+40		+15		+15
b		+5	+7	+22	
c	−4	+10		−8	
d	−10		−10		+20
e	+3	−3	+8		

2.55 A mass of 10 kg undergoes a process during which there is heat transfer from the mass at a rate of 5 kJ per kg, an elevation decrease of 50 m, and an increase in velocity from 15 m/s to 30 m/s. The specific internal energy decreases by 5 kJ/kg and the acceleration of gravity is constant at 9.7 m/s^2. Determine the work for the process, in kJ.

2.56 As shown in Fig. P2.56, a gas contained within a piston–cylinder assembly, initially at a volume of 0.1 m^3, undergoes a constant-pressure expansion at 2 bar to a final volume of 0.12 m^3, while being slowly heated through the base. The change in internal energy of the gas is 0.25 kJ. The piston and cylinder walls are fabricated from heat-resistant material, and the piston moves smoothly in the cylinder. The local atmospheric pressure is 1 bar.

(a) For the gas as the system, evaluate work and heat transfer, each in kJ.
(b) For the piston as the system, evaluate work and change in potential energy, each in kJ.

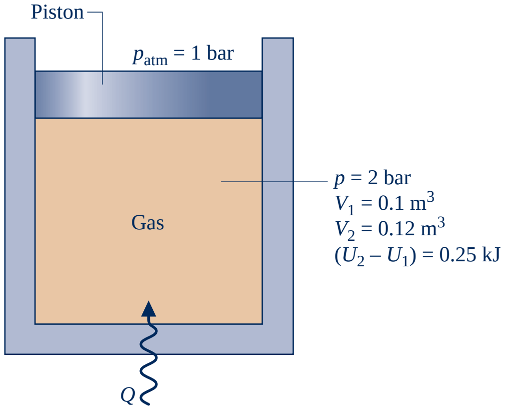


Fig. P2.56

2.57 A gas contained in a piston–cylinder assembly undergoes two processes, A and B, between *the same end states,* 1 and 2, where $p_1 = 1$ bar, $V_1 = 1\ \text{m}^3$, $U_1 = 400$ kJ and $p_2 = 10$ bar, $V_2 = 0.1\ \text{m}^3$, $U_2 = 450$ kJ:

Process A: Constant-volume process from state 1 to a pressure of 10 bar, followed by a constant-pressure process to state 2.

Process B: Process from 1 to 2 during which the pressure-volume relation is $pV = constant$.

Kinetic and potential effects can be ignored. For each of the processes A and B, (a) sketch the process on p–V coordinates, (b) evaluate the work, in kJ, and (c) evaluate the heat transfer, in kJ.

2.58 A gas contained within a piston–cylinder assembly undergoes two processes, A and B, between the *same end states,* 1 and 2, where $p_1 = 10$ bar, $V_1 = 0.1\ \text{m}^3$, $U_1 = 400$ kJ and $p_2 = 1$ bar, $V_2 = 1.0\ \text{m}^3$, $U_2 = 200$ kJ:

Process A: Process from 1 to 2 during which the pressure-volume relation is $pV = constant$.

Process B: Constant-volume process from state 1 to a pressure of 2 bar, followed by a linear pressure-volume process to state 2.

Kinetic and potential energy effects can be ignored. For each of the processes A and B, (a) sketch the process on p–V coordinates, (b) evaluate the work, in kJ, and (c) evaluate the heat transfer, in kJ.

2.59 An electric motor draws a current of 10 amp with a voltage of 110 V. The output shaft develops a torque of 10.2 N · m and a rotational speed of 1000 RPM. For operation at steady state, determine for the motor, each in kW

(a) the electric power required.
(b) the power developed by the output shaft.
(c) the rate of heat transfer.

2.60 As shown in Fig. P2.60, the outer surface of a transistor is cooled convectively by a fan-induced flow of air at a temperature of 25°C and a pressure of 1 atm. The transistor's outer surface area is $5 \times 10^{-4}\ \text{m}^2$. At steady state, the electrical power to the transistor is 3 W. Negligible heat transfer occurs through the base of the transistor. The convective heat transfer coefficient is $100\ \text{W/m}^2 \cdot \text{K}$. Determine (a) the rate of heat transfer between the transistor and the air, in W, and (b) the temperature at the transistor's outer surface, in °C.

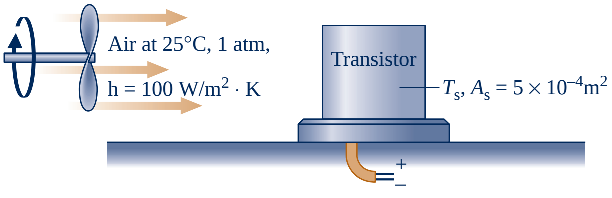


Fig. P2.60

2.61 One kg of Refrigerant 22, initially at $p_1 = 0.9$ MPa, $u_1 = 232.92$ kJ/kg, is contained within a rigid closed tank. The tank is fitted with a paddle wheel that transfers energy *to* the refrigerant at a constant rate of 0.1 kW. Heat transfer *from* the refrigerant *to* its surroundings occurs at a rate Kt, in kW, where K is a constant, in kW per minute, and t is time, in minutes. After 20 minutes of stirring, the refrigerant is at $p_2 = 1.2$ MPa, $u_2 = 276.67$ kJ/kg. No overall changes in kinetic or potential energy occur. (a) For the refrigerant, determine the work and heat transfer, each in kJ. (b) Determine the value of the constant K appearing in the given heat transfer relation, in kW/min.

2.62 A gas is contained in a vertical piston–cylinder assembly by a piston with a face area of 40 in.^{2} and weight of 100 lbf. The atmosphere exerts a pressure of 14.7 lbf/in.^{2} on top of the piston. A paddle wheel transfers 3 Btu of energy to the gas during a process in which the elevation of the piston increases by 1 ft. The piston and cylinder are poor thermal conductors, and friction between them can be neglected. Determine the change in internal energy of the gas, in Btu.

2.63 A gas is compressed in a piston–cylinder assembly from $p_1 = 2$ bar to $p_2 = 8$ bar, $V_2 = 0.02\ \text{m}^3$ in a process during which the relation between pressure and volume is $pV^{1.3} = constant$. The mass of the gas is 0.2 kg. If the specific internal energy of the gas increases by 50 kJ/kg during the process, determine the heat transfer, in kJ. Kinetic and potential energy changes are negligible.

2.64 Four kilograms of carbon monoxide (CO) is contained in a rigid tank with a volume of 1 m^3. The tank is fitted with a paddle wheel that transfers energy to the CO at a constant rate of 14 W for 1 h. During the process, the specific internal energy of the carbon monoxide increases by 10 kJ/kg. If no overall changes in kinetic and potential energy occur, determine

(a) the specific volume at the final state, in m^3/kg.
(b) the energy transfer by work, in kJ.
(c) the energy transfer by heat transfer, in kJ, and the direction of the heat transfer.

2.65 Helium gas is contained in a closed rigid tank. An electric resistor in the tank transfers energy *to* the gas at a constant rate of 1 kW. Heat transfer *from* the gas to its surroundings occurs at a rate of 5t watts, where t is time, in minutes. Plot the change in energy of the helium, in kJ, for $t \geq 0$ and comment.

2.66 Steam in a piston–cylinder assembly undergoes a *polytropic* process, with $n = 2$, from an initial state where $V_1 = 2\ \text{ft}^3$, $p_1 = 450$ lbf/in.^{2}, and $u_1 = 1322.4$ Btu/lb to a final state where $u_2 = 1036.0$ Btu/lb and $v_2 = 3.393$ ft^3/lb. The mass of the steam is 1.14 lb. Neglecting changes in kinetic and potential energy, determine the initial specific volume, in ft^3/lb, and the energy transfers by work and heat transfer, each in Btu.

2.67 A gas undergoes a process from state 1, where $p_1 = 40$ lbf/in.^{2}, $v_1 = 4.0$ ft^3/lb, to state 2, where $p_2 = 14$ lbf/in.^{2}, according to $pv^{1.2} = constant$. The relationship between pressure, specific volume, and specific internal energy is

$$u = \left(0.464\frac{\text{Btu}\cdot\text{in.}^2}{\text{lbf}\cdot\text{ft}^3}\right)pv - 0.7095\frac{\text{Btu}}{\text{lb}}$$

where p is in lbf/in.^{2}, v is in ft^3/lb, and u is in Btu/lb. Neglecting kinetic and potential energy effects, determine the heat transfer per unit mass, in Btu/lb.

2.68 A vertical piston–cylinder assembly with a piston of mass 25 kg and having a face area of 0.005 m^2 contains air. The mass of air is 2.5 g, and initially the air occupies a volume of 2.5 liters. The atmosphere exerts a pressure of 100 kPa on the top of the piston. The volume of the air slowly decreases to 0.001 m^3 as energy with a magnitude of 1 kJ is slowly removed by heat transfer. Neglecting friction between the piston and the cylinder wall, determine the change in specific internal energy of the air, in kJ/kg. Let $g = 9.8\ m/s^2$.

2.69 Gaseous CO_2 is contained in a vertical piston–cylinder assembly by a piston of mass 50 kg and having a face area of 0.01 m^2. The mass of the CO_2 is 4 g. The CO_2 initially occupies a volume of 0.005 m^3 and has a specific internal energy of 657 kJ/kg. The atmosphere exerts a pressure of 100 kPa on the top of the piston. Heat transfer in the amount of 1.95 kJ occurs slowly from the CO_2 to the surroundings, and the volume of the CO_2 decreases to 0.0025 m^3. Friction between the piston and the cylinder wall can be neglected. The local acceleration of gravity is 9.81 m/s^2. For the CO_2 determine (a) the pressure, in kPa, and (b) the final specific internal energy, in kJ/kg.

2.70 Figure P2.70 shows a gas contained in a vertical piston–cylinder assembly. A vertical shaft whose cross-sectional area is 0.8 cm^2 is attached to the top of the piston. The total mass of the piston and shaft is 25 kg. While the gas is slowly heated, the internal energy of the gas increases by 0.1 kJ, the potential energy of the piston–shaft combination increases by 0.2 kJ, and a force of 1334 N is exerted on the shaft as shown in the figure. The piston and cylinder are poor conductors, and friction between them is negligible. The local atmospheric pressure is 1 bar and $g = 9.81\ m/s^2$. Determine, (a) the work done by the shaft, (b) the work done in displacing the atmosphere, and (c) the heat transfer to the gas, all in kJ. (d) Using calculated and given data, develop a detailed *accounting* of the heat transfer of energy to the gas.

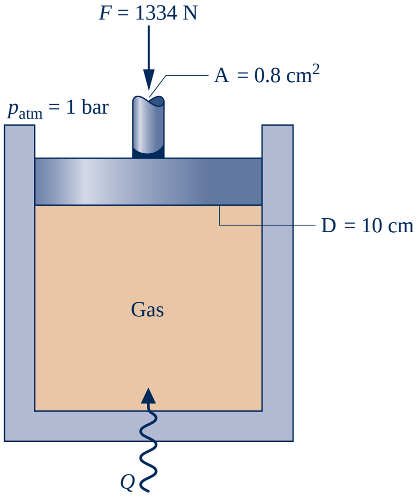


Fig. P2.70

Analyzing Thermodynamic Cycles

2.71 The following table gives data, in kJ, for a system undergoing a power cycle consisting of four processes in series. Determine, the (a) missing table entries, each in kJ, and (b) the thermal efficiency.

Process	ΔE	Q	W
1–2	−1200	0	
2–3		800	
3–4		−200	−200
4–1	400		600

2.72 The following table gives data, in Btu, for a system undergoing a power cycle consisting of four processes in series. Determine (a) the missing table entries, each in Btu, and (b) the thermal efficiency.

Process	ΔU	ΔKE	ΔPE	ΔE	Q	W
1–2	950	50	0		1000	
2–3		0	50	−450		450
3–4	−650		0	−600		0
4–1	200	−100	−50		0	

2.73 Figure P2.73 shows a power cycle executed by a gas in a piston-cylinder assembly. For process 1–2, $U_2 - U_1 = 15$ kJ. For process 3-1, $Q_{31} = 10$ kJ. There are no changes in kinetic or potential energy. Determine (a) the work for each process, in kJ, (b) the heat transfer for processes 1–2 and 2–3, each in kJ, and (c) the thermal efficiency.

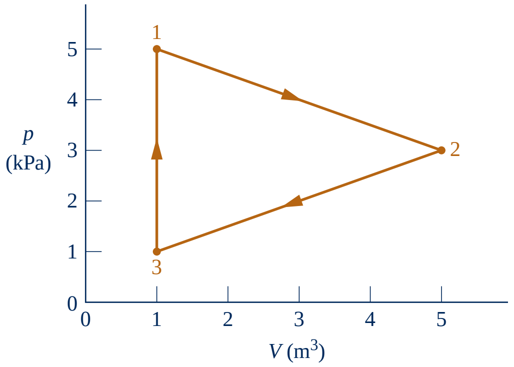


Fig. P2.73

2.74 A gas within a piston–cylinder assembly undergoes a thermodynamic cycle consisting of three processes in series, beginning at state 1 where $p_1 = 1$ bar, $V_1 = 1.5\ m^3$, as follows:

Process 1–2: Compression with $pV = constant$, $W_{12} = -104$ kJ, $U_1 = 512$ kJ, $U_2 = 690$ kJ.

Process 2–3: $W_{23} = 0$, $Q_{23} = -150$ kJ.

Process 3–1: $W_{31} = +50$ kJ.

There are no changes in kinetic or potential energy. (a) Determine Q_{12}, Q_{31}, and U_3, each in kJ. (b) Can this cycle be a power cycle? Explain.

2.75 A gas within a piston–cylinder assembly undergoes a thermodynamic cycle consisting of three processes:

Process 1–2: Compression with $pV = constant$, from $p_1 = 1$ bar, $V_1 = 2\ m^3$ to $V_2 = 0.2\ m^3$, $U_2 - U_1 = 100$ kJ.

Process 2–3: Constant volume to $p_3 = p_1$.

Process 3–1: Constant-pressure and adiabatic process.

There are no significant changes in kinetic or potential energy. Determine the net work of the cycle, in kJ, and the heat transfer for process 2–3, in kJ. Is this a power cycle or a refrigeration cycle? Explain.

2.76 A gas within a piston–cylinder assembly undergoes a thermodynamic cycle consisting of three processes:

Process 1–2: Constant volume, $V = 0.028\ \text{m}^3$, $U_2 - U_1 = 26.4$ kJ.

Process 2–3: Expansion with $pV = constant$, $U_3 = U_2$.

Process 3–1: Constant pressure, $p = 1.4$ bar, $W_{31} = -10.5$ kJ.

There are no significant changes in kinetic or potential energy.

(a) Sketch the cycle on a p–V diagram.
(b) Calculate the net work for the cycle, in kJ.
(c) Calculate the heat transfer for process 2–3, in kJ.
(d) Calculate the heat transfer for process 3–1, in kJ.

Is this a power cycle or a refrigeration cycle?

2.77 As shown in Fig. P2.77, a gas within a piston–cylinder assembly undergoes a thermodynamic cycle consisting of three processes in series:

Process 1–2: Compression with $U_2 = U_1$.

Process 2–3: Constant-volume cooling to $p_3 = 140$ kPa, $V_3 = 0.028\ \text{m}^3$.

Process 3–1: Constant-pressure expansion with $W_{31} = 10.5$ kJ.

For the cycle, $W_{\text{cycle}} = -8.3$ kJ. There are no changes in kinetic or potential energy. Determine (a) the volume at state 1, in m^3, (b) the work and heat transfer for process 1-2, each in kJ. (c) Can this be a power cycle? A refrigeration cycle? Explain.

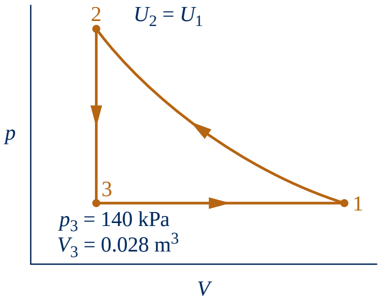


Fig. P2.77

2.78 For a power cycle operating as in Fig. 2.17*a*, the heat transfers are $Q_{\text{in}} = 75$ kJ and $Q_{\text{out}} = 50$ kJ. Determine the net work, in kJ, and the thermal efficiency.

2.79 The thermal efficiency of a power cycle operating as shown in Fig. 2.17*a* is 30%, and Q_{out} is 20 kJ. Determine the net work developed and the heat transfer Q_{in}, each in kJ.

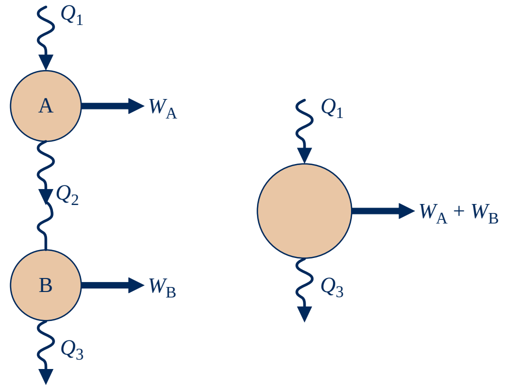
2.80 For a power cycle operating as in Fig. 2.17*a*, $W_{\text{cycle}} = 800$ Btu and $Q_{\text{out}} = 1800$ Btu. What is the thermal efficiency?

2.81 A system undergoing a power cycle requires an energy input by heat transfer of 10^4 Btu for each kW · h of net work developed. Determine the thermal efficiency.

2.82 A power cycle receives energy by heat transfer from the combustion of fuel and develops power at a net rate of 150 MW. The thermal efficiency of the cycle is 40%.

(a) Determine the net rate at which the cycle receives energy by heat transfer, in MW.
(b) For 8000 hours of operation annually, determine the net work output, in kW · h per year.
(c) Evaluating the net work output at \$0.08 per kW · h, determine the value of net work, in \$ per year.

2.83 Figure P2.83 shows two power cycles, A and B, operating in series, with the energy transfer by heat *into* cycle B equal in magnitude to the energy transfer by heat *from* cycle A. All energy transfers are positive in the directions of the arrows. Determine an expression for the thermal efficiency of an *overall* cycle consisting of cycles A and B together in terms of their individual thermal efficiencies.



(*a*) A and B in series (*b*) Overall cycle

Fig. P2.83

2.84 Shown in Fig. P2.84 is a *cogeneration* power plant operating in a thermodynamic cycle at steady state. The plant provides electricity to a community at a rate of 80 MW. The energy discharged from the power plant by heat transfer is denoted on the figure by $\dot{Q}_{\text{out}}$. Of this, 70 MW is provided to the community for water heating and the remainder is discarded to the environment without use. The electricity is valued at \$0.08 per kW · h. If the cycle thermal efficiency is 40%, determine the (a) rate energy is added by heat transfer, $\dot{Q}_{\text{in}}$, in MW, (b) rate energy is discarded to the environment, in MW, and (c) value of the electricity generated, in \$ per year.

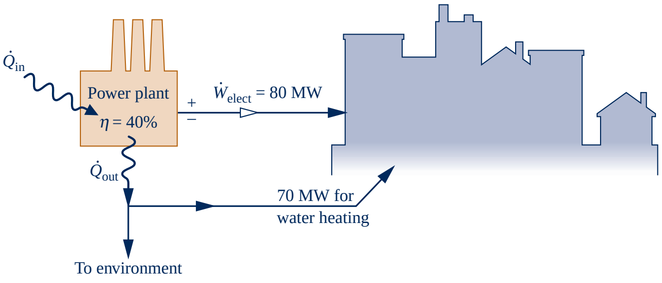


Fig. P2.84

2.85 A refrigeration cycle operating as shown in Fig. 2.17*b* has $Q_{\text{out}} = 1000$ Btu and $W_{\text{cycle}} = 300$ Btu. Determine the coefficient of performance for the cycle.

2.86 A refrigeration cycle operating as shown in Fig. 2.17*b* has a coefficient of performance $\beta = 1.8$. For the cycle, $Q_{\text{out}} = 250$ kJ. Determine Q_{in} and W_{cycle}, each in kJ.

2.87 The refrigerator shown in Fig. P2.87 steadily receives a power input of 0.15 kW while rejecting energy by heat transfer to the surroundings at a rate of 0.6 kW. Determine the rate at which energy is removed by heat transfer from the refrigerated space, in kW, and the refrigerator's coefficient of performance.

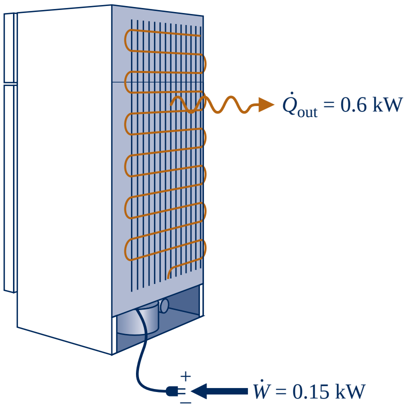


Fig. P2.87

2.88 For a refrigerator with automatic defrost and a top-mounted freezer, the annual cost of electricity is $55. (a) Evaluating electricity at 8 cents per kW · h, determine the refrigerator's annual electricity requirement, in kW · h. (b) If the refrigerator's coefficient of performance is 3, determine the amount of energy removed from its refrigerated space annually, in MJ.

2.89 A household refrigerator operating steadily and with a coefficient of performance of 2.4 removes energy from a refrigerated space at a rate of 600 Btu/h. Evaluating electricity at $0.08 per kW · h, determine the cost of electricity in a month when the refrigerator operates for 360 hours.

2.90 A heat pump cycle operating at steady state receives energy by heat transfer from well water at 10°C and discharges energy by heat transfer to a building at the rate of 1.2×10^5 kJ/h. Over a period of 14 days, an electric meter records that 1490 kW · h of electricity is provided to the heat pump. These are the only energy transfers involved. Determine (a) the amount of energy that the heat pump receives over the 14-day period from the well water by heat transfer, in kJ, and (b) the heat pump's coefficient of performance.

2.91 A heat pump maintains a dwelling at 68°F. When operating steadily, the power input to the heat pump is 5 hp, and the heat pump receives energy by heat transfer from 55°F well water at a rate of 500 Btu/min.

(a) Determine the coefficient of performance.
(b) Evaluating electricity at $ 0.10 per kW · h, determine the cost of electricity in a month when the heat pump operates for 300 hours.

2.92 A heat pump cycle delivers energy by heat transfer to a dwelling at a rate of 40,000 Btu/h. The coefficient of performance of the cycle is 2.8.

(a) Determine the power input to the cycle, in hp.
(b) Evaluating electricity at $0.085 per kW · h, determine the cost of electricity during the heating season when the heat pump operates for 2000 hours.

2.93 An air-conditioning unit with a coefficient of performance of 2.93 provides 5000 Btu/h of cooling while operating during the cooling season 8 hours per day for 125 days. If you pay 10 cents per kW · h for electricity, determine the cost, in dollars, for the cooling season.

Reviewing Concepts

2.94 Answer the following true or false. Explain.

(a) As a spring is compressed adiabatically, its internal energy increases.
(b) Energy transfers by heat are induced *only* as a result of a temperature difference between a system and its surroundings.
(c) The total energy of a closed system can change as a result of energy transfer across the system boundary by heat and work and energy transfer accompanying mass flow across the boundary.
(d) The change in kinetic energy, in Btu, of a 10-lb mass whose velocity decreases from 100 ft/s to 50 ft/s is 1.5 Btu.
(e) In this book, heat transfer *to* a closed system and work done *on* a closed system are each considered positive: $Q > 0$ and $W > 0$, respectively.

2.95 Answer the following true or false. Explain.

(a) In principle, expansion work can be evaluated using $\int p\, dV$ for both actual and quasiequilibrium expansion processes.
(b) The change in the *internal energy* of a system between two states is the change in the total energy of the system between the two states less the changes of the system's kinetic and gravitational potential energies between these states.
(c) For heat pumps, the value of the coefficient of performance is *never* greater than 1.
(d) The change in gravitational potential energy of a 2-lb mass whose elevation decreases by 40 ft where $g = 32.2$ ft/s^2 is −2576 ft · lbf.
(e) The rate of heat transfer from a hot baked potato to ambient air is greater with forced convection than natural convection.

2.96 Answer the following true or false. Explain.

(a) A system is at *steady state* if no more than one of its properties changes with time.
(b) Only *changes* in the energy of a system between two states have significance; no significance can be attached to the energy *at* a state.
(c) The rate of heat transfer by conduction through a plane wall is greater if the wall is fabricated from plywood than from brick, assuming the same wall area and temperature gradient.

(d) If a system undergoes a process involving heat transfer with its surroundings but no work, that process is said to be *adiabatic*.
(e) Thermal radiation can occur in a vacuum.

2.97 Answer the following true or false. Explain.

(a) Work is done by a system on its surroundings if the sole effect on everything external to the system could have been the raising of a weight.
(b) Cooling of computer components achieved by a fan-induced flow of air falls in the realm of radiation heat transfer.
(c) For every thermodynamic cycle, the *net* amounts of energy transfer by heat and work per cycle are equal.
(d) A flywheel spinning owing to an input of electricity stores energy as internal energy.
(e) Kinetic and potential energy are each extensive properties of a system.

▶ DESIGN & OPEN-ENDED PROBLEMS: EXPLORING ENGINEERING PRACTICE

2.1D Visit a local appliance store and collect data on energy requirements for different models within various classes of appliances, including but not limited to refrigerators with and without ice makers, dishwashers, and clothes washers and driers. Prepare a memorandum ranking the different models in each class on an energy-use basis together with an accompanying discussion considering retail cost and other pertinent issues.

2.2D Select an item that can be produced using recycled materials such as an aluminum can, a glass bottle, or a plastic or paper grocery bag. Research the materials, energy requirements, manufacturing methods, environmental impacts, and costs associated with producing the item from raw materials versus recycled materials. Write a report including at least three references.

2.3D Design a go-anywhere, use-anywhere wind screen for outdoor recreational and casual-living activities, including sunbathing, reading, cooking, and picnicking. The wind screen must be lightweight, portable, easy to deploy, and low cost. A key constraint is that the wind screen can be set up anywhere, including hard surfaces such as parking lots for tailgating, wood decks, brick and concrete patios, and at the beach. A cost analysis should accompany the design.

2.4D In living things, energy is stored in the molecule *adenosine triphosphate,* called ATP for short. ATP is said to *act like a battery,* storing energy when it is not needed and instantly releasing energy when it is required. Investigate how energy is stored and the role of ATP in biological processes. Write a report including at least three references.

2.5D The global reach of the Internet supports a rapid increase in consumer and business *e-commerce*. Some say e-commerce will result in net reductions in both energy use and global climate change. Using the Internet, interviews with experts, and design-group *brainstorming*, identify several major ways e-commerce can lead to such reductions. Report your findings in a memorandum having at least three references.

2.6D Develop a list of the most common residential cooling options in your locale. For these options and assuming a 2300-ft^2 home, compare installation cost, carbon footprint, and annual electricity charges. Which option is the most economical if a 12-year life is assumed? What if electricity costs twice its current cost? Prepare a poster presentation of your findings.

2.7D Homeowners concerned about interruption of electrical power from their local utility because of weather-related and utility system outages can acquire a standby generator that produces electricity using the home's existing natural gas or liquid propane (LP) fuel source. For a single-family dwelling of your choice, identify a standby generator that would provide electricity during an outage to a set of essential devices and appliances you specify. Summarize your findings in a memorandum including installed-cost and operating-cost data.

2.8D Despite the promise of nanotechnology (see *Horizons* in Secs. 1.6 and 2.2), some say it involves risks requiring scrutiny. For instance, the tiny size of nanoparticles may allow them to evade the natural defenses of the human body, and manufacturing at the nanoscale may lead to environmental burdens and excessive energy resource use. Research the risks that accompany widespread production and deployment of nanotechnology. For each risk identified, develop policy recommendations on safeguards for consumers and the environment. Write a report with at least three references.

2.9D The object of this project is to create a preliminary design of an energy-efficient dwelling at a locale of your choice. Consider factors including, but not limited to, placement of the dwelling on the lot, means for heating and cooling the dwelling, means for providing hot water, appliances, and building materials. The total cost must be no more than the average of newly constructed dwellings in the locale selected. Prepare a PowerPoint presentation of your design, including at least three references.

2.10D An advertisement describes a portable heater claimed to cut home heating bills by up to 50%. The heater is said to be able to heat large rooms in minutes without having a high outer-surface temperature, reducing humidity and oxygen levels, or producing carbon monoxide. A typical deployment is shown in Fig. P2.10D. The heater is an enclosure containing electrically-powered quartz infrared lamps that shine on copper tubes. Air drawn into the enclosure by a fan flows over the tubes and then is directed back into the living space. According to the advertisement, a heater capable of heating a room with up to 300 ft^2 of floor area costs about \$400 while one for a room with up to 1000 ft^2 of floor area costs about \$500. Critically evaluate the technical and economic merit of such heaters. Write a report including at least three references.

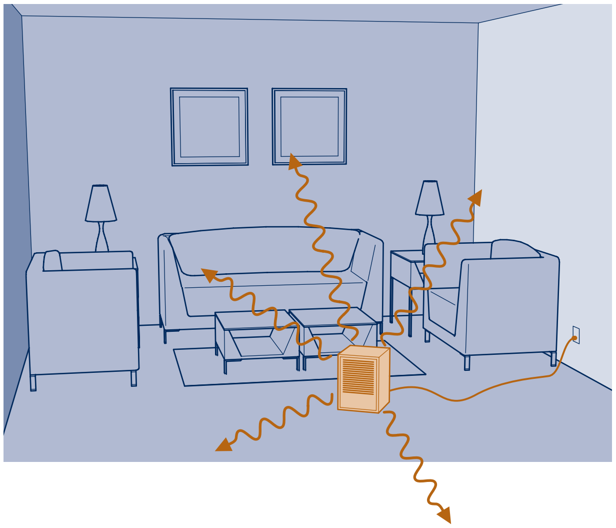


Fig. P2.10D

2.11D An inventor proposes *borrowing* water from municipal water mains and storing it *temporarily* in a tank on the premises of a dwelling equipped with a heat pump. As shown in Fig. P2.11D, the stored water serves as the cold body for the heat pump and the dwelling itself serves as the hot body. To maintain the cold body temperature within a proper operating range, water is drawn from the mains periodically and an equal amount of water is returned to the mains. As the invention requires no *net* water from the mains, the inventor maintains that nothing should be paid for water usage. The inventor also maintains that this approach not only gives a coefficient of performance superior to those of *air-source* heat pumps but also avoids the installation costs associated with *ground-source* heat pumps. In all, significant cost savings result, the inventor says. Critically evaluate the inventor's claims. Write a report including at least three references.

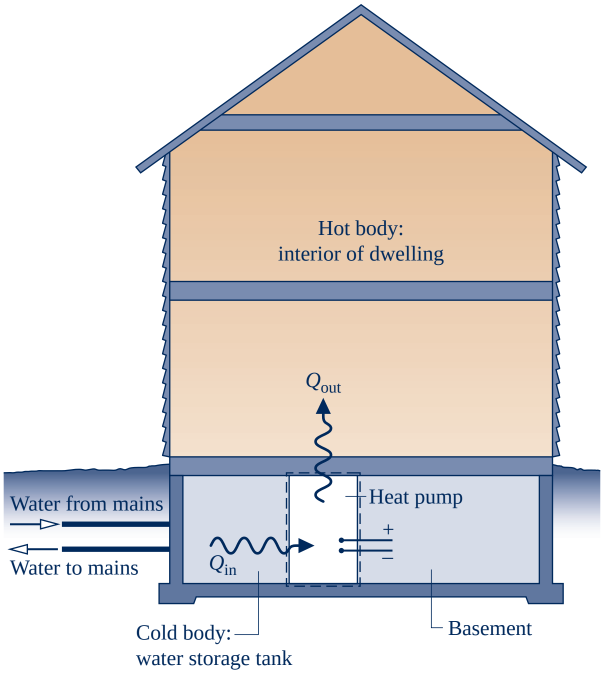


Fig. P2.11D