

# Chapter 4

## ENERGY ANALYSIS OF CLOSED SYSTEMS

In Chap. 2, we considered various forms of energy and energy transfer, and we developed a general relation for the conservation of energy principle or energy balance. Then in Chap. 3, we learned how to determine the thermodynamics properties of substances. In this chapter, we apply the energy balance relation to systems that do not involve any mass flow across their boundaries; that is, closed systems.

We start this chapter with a discussion of the *moving boundary work* or *P dV work* commonly encountered in reciprocating devices such as automotive engines and compressors. We continue by applying the *general energy balance* relation, which is simply expressed as  $E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}}$ , to systems that involve pure substance. Then we define *specific heats*, obtain relations for the internal energy and enthalpy of *ideal gases* in terms of specific heats and temperature changes, and perform energy balances on various systems that involve ideal gases. We repeat this for systems that involve solids and liquids, which are approximated as *incompressible substances*.

### Objectives

The objectives of Chapter 4 are to:

- Examine the moving boundary work or  $P dV$  work commonly encountered in reciprocating devices such as automotive engines and compressors.
- Identify the first law of thermodynamics as simply a statement of the conservation of energy principle for closed (fixed mass) systems.
- Develop the general energy balance applied to closed systems.
- Define the specific heat at constant volume and the specific heat at constant pressure.
- Relate the specific heats to the calculation of the changes in internal energy and enthalpy of ideal gases.
- Describe incompressible substances and determine the changes in their internal energy and enthalpy.
- Solve energy balance problems for closed (fixed mass) systems that involve heat and work interactions for general pure substances, ideal gases, and incompressible substances.



## INTERACTIVE TUTORIAL

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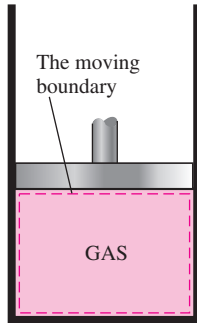


FIGURE 4-1

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

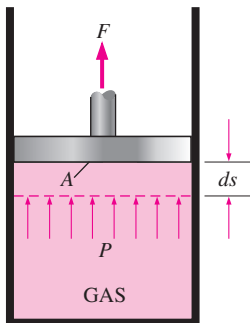


FIGURE 4-2

A gas does a differential amount of work  $\delta W_b$  as it forces the piston to move by a differential amount  $ds$ .

## 4-1 ■ MOVING BOUNDARY WORK

One form of mechanical work frequently encountered in practice is associated with the expansion or compression of a gas in a piston–cylinder device. During this process, part of the boundary (the inner face of the piston) moves back and forth. Therefore, the expansion and compression work is often called **moving boundary work**, or simply **boundary work** (Fig. 4–1). Some call it the  $P dV$  work for reasons explained later. Moving boundary work is the primary form of work involved in *automobile engines*. During their expansion, the combustion gases force the piston to move, which in turn forces the crankshaft to rotate.

The moving boundary work associated with real engines or compressors cannot be determined exactly from a thermodynamic analysis alone because the piston usually moves at very high speeds, making it difficult for the gas inside to maintain equilibrium. Then the states through which the system passes during the process cannot be specified, and no process path can be drawn. Work, being a path function, cannot be determined analytically without a knowledge of the path. Therefore, the boundary work in real engines or compressors is determined by direct measurements.

In this section, we analyze the moving boundary work for a *quasi-equilibrium process*, a process during which the system remains nearly in equilibrium at all times. A quasi-equilibrium process, also called a *quasi-static process*, is closely approximated by real engines, especially when the piston moves at low velocities. Under identical conditions, the work output of the engines is found to be a maximum, and the work input to the compressors to be a minimum when quasi-equilibrium processes are used in place of nonquasi-equilibrium processes. Below, the work associated with a moving boundary is evaluated for a quasi-equilibrium process.

Consider the gas enclosed in the piston–cylinder device shown in Fig. 4–2. The initial pressure of the gas is  $P$ , the total volume is  $V$ , and the cross-sectional area of the piston is  $A$ . If the piston is allowed to move a distance  $ds$  in a quasi-equilibrium manner, the differential work done during this process is

$$\delta W_b = F ds = PA ds = P dV \quad (4-1)$$

That is, the boundary work in the differential form is equal to the product of the absolute pressure  $P$  and the differential change in the volume  $dV$  of the system. This expression also explains why the moving boundary work is sometimes called the  $P dV$  work.

Note in Eq. 4–1 that  $P$  is the absolute pressure, which is always positive. However, the volume change  $dV$  is positive during an expansion process (volume increasing) and negative during a compression process (volume decreasing). Thus, the boundary work is positive during an expansion process and negative during a compression process. Therefore, Eq. 4–1 can be viewed as an expression for boundary work output,  $W_{b,\text{out}}$ . A negative result indicates boundary work input (compression).

The total boundary work done during the entire process as the piston moves is obtained by adding all the differential works from the initial state to the final state:

$$W_b = \int_1^2 P dV \quad (\text{kJ}) \quad (4-2)$$

This integral can be evaluated only if we know the functional relationship between  $P$  and  $V$  during the process. That is,  $P = f(V)$  should be available. Note that  $P = f(V)$  is simply the equation of the process path on a  $P$ - $V$  diagram.

The quasi-equilibrium expansion process described is shown on a  $P$ - $V$  diagram in Fig. 4-3. On this diagram, the differential area  $dA$  is equal to  $P dV$ , which is the differential work. The total area  $A$  under the process curve 1-2 is obtained by adding these differential areas:

$$\text{Area} = A = \int_1^2 dA = \int_1^2 P dV \quad (4-3)$$

A comparison of this equation with Eq. 4-2 reveals that *the area under the process curve on a  $P$ - $V$  diagram is equal, in magnitude, to the work done during a quasi-equilibrium expansion or compression process of a closed system.* (On the  $P$ - $v$  diagram, it represents the boundary work done per unit mass.)

A gas can follow several different paths as it expands from state 1 to state 2. In general, each path will have a different area underneath it, and since this area represents the magnitude of the work, the work done will be different for each process (Fig. 4-4). This is expected, since work is a path function (i.e., it depends on the path followed as well as the end states). If work were not a path function, no cyclic devices (car engines, power plants) could operate as work-producing devices. The work produced by these devices during one part of the cycle would have to be consumed during another part, and there would be no net work output. The cycle shown in Fig. 4-5 produces a net work output because the work done by the system during the expansion process (area under path A) is greater than the work done on the system during the compression part of the cycle (area under path B), and the difference between these two is the net work done during the cycle (the colored area).

If the relationship between  $P$  and  $V$  during an expansion or a compression process is given in terms of experimental data instead of in a functional form, obviously we cannot perform the integration analytically. But we can always plot the  $P$ - $V$  diagram of the process, using these data points, and calculate the area underneath graphically to determine the work done.

Strictly speaking, the pressure  $P$  in Eq. 4-2 is the pressure at the inner surface of the piston. It becomes equal to the pressure of the gas in the cylinder only if the process is quasi-equilibrium and thus the entire gas in the cylinder is at the same pressure at any given time. Equation 4-2 can also be used for nonquasi-equilibrium processes provided that the pressure *at the inner face of the piston* is used for  $P$ . (Besides, we cannot speak of the pressure of a *system* during a nonquasi-equilibrium process since properties are defined for equilibrium states only.) Therefore, we can generalize the boundary work relation by expressing it as

$$W_b = \int_1^2 P_i dV \quad (4-4)$$

where  $P_i$  is the pressure at the inner face of the piston.

Note that work is a mechanism for energy interaction between a system and its surroundings, and  $W_b$  represents the amount of energy transferred from the system during an expansion process (or to the system during a

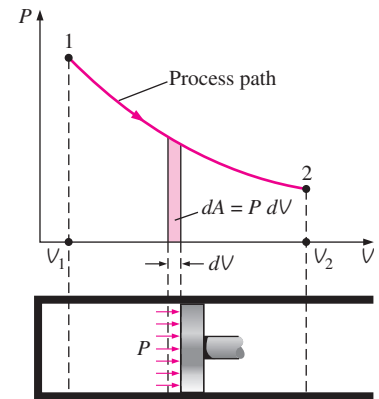


FIGURE 4-3

The area under the process curve on a  $P$ - $V$  diagram represents the boundary work.

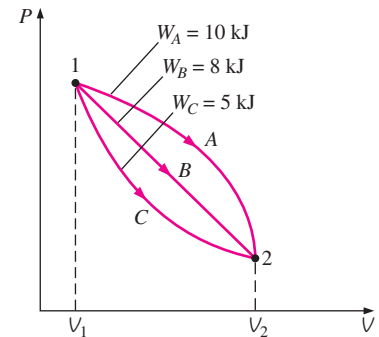


FIGURE 4-4

The boundary work done during a process depends on the path followed as well as the end states.

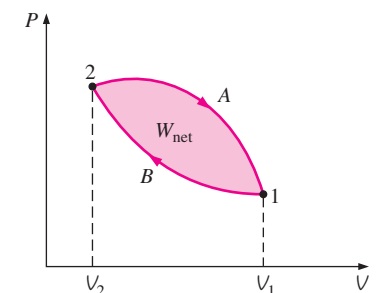


FIGURE 4-5

The net work done during a cycle is the difference between the work done by the system and the work done on the system.

compression process). Therefore, it has to appear somewhere else and we must be able to account for it since energy is conserved. In a car engine, for example, the boundary work done by the expanding hot gases is used to overcome friction between the piston and the cylinder, to push atmospheric air out of the way, and to rotate the crankshaft. Therefore,

$$W_b = W_{\text{friction}} + W_{\text{atm}} + W_{\text{crank}} = \int_1^2 (F_{\text{friction}} + P_{\text{atm}}A + F_{\text{crank}}) dx \quad (4-5)$$

Of course the work used to overcome friction appears as frictional heat and the energy transmitted through the crankshaft is transmitted to other components (such as the wheels) to perform certain functions. But note that the energy transferred by the system as work must equal the energy received by the crankshaft, the atmosphere, and the energy used to overcome friction.

The use of the boundary work relation is not limited to the quasi-equilibrium processes of gases only. It can also be used for solids and liquids.

#### EXAMPLE 4-1 Boundary Work for a Constant-Volume Process

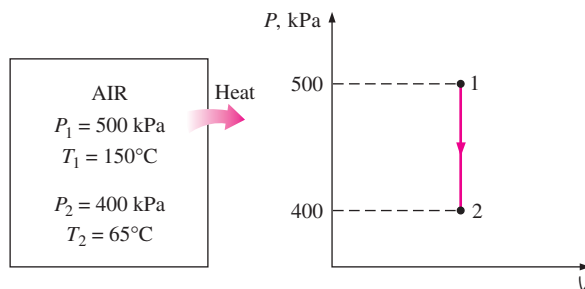
A rigid tank contains air at 500 kPa and 150°C. As a result of heat transfer to the surroundings, the temperature and pressure inside the tank drop to 65°C and 400 kPa, respectively. Determine the boundary work done during this process.

**Solution** Air in a rigid tank is cooled, and both the pressure and temperature drop. The boundary work done is to be determined.

**Analysis** A sketch of the system and the  $P$ - $V$  diagram of the process are shown in Fig. 4-6. The boundary work can be determined from Eq. 4-2 to be

$$W_b = \int_1^2 P dV \stackrel{0}{=} 0$$

**Discussion** This is expected since a rigid tank has a constant volume and  $dV = 0$  in this equation. Therefore, there is no boundary work done during this process. That is, the boundary work done during a constant-volume process is always zero. This is also evident from the  $P$ - $V$  diagram of the process (the area under the process curve is zero).



**FIGURE 4-6**  
Schematic and  $P$ - $V$  diagram for Example 4-1.

**EXAMPLE 4-2** Boundary Work for a Constant-Pressure Process

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

**Solution** Steam in a piston cylinder device is heated and the temperature rises at constant pressure. The boundary work done is to be determined.

**Analysis** A sketch of the system and the  $P$ - $v$  diagram of the process are shown in Fig. 4-7.

**Assumption** The expansion process is quasi-equilibrium.

**Analysis** Even though it is not explicitly stated, the pressure of the steam within the cylinder remains constant during this process since both the atmospheric pressure and the weight of the piston remain constant. Therefore, this is a constant-pressure process, and, from Eq. 4-2

$$W_b = \int_1^2 P dV = P_0 \int_1^2 dV = P_0(V_2 - V_1) \quad (4-6)$$

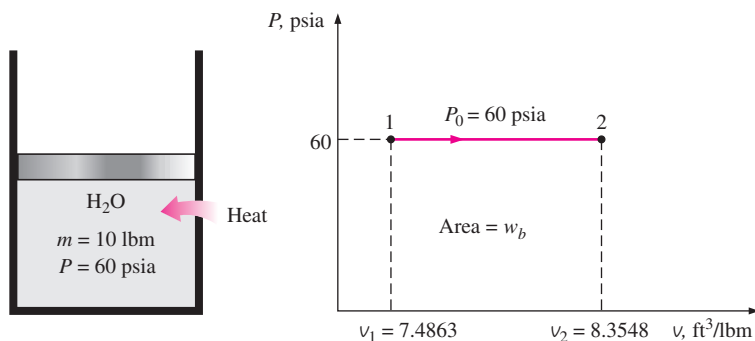
or

$$W_b = mP_0(v_2 - v_1)$$

since  $V = mv$ . From the superheated vapor table (Table A-6E), the specific volumes are determined to be  $v_1 = 7.4863 \text{ ft}^3/\text{lbm}$  at state 1 (60 psia, 320°F) and  $v_2 = 8.3548 \text{ ft}^3/\text{lbm}$  at state 2 (60 psia, 400°F). Substituting these values yields

$$\begin{aligned} W_b &= (10 \text{ lbm})(60 \text{ psia})[(8.3548 - 7.4863) \text{ ft}^3/\text{lbm}] \left( \frac{1 \text{ Btu}}{5.404 \text{ psia} \cdot \text{ft}^3} \right) \\ &= \mathbf{96.4 \text{ Btu}} \end{aligned}$$

**Discussion** The positive sign indicates that the work is done by the system. That is, the steam used 96.4 Btu of its energy to do this work. The magnitude of this work could also be determined by calculating the area under the process curve on the  $P$ - $v$  diagram, which is simply  $P_0 \Delta V$  for this case.



**FIGURE 4-7**

Schematic and  $P$ - $v$  diagram for Example 4-2.

**EXAMPLE 4–3 Isothermal Compression of an Ideal Gas**

A piston–cylinder device initially contains  $0.4 \text{ m}^3$  of air at  $100 \text{ kPa}$  and  $80^\circ\text{C}$ . The air is now compressed to  $0.1 \text{ m}^3$  in such a way that the temperature inside the cylinder remains constant. Determine the work done during this process.

**Solution** Air in a piston–cylinder device is compressed isothermally. The boundary work done is to be determined.

**Analysis** A sketch of the system and the  $P$ - $V$  diagram of the process are shown in Fig. 4–8.

**Assumptions** **1** The compression process is quasi-equilibrium. **2** At specified conditions, air can be considered to be an ideal gas since it is at a high temperature and low pressure relative to its critical-point values.

**Analysis** For an ideal gas at constant temperature  $T_0$ ,

$$PV = mRT_0 = C \quad \text{or} \quad P = \frac{C}{V}$$

where  $C$  is a constant. Substituting this into Eq. 4–2, we have

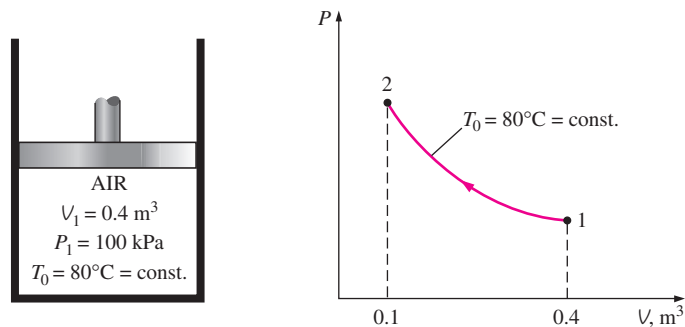
$$W_b = \int_1^2 P dV = \int_1^2 \frac{C}{V} dV = C \int_1^2 \frac{dV}{V} = C \ln \frac{V_2}{V_1} = P_1 V_1 \ln \frac{V_2}{V_1} \quad (4-7)$$

In Eq. 4–7,  $P_1 V_1$  can be replaced by  $P_2 V_2$  or  $mRT_0$ . Also,  $V_2/V_1$  can be replaced by  $P_1/P_2$  for this case since  $P_1 V_1 = P_2 V_2$ .

Substituting the numerical values into Eq. 4–7 yields

$$\begin{aligned} W_b &= (100 \text{ kPa})(0.4 \text{ m}^3) \left( \ln \frac{0.1}{0.4} \right) \left( \frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3} \right) \\ &= -55.5 \text{ kJ} \end{aligned}$$

**Discussion** The negative sign indicates that this work is done on the system (a work input), which is always the case for compression processes.



**FIGURE 4–8**

Schematic and  $P$ - $V$  diagram for Example 4–3.

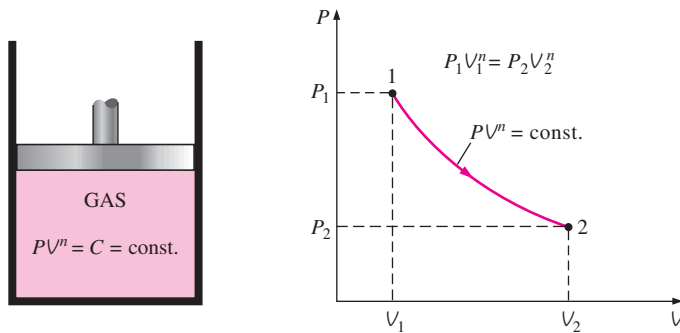


FIGURE 4-9

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

## Polytropic Process

During actual expansion and compression processes of gases, pressure and volume are often related by  $PV^n = C$ , where  $n$  and  $C$  are constants. A process of this kind is called a **polytropic process** (Fig. 4-9). Below we develop a general expression for the work done during a polytropic process. The pressure for a polytropic process can be expressed as

$$P = CV^{-n} \quad (4-8)$$

Substituting this relation into Eq. 4-2, we obtain

$$W_b = \int_1^2 P dV = \int_1^2 CV^{-n} dV = C \frac{V_2^{-n+1} - V_1^{-n+1}}{-n+1} = \frac{P_2V_2 - P_1V_1}{1-n} \quad (4-9)$$

since  $C = P_1V_1^n = P_2V_2^n$ . For an ideal gas ( $PV = mRT$ ), this equation can also be written as

$$W_b = \frac{mR(T_2 - T_1)}{1-n} \quad n \neq 1 \quad (\text{kJ}) \quad (4-10)$$

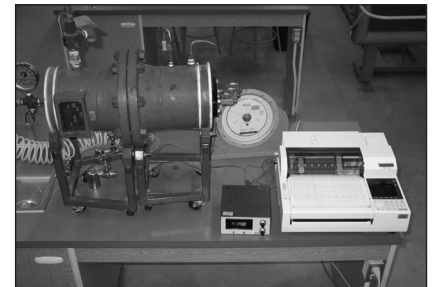
For the special case of  $n = 1$  the boundary work becomes

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

For an ideal gas this result is equivalent to the isothermal process discussed in the previous example.



### EXPERIMENT



Use actual data from the experiment shown here to find the **polytropic exponent** for expanding air. See end-of-chapter problem 4-184.

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### EXAMPLE 4-4 Expansion of a Gas against a Spring

A piston-cylinder device contains  $0.05 \text{ m}^3$  of a gas initially at  $200 \text{ kPa}$ . At this state, a linear spring that has a spring constant of  $150 \text{ kN/m}$  is touching the piston but exerting no force on it. Now heat is transferred to the gas, causing the piston to rise and to compress the spring until the volume inside the cylinder doubles. If the cross-sectional area of the piston is  $0.25 \text{ m}^2$ , determine (a) the final pressure inside the cylinder, (b) the total work done by

the gas, and (c) the fraction of this work done against the spring to compress it.

**Solution** A gas in a piston–cylinder device equipped with a linear spring expands as a result of heating. The final gas pressure, the total work done, and the fraction of the work done to compress the spring are to be determined.

**Assumptions** **1** The expansion process is quasi-equilibrium. **2** The spring is linear in the range of interest.

**Analysis** A sketch of the system and the  $P$ - $V$  diagram of the process are shown in Fig. 4–10.

(a) The enclosed volume at the final state is

$$V_2 = 2V_1 = (2)(0.05 \text{ m}^3) = 0.1 \text{ m}^3$$

Then the displacement of the piston (and of the spring) becomes

$$x = \frac{\Delta V}{A} = \frac{(0.1 - 0.05) \text{ m}^3}{0.25 \text{ m}^2} = 0.2 \text{ m}$$

The force applied by the linear spring at the final state is

$$F = kx = (150 \text{ kN/m})(0.2 \text{ m}) = 30 \text{ kN}$$

The additional pressure applied by the spring on the gas at this state is

$$P = \frac{F}{A} = \frac{30 \text{ kN}}{0.25 \text{ m}^2} = 120 \text{ kPa}$$

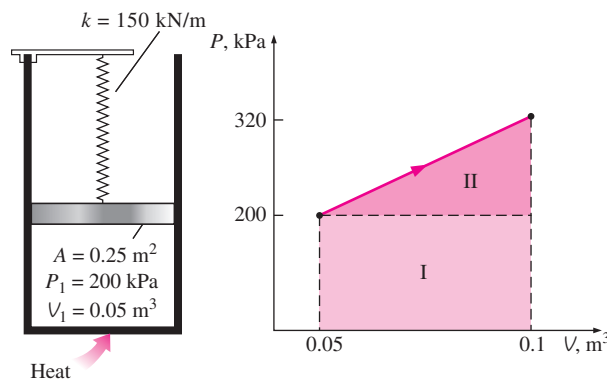
Without the spring, the pressure of the gas would remain constant at 200 kPa while the piston is rising. But under the effect of the spring, the pressure rises linearly from 200 kPa to

$$200 + 120 = \mathbf{320 \text{ kPa}}$$

at the final state.

(b) An easy way of finding the work done is to plot the process on a  $P$ - $V$  diagram and find the area under the process curve. From Fig. 4–10 the area under the process curve (a trapezoid) is determined to be

$$W = \text{area} = \frac{(200 + 320) \text{ kPa}}{2} [(0.1 - 0.05) \text{ m}^3] \left( \frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3} \right) = \mathbf{13 \text{ kJ}}$$



**FIGURE 4–10**

Schematic and  $P$ - $V$  diagram for Example 4–4.

Note that the work is done by the system.

(c) The work represented by the rectangular area (region I) is done against the piston and the atmosphere, and the work represented by the triangular area (region II) is done against the spring. Thus,

$$W_{\text{spring}} = \frac{1}{2}[(320 - 200) \text{ kPa}](0.05 \text{ m}^3) \left( \frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3} \right) = \mathbf{3 \text{ kJ}}$$

**Discussion** This result could also be obtained from

$$W_{\text{spring}} = \frac{1}{2}k(x_2^2 - x_1^2) = \frac{1}{2}(150 \text{ kN/m})[(0.2 \text{ m})^2 - 0^2] \left( \frac{1 \text{ kJ}}{1 \text{ kN} \cdot \text{m}} \right) = 3 \text{ kJ}$$

## 4-2 ■ ENERGY BALANCE FOR CLOSED SYSTEMS

Energy balance for any system undergoing any kind of process was expressed as (see Chap. 2)

$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{\text{system}}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc., energies}}} \quad (\text{kJ}) \quad (4-11)$$

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

$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{\text{system}}/dt}_{\substack{\text{Rate of change in internal,} \\ \text{kinetic, potential, etc., energies}}} \quad (\text{kW}) \quad (4-12)$$

For constant rates, the total quantities during a time interval  $\Delta t$  are related to the quantities per unit time as

$$Q = \dot{Q}\Delta t, \quad W = \dot{W}\Delta t, \quad \text{and} \quad \Delta E = (dE/dt)\Delta t \quad (\text{kJ}) \quad (4-13)$$

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

$$e_{\text{in}} - e_{\text{out}} = \Delta e_{\text{system}} \quad (\text{kJ/kg}) \quad (4-14)$$

which is obtained by dividing all the quantities in Eq. 4-11 by the mass  $m$  of the system. Energy balance can also be expressed in the differential form as

$$\delta E_{\text{in}} - \delta E_{\text{out}} = dE_{\text{system}} \quad \text{or} \quad \delta e_{\text{in}} - \delta e_{\text{out}} = de_{\text{system}} \quad (4-15)$$

For a closed system undergoing a **cycle**, the initial and final states are identical, and thus  $\Delta E_{\text{system}} = E_2 - E_1 = 0$ . Then the energy balance for a cycle simplifies to  $E_{\text{in}} - E_{\text{out}} = 0$  or  $E_{\text{in}} = E_{\text{out}}$ . Noting that a closed system does not involve any mass flow across its boundaries, the energy balance for a cycle can be expressed in terms of heat and work interactions as

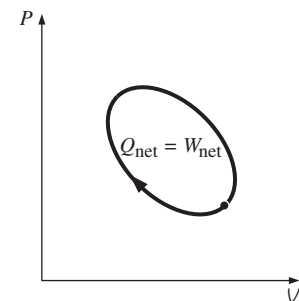
$$W_{\text{net,out}} = Q_{\text{net,in}} \quad \text{or} \quad \dot{W}_{\text{net,out}} = \dot{Q}_{\text{net,in}} \quad (\text{for a cycle}) \quad (4-16)$$

That is, the net work output during a cycle is equal to net heat input (Fig. 4-11).



**INTERACTIVE  
TUTORIAL**

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**FIGURE 4-11**

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

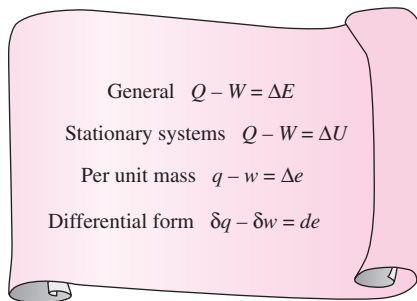


FIGURE 4-12

Various forms of the first-law relation for closed systems.

The energy balance (or the first-law) relations already given are intuitive in nature and are easy to use when the magnitudes and directions of heat and work transfers are known. However, when performing a general analytical study or solving a problem that involves an unknown heat or work interaction, we need to assume a direction for the heat or work interactions. In such cases, it is common practice to use the classical thermodynamics sign convention and to assume heat to be transferred *into the system* (heat input) in the amount of  $Q$  and work to be done *by the system* (work output) in the amount of  $W$ , and then to solve the problem. The energy balance relation in that case for a closed system becomes

$$Q_{\text{net,in}} - W_{\text{net,out}} = \Delta E_{\text{system}} \quad \text{or} \quad Q - W = \Delta E \quad (4-17)$$

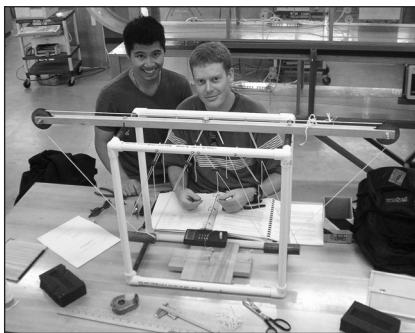
where  $Q = Q_{\text{net,in}} = Q_{\text{in}} - Q_{\text{out}}$  is the *net heat input* and  $W = W_{\text{net,out}} = W_{\text{out}} - W_{\text{in}}$  is the *net work output*. Obtaining a negative quantity for  $Q$  or  $W$  simply means that the assumed direction for that quantity is wrong and should be reversed. Various forms of this “traditional” first-law relation for closed systems are given in Fig. 4-12.

The first law cannot be proven mathematically, but no process in nature is known to have violated the first law, and this should be taken as sufficient proof. Note that if it were possible to prove the first law on the basis of other physical principles, the first law then would be a consequence of those principles instead of being a fundamental physical law itself.

As energy quantities, heat and work are not that different, and you probably wonder why we keep distinguishing them. After all, the change in the energy content of a system is equal to the amount of energy that crosses the system boundaries, and it makes no difference whether the energy crosses the boundary as heat or work. It seems as if the first-law relations would be much simpler if we had just one quantity that we could call *energy interaction* to represent both heat and work. Well, from the first-law point of view, heat and work are not different at all. From the second-law point of view, however, heat and work are very different, as is discussed in later chapters.



## EXPERIMENT



Use actual data from the experiment shown here to verify the **first law of thermodynamics**. See end-of-chapter problem 4-185.

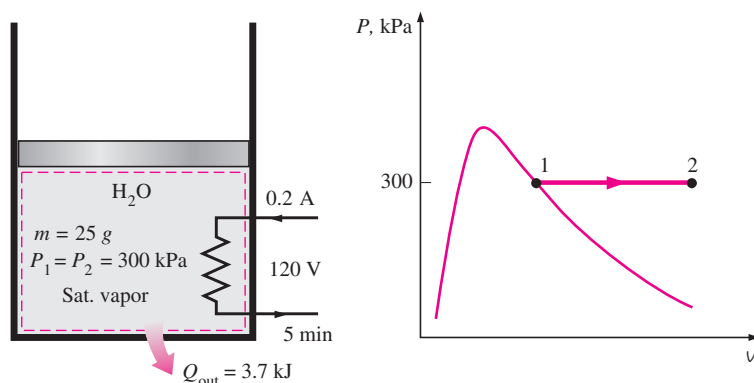
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## EXAMPLE 4-5 Electric Heating of a Gas at Constant Pressure

A piston-cylinder device contains 25 g of saturated water vapor that is maintained at a constant pressure of 300 kPa. A resistance heater within the cylinder is turned on and passes a current of 0.2 A for 5 min from a 120-V source. At the same time, a heat loss of 3.7 kJ occurs. (a) Show that for a closed system the boundary work  $W_b$  and the change in internal energy  $\Delta U$  in the first-law relation can be combined into one term,  $\Delta H$ , for a constant-pressure process. (b) Determine the final temperature of the steam.

**Solution** Saturated water vapor in a piston-cylinder device expands at constant pressure as a result of heating. It is to be shown that  $\Delta U + W_b = \Delta H$ , and the final temperature is to be determined.

**Assumptions** 1 The tank is stationary and thus the kinetic and potential energy changes are zero,  $\Delta KE = \Delta PE = 0$ . Therefore,  $\Delta E = \Delta U$  and internal energy is the only form of energy of the system that may change during this process. 2 Electrical wires constitute a very small part of the system, and thus the energy change of the wires can be neglected.



**FIGURE 4-13**  
Schematic and  $P$ - $v$  diagram for Example 4-5.

**Analysis** We take the contents of the cylinder, including the resistance wires, as the *system* (Fig. 4-13). This is a *closed system* since no mass crosses the system boundary during the process. We observe that a piston-cylinder device typically involves a moving boundary and thus boundary work  $W_b$ . The pressure remains constant during the process and thus  $P_2 = P_1$ . Also, heat is lost from the system and electrical work  $W_e$  is done on the system.

(a) This part of the solution involves a general analysis for a closed system undergoing a quasi-equilibrium constant-pressure process, and thus we consider a general closed system. We take the direction of heat transfer  $Q$  to be to the system and the work  $W$  to be done by the system. We also express the work as the sum of boundary and other forms of work (such as electrical and shaft). Then the energy balance can be expressed as

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

$$Q - W = \Delta U + \Delta KE^0 + \Delta PE^0$$

$$Q - W_{\text{other}} - W_b = U_2 - U_1$$

For a constant-pressure process, the boundary work is given as  $W_b = P_0(V_2 - V_1)$ . Substituting this into the preceding relation gives

$$Q - W_{\text{other}} - P_0(V_2 - V_1) = U_2 - U_1$$

However,

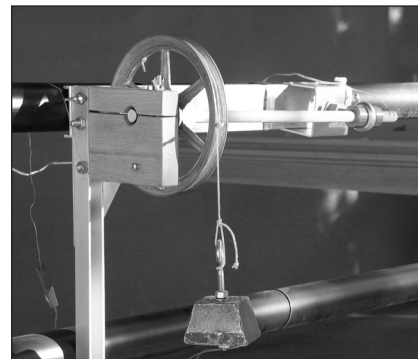
$$P_0 = P_2 = P_1 \rightarrow Q - W_{\text{other}} = (U_2 + P_2V_2) - (U_1 + P_1V_1)$$

Also  $H = U + PV$ , and thus

$$Q - W_{\text{other}} = H_2 - H_1 \quad (\text{kJ}) \quad (4-18)$$

which is the desired relation (Fig. 4-14). This equation is very convenient to use in the analysis of closed systems undergoing a constant-pressure quasi-equilibrium process since the boundary work is automatically taken care of by the enthalpy terms, and one no longer needs to determine it separately.

### EXPERIMENT



Use actual data from the experiment shown here to verify the **first law of thermodynamics**. See end-of-chapter problem 4-186.

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### EXPERIMENT



Use actual data from the experiment shown here to verify the **first law of thermodynamics**. See end-of-chapter problem 4-187.

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## EXPERIMENT



Use actual data from the experiment shown here to verify the **first law of thermodynamics**. See end-of-chapter problem 4–188.

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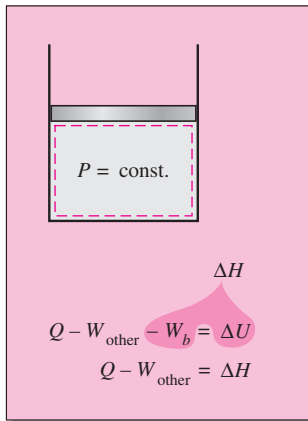


FIGURE 4–14

For a closed system undergoing a quasi-equilibrium,  $P = \text{constant}$  process,  $\Delta U + W_b = \Delta H$ .

(b) The only other form of work in this case is the electrical work, which can be determined from

$$W_e = VI \Delta t = (120 \text{ V})(0.2 \text{ A})(300 \text{ s}) \left( \frac{1 \text{ kJ/s}}{1000 \text{ VA}} \right) = 7.2 \text{ kJ}$$

$$\text{State 1: } \left. \begin{array}{l} P_1 = 300 \text{ kPa} \\ \text{sat. vapor} \end{array} \right\} h_1 = h_g @ 300 \text{ kPa} = 2724.9 \text{ kJ/kg} \quad (\text{Table A-5})$$

The enthalpy at the final state can be determined directly from Eq. 4–18 by expressing heat transfer from the system and work done on the system as negative quantities (since their directions are opposite to the assumed directions). Alternately, we can use the general energy balance relation with the simplification that the boundary work is considered automatically by replacing  $\Delta U$  by  $\Delta H$  for a constant-pressure expansion or compression process:

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

$$W_{e,\text{in}} - Q_{\text{out}} - W_b = \Delta U$$

$$W_{e,\text{in}} - Q_{\text{out}} = \Delta H = m(h_2 - h_1) \quad (\text{since } P = \text{constant})$$

$$7.2 \text{ kJ} - 3.7 \text{ kJ} = (0.025 \text{ kg})(h_2 - 2724.9 \text{ kJ/kg})$$

$$h_2 = 2864.9 \text{ kJ/kg}$$

Now the final state is completely specified since we know both the pressure and the enthalpy. The temperature at this state is

$$\text{State 2: } \left. \begin{array}{l} P_2 = 300 \text{ kPa} \\ h_2 = 2864.9 \text{ kJ/kg} \end{array} \right\} T_2 = 200^\circ\text{C} \quad (\text{Table A-6})$$

Therefore, the steam will be at  $200^\circ\text{C}$  at the end of this process.

**Discussion** Strictly speaking, the potential energy change of the steam is not zero for this process since the center of gravity of the steam rose somewhat. Assuming an elevation change of 1 m (which is rather unlikely), the change in the potential energy of the steam would be 0.0002 kJ, which is very small compared to the other terms in the first-law relation. Therefore, in problems of this kind, the potential energy term is always neglected.

#### EXAMPLE 4–6 Unrestrained Expansion of Water

A rigid tank is divided into two equal parts by a partition. Initially, one side of the tank contains 5 kg of water at 200 kPa and  $25^\circ\text{C}$ , and the other side is evacuated. The partition is then removed, and the water expands into the entire tank. The water is allowed to exchange heat with its surroundings until the temperature in the tank returns to the initial value of  $25^\circ\text{C}$ . Determine (a) the volume of the tank, (b) the final pressure, and (c) the heat transfer for this process.

**Solution** One half of a rigid tank is filled with liquid water while the other side is evacuated. The partition between the two parts is removed and water is allowed to expand and fill the entire tank while the temperature is maintained constant. The volume of tank, the final pressure, and the heat transfer are to be determined.

**Assumptions** **1** The system is stationary and thus the kinetic and potential energy changes are zero,  $\Delta KE = \Delta PE = 0$  and  $\Delta E = \Delta U$ . **2** The direction of heat transfer is to the system (heat gain,  $Q_{in}$ ). A negative result for  $Q_{in}$  indicates the assumed direction is wrong and thus it is a heat loss. **3** The volume of the rigid tank is constant, and thus there is no energy transfer as boundary work. **4** There is no electrical, shaft, or any other kind of work involved.

**Analysis** We take the contents of the tank, including the evacuated space, as the *system* (Fig. 4–15). This is a *closed system* since no mass crosses the system boundary during the process. We observe that the water fills the entire tank when the partition is removed (possibly as a liquid–vapor mixture).

(a) Initially the water in the tank exists as a compressed liquid since its pressure (200 kPa) is greater than the saturation pressure at 25°C (3.1698 kPa). Approximating the compressed liquid as a saturated liquid at the given temperature, we find

$$v_1 \cong v_f @ 25^\circ\text{C} = 0.001003 \text{ m}^3/\text{kg} \cong 0.001 \text{ m}^3/\text{kg} \quad (\text{Table A-4})$$

Then the initial volume of the water is

$$V_1 = m v_1 = (5 \text{ kg})(0.001 \text{ m}^3/\text{kg}) = 0.005 \text{ m}^3$$

The total volume of the tank is twice this amount:

$$V_{\text{tank}} = (2)(0.005 \text{ m}^3) = \mathbf{0.01 \text{ m}^3}$$

(b) At the final state, the specific volume of the water is

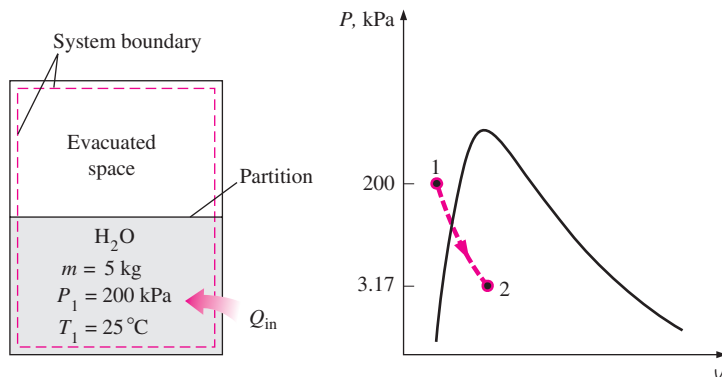
$$v_2 = \frac{V_2}{m} = \frac{0.01 \text{ m}^3}{5 \text{ kg}} = 0.002 \text{ m}^3/\text{kg}$$

which is twice the initial value of the specific volume. This result is expected since the volume doubles while the amount of mass remains constant.

At 25°C:  $v_f = 0.001003 \text{ m}^3/\text{kg}$  and  $v_g = 43.340 \text{ m}^3/\text{kg}$  (Table A–4)

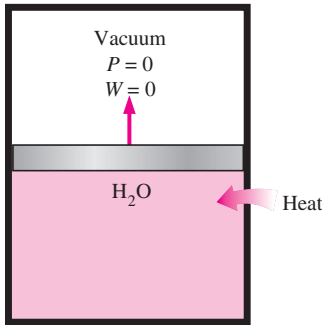
Since  $v_f < v_2 < v_g$ , the water is a saturated liquid–vapor mixture at the final state, and thus the pressure is the saturation pressure at 25°C:

$$P_2 = P_{\text{sat}} @ 25^\circ\text{C} = \mathbf{3.1698 \text{ kPa}} \quad (\text{Table A-4})$$

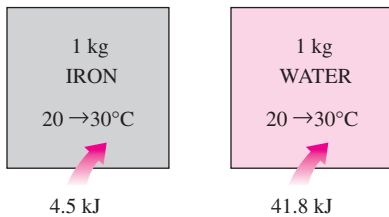


**FIGURE 4–15**

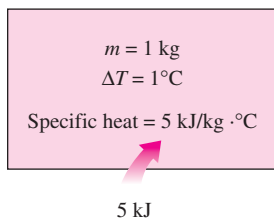
Schematic and  $P$ - $v$  diagram for Example 4–6.


**FIGURE 4-16**

Expansion against a vacuum involves no work and thus no energy transfer.


**FIGURE 4-17**

It takes different amounts of energy to raise the temperature of different substances by the same amount.


**FIGURE 4-18**

Specific heat is the energy required to raise the temperature of a unit mass of a substance by one degree in a specified way.



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(c) Under stated assumptions and observations, the energy balance on the system can be expressed as

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

$$Q_{\text{in}} = \Delta U = m(u_2 - u_1)$$

Notice that even though the water is expanding during this process, the system chosen involves fixed boundaries only (the dashed lines) and therefore the moving boundary work is zero (Fig. 4-16). Then  $W = 0$  since the system does not involve any other forms of work. (Can you reach the same conclusion by choosing the water as our system?) Initially,

$$u_1 \cong u_f @ 25^\circ\text{C} = 104.83 \text{ kJ/kg}$$

The quality at the final state is determined from the specific volume information:

$$x_2 = \frac{v_2 - v_f}{v_{fg}} = \frac{0.002 - 0.001}{43.34 - 0.001} = 2.3 \times 10^{-5}$$

Then

$$\begin{aligned} u_2 &= u_f + x_2 u_{fg} \\ &= 104.83 \text{ kJ/kg} + (2.3 \times 10^{-5})(2304.3 \text{ kJ/kg}) \\ &= 104.88 \text{ kJ/kg} \end{aligned}$$

Substituting yields

$$Q_{\text{in}} = (5 \text{ kg})[(104.88 - 104.83) \text{ kJ/kg}] = \mathbf{0.25 \text{ kJ}}$$

**Discussion** The positive sign indicates that the assumed direction is correct, and heat is transferred to the water.

### 4-3 ■ SPECIFIC HEATS

We know from experience that it takes different amounts of energy to raise the temperature of identical masses of different substances by one degree. For example, we need about 4.5 kJ of energy to raise the temperature of 1 kg of iron from 20 to 30°C, whereas it takes about 9 times this energy (41.8 kJ to be exact) to raise the temperature of 1 kg of liquid water by the same amount (Fig. 4-17). Therefore, it is desirable to have a property that will enable us to compare the energy storage capabilities of various substances. This property is the specific heat.

The **specific heat** is defined as *the energy required to raise the temperature of a unit mass of a substance by one degree* (Fig. 4-18). In general, this energy depends on how the process is executed. In thermodynamics, we are interested in two kinds of specific heats: **specific heat at constant volume**  $c_v$  and **specific heat at constant pressure**  $c_p$ .

Physically, the specific heat at constant volume  $c_v$  can be viewed as *the energy required to raise the temperature of the unit mass of a substance by one degree as the volume is maintained constant*. The energy required to

do the same as the pressure is maintained constant is the specific heat at constant pressure  $c_p$ . This is illustrated in Fig. 4–19. The specific heat at constant pressure  $c_p$  is always greater than  $c_v$  because at constant pressure the system is allowed to expand and the energy for this expansion work must also be supplied to the system.

Now we attempt to express the specific heats in terms of other thermodynamic properties. First, consider a fixed mass in a stationary closed system undergoing a constant-volume process (and thus no expansion or compression work is involved). The conservation of energy principle  $e_{in} - e_{out} = \Delta e_{system}$  for this process can be expressed in the differential form as

$$\delta e_{in} - \delta e_{out} = du$$

The left-hand side of this equation represents the net amount of energy transferred to the system. From the definition of  $c_v$ , this energy must be equal to  $c_v dT$ , where  $dT$  is the differential change in temperature. Thus,

$$c_v dT = du \quad \text{at constant volume}$$

or

$$c_v = \left( \frac{\partial u}{\partial T} \right)_v \quad (4-19)$$

Similarly, an expression for the specific heat at constant pressure  $c_p$  can be obtained by considering a constant-pressure expansion or compression process. It yields

$$c_p = \left( \frac{\partial h}{\partial T} \right)_p \quad (4-20)$$

Equations 4–19 and 4–20 are the defining equations for  $c_v$  and  $c_p$ , and their interpretation is given in Fig. 4–20.

Note that  $c_v$  and  $c_p$  are expressed in terms of other properties; thus, they must be properties themselves. Like any other property, the specific heats of a substance depend on the state that, in general, is specified by two independent, intensive properties. That is, the energy required to raise the temperature of a substance by one degree is different at different temperatures and pressures (Fig. 4–21). But this difference is usually not very large.

A few observations can be made from Eqs. 4–19 and 4–20. First, these equations are *property relations* and as such are *independent of the type of processes*. They are valid for *any* substance undergoing *any* process. The only relevance  $c_v$  has to a constant-volume process is that  $c_v$  happens to be the energy transferred to a system during a constant-volume process per unit mass per unit degree rise in temperature. This is how the values of  $c_v$  are determined. This is also how the name *specific heat at constant volume* originated. Likewise, the energy transferred to a system per unit mass per unit temperature rise during a constant-pressure process happens to be equal to  $c_p$ . This is how the values of  $c_p$  can be determined and also explains the origin of the name *specific heat at constant pressure*.

Another observation that can be made from Eqs. 4–19 and 4–20 is that  $c_v$  is related to the changes in *internal energy* and  $c_p$  to the changes in *enthalpy*. In fact, it would be more proper to define  $c_v$  as *the change in the internal energy of a substance per unit change in temperature at constant*

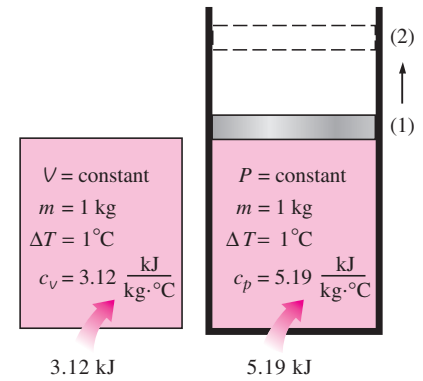


FIGURE 4–19

Constant-volume and constant-pressure specific heats  $c_v$  and  $c_p$  (values given are for helium gas).

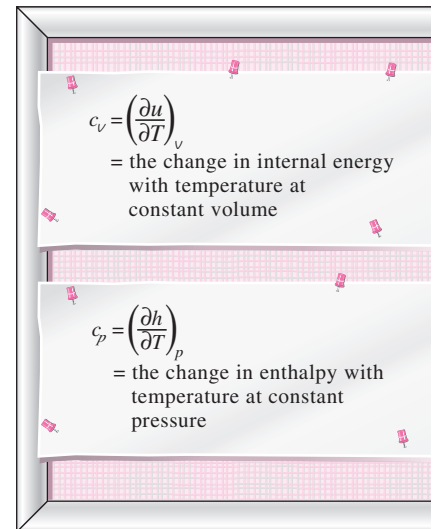
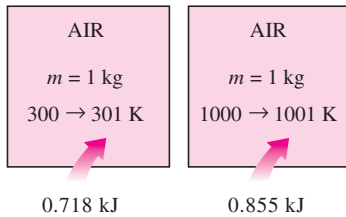


FIGURE 4–20

Formal definitions of  $c_v$  and  $c_p$ .



**FIGURE 4-21**

The specific heat of a substance changes with temperature.

volume. Likewise,  $c_p$  can be defined as *the change in the enthalpy of a substance per unit change in temperature at constant pressure*. In other words,  $c_v$  is a measure of the variation of internal energy of a substance with temperature, and  $c_p$  is a measure of the variation of enthalpy of a substance with temperature.

Both the internal energy and enthalpy of a substance can be changed by the transfer of *energy* in any form, with heat being only one of them. Therefore, the term *specific energy* is probably more appropriate than the term *specific heat*, which implies that energy is transferred (and stored) in the form of heat.

A common unit for specific heats is  $\text{kJ/kg} \cdot ^\circ\text{C}$  or  $\text{kJ/kg} \cdot \text{K}$ . Notice that these two units are *identical* since  $\Delta T(^{\circ}\text{C}) = \Delta T(\text{K})$ , and  $1^{\circ}\text{C}$  change in temperature is equivalent to a change of 1 K. The specific heats are sometimes given on a *molar basis*. They are then denoted by  $\bar{c}_v$  and  $\bar{c}_p$  and have the unit  $\text{kJ/kmol} \cdot ^\circ\text{C}$  or  $\text{kJ/kmol} \cdot \text{K}$ .



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## 4-4 ■ INTERNAL ENERGY, ENTHALPY, AND SPECIFIC HEATS OF IDEAL GASES

We defined an ideal gas as a gas whose temperature, pressure, and specific volume are related by

$$Pv = RT$$

It has been demonstrated mathematically (Chap. 12) and experimentally (Joule, 1843) that for an ideal gas the internal energy is a function of the temperature only. That is,

$$u = u(T) \quad (4-21)$$

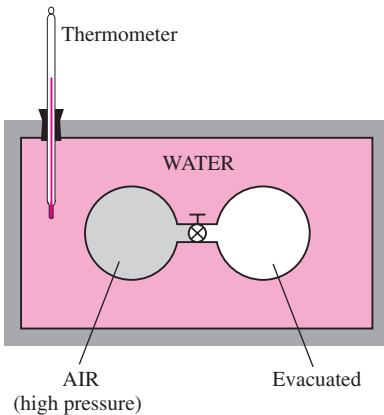
In his classical experiment, Joule submerged two tanks connected with a pipe and a valve in a water bath, as shown in Fig. 4-22. Initially, one tank contained air at a high pressure and the other tank was evacuated. When thermal equilibrium was attained, he opened the valve to let air pass from one tank to the other until the pressures equalized. Joule observed no change in the temperature of the water bath and assumed that no heat was transferred to or from the air. Since there was also no work done, he concluded that the internal energy of the air did not change even though the volume and the pressure changed. Therefore, he reasoned, the internal energy is a function of temperature only and not a function of pressure or specific volume. (Joule later showed that for gases that deviate significantly from ideal-gas behavior, the internal energy is not a function of temperature alone.)

Using the definition of enthalpy and the equation of state of an ideal gas, we have

$$\left. \begin{aligned} h &= u + Pv \\ Pv &= RT \end{aligned} \right\} h = u + RT$$

Since  $R$  is constant and  $u = u(T)$ , it follows that the enthalpy of an ideal gas is also a function of temperature only:

$$h = h(T) \quad (4-22)$$



**FIGURE 4-22**

Schematic of the experimental apparatus used by Joule.

Since  $u$  and  $h$  depend only on temperature for an ideal gas, the specific heats  $c_v$  and  $c_p$  also depend, at most, on temperature only. Therefore, at a given temperature,  $u$ ,  $h$ ,  $c_v$ , and  $c_p$  of an ideal gas have fixed values regardless of the specific volume or pressure (Fig. 4–23). Thus, for ideal gases, the partial derivatives in Eqs. 4–19 and 4–20 can be replaced by ordinary derivatives. Then the differential changes in the internal energy and enthalpy of an ideal gas can be expressed as

$$du = c_v(T) dT \quad (4-23)$$

and

$$dh = c_p(T) dT \quad (4-24)$$

The change in internal energy or enthalpy for an ideal gas during a process from state 1 to state 2 is determined by integrating these equations:

$$\Delta u = u_2 - u_1 = \int_1^2 c_v(T) dT \quad (\text{kJ/kg}) \quad (4-25)$$

and

$$\Delta h = h_2 - h_1 = \int_1^2 c_p(T) dT \quad (\text{kJ/kg}) \quad (4-26)$$

To carry out these integrations, we need to have relations for  $c_v$  and  $c_p$  as functions of temperature.

At low pressures, all real gases approach ideal-gas behavior, and therefore their specific heats depend on temperature only. The specific heats of real gases at low pressures are called *ideal-gas specific heats*, or *zero-pressure specific heats*, and are often denoted  $c_{p0}$  and  $c_{v0}$ . Accurate analytical expressions for ideal-gas specific heats, based on direct measurements or calculations from statistical behavior of molecules, are available and are given as third-degree polynomials in the appendix (Table A–2c) for several gases. A plot of  $\bar{c}_{p0}(T)$  data for some common gases is given in Fig. 4–24.

The use of ideal-gas specific heat data is limited to low pressures, but these data can also be used at moderately high pressures with reasonable accuracy as long as the gas does not deviate from ideal-gas behavior significantly.

The integrations in Eqs. 4–25 and 4–26 are straightforward but rather time-consuming and thus impractical. To avoid these laborious calculations,  $u$  and  $h$  data for a number of gases have been tabulated over small temperature intervals. These tables are obtained by choosing an arbitrary reference point and performing the integrations in Eqs. 4–25 and 4–26 by treating state 1 as the reference state. In the ideal-gas tables given in the appendix, zero kelvin is chosen as the reference state, and both the enthalpy and the internal energy are assigned zero values at that state (Fig. 4–25). The choice of the reference state has no effect on  $\Delta u$  or  $\Delta h$  calculations. The  $u$  and  $h$  data are given in kJ/kg for air (Table A–17) and usually in kJ/kmol for other gases. The unit kJ/kmol is very convenient in the thermodynamic analysis of chemical reactions.

Some observations can be made from Fig. 4–24. First, the specific heats of gases with complex molecules (molecules with two or more atoms) are higher and increase with temperature. Also, the variation of specific heats

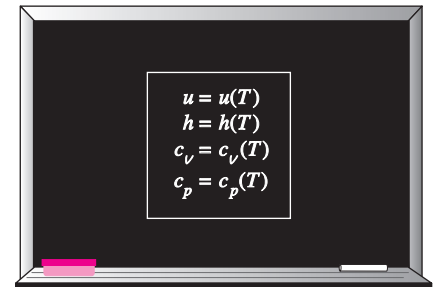


FIGURE 4–23

For ideal gases,  $u$ ,  $h$ ,  $c_v$ , and  $c_p$  vary with temperature only.

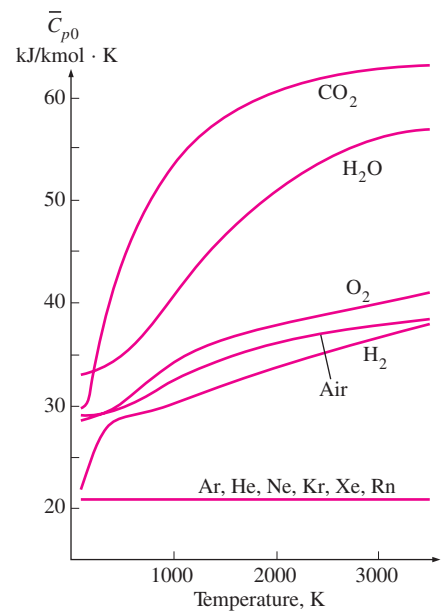


FIGURE 4–24

Ideal-gas constant-pressure specific heats for some gases (see Table A–2c for  $c_p$  equations).

AIR		
$T, \text{K}$	$u, \text{kJ/kg}$	$h, \text{kJ/kg}$
0	0	0
...	...	...
300	214.07	300.19
310	221.25	310.24
...	...	...

FIGURE 4–25

In the preparation of ideal-gas tables, 0 K is chosen as the reference temperature.

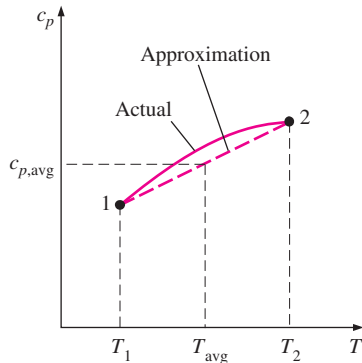


FIGURE 4–26

For small temperature intervals, the specific heats may be assumed to vary linearly with temperature.

with temperature is smooth and may be approximated as linear over small temperature intervals (a few hundred degrees or less). Therefore the specific heat functions in Eqs. 4–25 and 4–26 can be replaced by the constant average specific heat values. Then the integrations in these equations can be performed, yielding

$$u_2 - u_1 = c_{v,\text{avg}}(T_2 - T_1) \quad (\text{kJ/kg}) \quad (4-27)$$

and

$$h_2 - h_1 = c_{p,\text{avg}}(T_2 - T_1) \quad (\text{kJ/kg}) \quad (4-28)$$

The specific heat values for some common gases are listed as a function of temperature in Table A–2b. The average specific heats  $c_{p,\text{avg}}$  and  $c_{v,\text{avg}}$  are evaluated from this table at the average temperature  $(T_1 + T_2)/2$ , as shown in Fig. 4–26. If the final temperature  $T_2$  is not known, the specific heats may be evaluated at  $T_1$  or at the anticipated average temperature. Then  $T_2$  can be determined by using these specific heat values. The value of  $T_2$  can be refined, if necessary, by evaluating the specific heats at the new average temperature.

Another way of determining the average specific heats is to evaluate them at  $T_1$  and  $T_2$  and then take their average. Usually both methods give reasonably good results, and one is not necessarily better than the other.

Another observation that can be made from Fig. 4–24 is that the ideal-gas specific heats of *monatomic gases* such as argon, neon, and helium remain constant over the entire temperature range. Thus,  $\Delta u$  and  $\Delta h$  of monatomic gases can easily be evaluated from Eqs. 4–27 and 4–28.

Note that the  $\Delta u$  and  $\Delta h$  relations given previously are not restricted to any kind of process. They are valid for all processes. The presence of the constant-volume specific heat  $c_v$  in an equation should not lead one to believe that this equation is valid for a constant-volume process only. On the contrary, the relation  $\Delta u = c_{v,\text{avg}} \Delta T$  is valid for *any* ideal gas undergoing *any* process (Fig. 4–27). A similar argument can be given for  $c_p$  and  $\Delta h$ .

To summarize, there are three ways to determine the internal energy and enthalpy changes of ideal gases (Fig. 4–28):

1. By using the tabulated  $u$  and  $h$  data. This is the easiest and most accurate way when tables are readily available.
2. By using the  $c_v$  or  $c_p$  relations as a function of temperature and performing the integrations. This is very inconvenient for hand calculations but quite desirable for computerized calculations. The results obtained are very accurate.
3. By using average specific heats. This is very simple and certainly very convenient when property tables are not available. The results obtained are reasonably accurate if the temperature interval is not very large.

## Specific Heat Relations of Ideal Gases

A special relationship between  $c_p$  and  $c_v$  for ideal gases can be obtained by differentiating the relation  $h = u + RT$ , which yields

$$dh = du + R dT$$

Replacing  $dh$  by  $c_p dT$  and  $du$  by  $c_v dT$  and dividing the resulting expression by  $dT$ , we obtain

$$c_p = c_v + R \quad (\text{kJ/kg} \cdot \text{K}) \quad (4-29)$$

This is an important relationship for ideal gases since it enables us to determine  $c_v$  from a knowledge of  $c_p$  and the gas constant  $R$ .

When the specific heats are given on a molar basis,  $R$  in the above equation should be replaced by the universal gas constant  $R_u$  (Fig. 4-29).

$$\bar{c}_p = \bar{c}_v + R_u \quad (\text{kJ/kmol} \cdot \text{K}) \quad (4-30)$$

At this point, we introduce another ideal-gas property called the **specific heat ratio**  $k$ , defined as

$$k = \frac{c_p}{c_v} \quad (4-31)$$

The specific ratio also varies with temperature, but this variation is very mild. For monatomic gases, its value is essentially constant at 1.667. Many diatomic gases, including air, have a specific heat ratio of about 1.4 at room temperature.

#### EXAMPLE 4-7 Evaluation of the $\Delta u$ of an Ideal Gas

Air at 300 K and 200 kPa is heated at constant pressure to 600 K. Determine the change in internal energy of air per unit mass, using (a) data from the air table (Table A-17), (b) the functional form of the specific heat (Table A-2c), and (c) the average specific heat value (Table A-2b).

**Solution** The internal energy change of air is to be determined in three different ways.

**Assumptions** At specified conditions, air can be considered to be an ideal gas since it is at a high temperature and low pressure relative to its critical-point values.

**Analysis** The internal energy change  $\Delta u$  of ideal gases depends on the initial and final temperatures only, and not on the type of process. Thus, the following solution is valid for any kind of process.

(a) One way of determining the change in internal energy of air is to read the  $u$  values at  $T_1$  and  $T_2$  from Table A-17 and take the difference:

$$u_1 = u_{@ 300 \text{ K}} = 214.07 \text{ kJ/kg}$$

$$u_2 = u_{@ 600 \text{ K}} = 434.78 \text{ kJ/kg}$$

Thus,

$$\Delta u = u_2 - u_1 = (434.78 - 214.07) \text{ kJ/kg} = \mathbf{220.71 \text{ kJ/kg}}$$

(b) The  $\bar{c}_p(T)$  of air is given in Table A-2c in the form of a third-degree polynomial expressed as

$$\bar{c}_p(T) = a + bT + cT^2 + dT^3$$

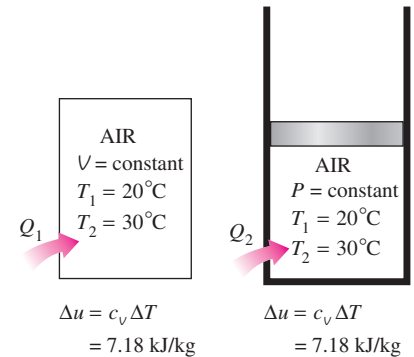


FIGURE 4-27

The relation  $\Delta u = c_v \Delta T$  is valid for any kind of process, constant-volume or not.

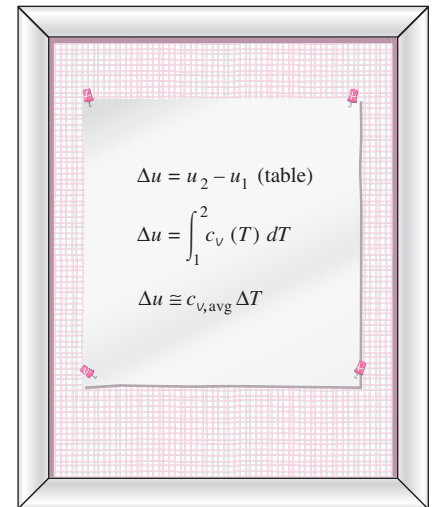


FIGURE 4-28

Three ways of calculating  $\Delta u$ .

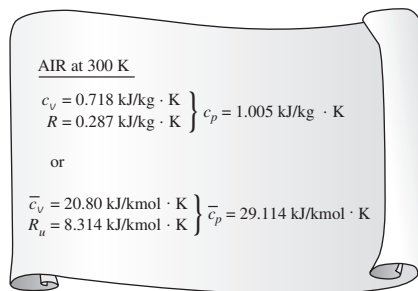


FIGURE 4–29

The  $c_p$  of an ideal gas can be determined from a knowledge of  $c_v$  and  $R$ .

where  $a = 28.11$ ,  $b = 0.1967 \times 10^{-2}$ ,  $c = 0.4802 \times 10^{-5}$ , and  $d = -1.966 \times 10^{-9}$ . From Eq. 4–30,

$$\bar{c}_v(T) = \bar{c}_p - R_u = (a - R_u) + bT + cT^2 + dT^3$$

From Eq. 4–25,

$$\Delta \bar{u} = \int_1^2 \bar{c}_v(T) dT = \int_{T_1}^{T_2} [(a - R_u) + bT + cT^2 + dT^3] dT$$

Performing the integration and substituting the values, we obtain

$$\Delta \bar{u} = 6447 \text{ kJ/kmol}$$

The change in the internal energy on a unit-mass basis is determined by dividing this value by the molar mass of air (Table A–1):

$$\Delta u = \frac{\Delta \bar{u}}{M} = \frac{6447 \text{ kJ/kmol}}{28.97 \text{ kg/kmol}} = \mathbf{222.5 \text{ kJ/kg}}$$

which differs from the tabulated value by 0.8 percent.

(c) The average value of the constant-volume specific heat  $c_{v,\text{avg}}$  is determined from Table A–2b at the average temperature of  $(T_1 + T_2)/2 = 450 \text{ K}$  to be

$$c_{v,\text{avg}} = c_{v@450\text{K}} = 0.733 \text{ kJ/kg} \cdot \text{K}$$

Thus,

$$\begin{aligned} \Delta u &= c_{v,\text{avg}}(T_2 - T_1) = (0.733 \text{ kJ/kg} \cdot \text{K})[(600 - 300)\text{K}] \\ &= 220 \text{ kJ/kg} \end{aligned}$$

**Discussion** This answer differs from the tabulated value (220.71 kJ/kg) by only 0.4 percent. This close agreement is not surprising since the assumption that  $c_v$  varies linearly with temperature is a reasonable one at temperature intervals of only a few hundred degrees. If we had used the  $c_v$  value at  $T_1 = 300 \text{ K}$  instead of at  $T_{\text{avg}}$ , the result would be 215.4 kJ/kg, which is in error by about 2 percent. Errors of this magnitude are acceptable for most engineering purposes.

### EXAMPLE 4–8 Heating of a Gas in a Tank by Stirring

An insulated rigid tank initially contains 1.5 lbm of helium at 80°F and 50 psia. A paddle wheel with a power rating of 0.02 hp is operated within the tank for 30 min. Determine (a) the final temperature and (b) the final pressure of the helium gas.

**Solution** Helium gas in an insulated rigid tank is stirred by a paddle wheel. The final temperature and pressure of helium are to be determined.

**Assumptions** **1** Helium is an ideal gas since it is at a very high temperature relative to its critical-point value of  $-451^\circ\text{F}$ . **2** Constant specific heats can be used for helium. **3** The system is stationary and thus the kinetic and potential energy changes are zero,  $\Delta\text{KE} = \Delta\text{PE} = 0$  and  $\Delta E = \Delta U$ . **4** The volume of the tank is constant, and thus there is no boundary work. **5** The system is adiabatic and thus there is no heat transfer.

**Analysis** We take the contents of the tank as the *system* (Fig. 4–30). This is a *closed system* since no mass crosses the system boundary during the process. We observe that there is shaft work done on the system.

(a) The amount of paddle-wheel work done on the system is

$$W_{\text{sh}} = \dot{W}_{\text{sh}} \Delta t = (0.02 \text{ hp})(0.5 \text{ h}) \left( \frac{2545 \text{ Btu/h}}{1 \text{ hp}} \right) = 25.45 \text{ Btu}$$

Under the stated assumptions and observations, the energy balance on the system can be expressed as

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

$$W_{\text{sh, in}} = \Delta U = m(u_2 - u_1) = mc_{v, \text{avg}}(T_2 - T_1)$$

As we pointed out earlier, the ideal-gas specific heats of monatomic gases (helium being one of them) are constant. The  $c_v$  value of helium is determined from Table A–2Ea to be  $c_v = 0.753 \text{ Btu/lbm} \cdot ^\circ\text{F}$ . Substituting this and other known quantities into the above equation, we obtain

$$25.45 \text{ Btu} = (1.5 \text{ lbm})(0.753 \text{ Btu/lbm} \cdot ^\circ\text{F})(T_2 - 80^\circ\text{F})$$

$$T_2 = \mathbf{102.5^\circ\text{F}}$$

(b) The final pressure is determined from the ideal-gas relation

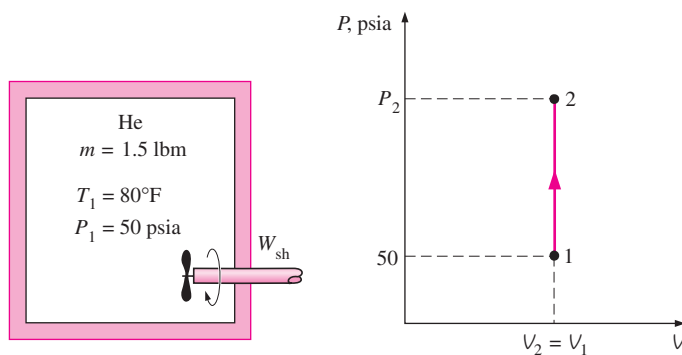
$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

where  $V_1$  and  $V_2$  are identical and cancel out. Then the final pressure becomes

$$\frac{50 \text{ psia}}{(80 + 460) \text{ R}} = \frac{P_2}{(102.5 + 460) \text{ R}}$$

$$P_2 = \mathbf{52.1 \text{ psia}}$$

**Discussion** Note that the pressure in the ideal-gas relation is always the absolute pressure.



**FIGURE 4–30**

Schematic and  $P$ - $V$  diagram for Example 4–8.

**EXAMPLE 4–9 Heating of a Gas by a Resistance Heater**

A piston–cylinder device initially contains 0.5 m<sup>3</sup> of nitrogen gas at 400 kPa and 27°C. An electric heater within the device is turned on and is allowed to pass a current of 2 A for 5 min from a 120-V source. Nitrogen expands at constant pressure, and a heat loss of 2800 J occurs during the process. Determine the final temperature of nitrogen.

**Solution** Nitrogen gas in a piston–cylinder device is heated by an electric resistance heater. Nitrogen expands at constant pressure while some heat is lost. The final temperature of nitrogen is to be determined.

**Assumptions** **1** Nitrogen is an ideal gas since it is at a high temperature and low pressure relative to its critical-point values of –147°C, and 3.39 MPa. **2** The system is stationary and thus the kinetic and potential energy changes are zero,  $\Delta KE = \Delta PE = 0$  and  $\Delta E = \Delta U$ . **3** The pressure remains constant during the process and thus  $P_2 = P_1$ . **4** Nitrogen has constant specific heats at room temperature.

**Analysis** We take the contents of the cylinder as the *system* (Fig. 4–31). This is a *closed system* since no mass crosses the system boundary during the process. We observe that a piston–cylinder device typically involves a moving boundary and thus boundary work,  $W_b$ . Also, heat is lost from the system and electrical work  $W_e$  is done on the system.

First, let us determine the electrical work done on the nitrogen:

$$W_e = VI \Delta t = (120 \text{ V})(2 \text{ A})(5 \times 60 \text{ s}) \left( \frac{1 \text{ kJ/s}}{1000 \text{ VA}} \right) = 72 \text{ kJ}$$

The mass of nitrogen is determined from the ideal-gas relation:

$$m = \frac{P_1 V_1}{RT_1} = \frac{(400 \text{ kPa})(0.5 \text{ m}^3)}{(0.297 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(300 \text{ K})} = 2.245 \text{ kg}$$

Under the stated assumptions and observations, the energy balance on the system can be expressed as

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

$$W_{e,\text{in}} - Q_{\text{out}} - W_{b,\text{out}} = \Delta U$$

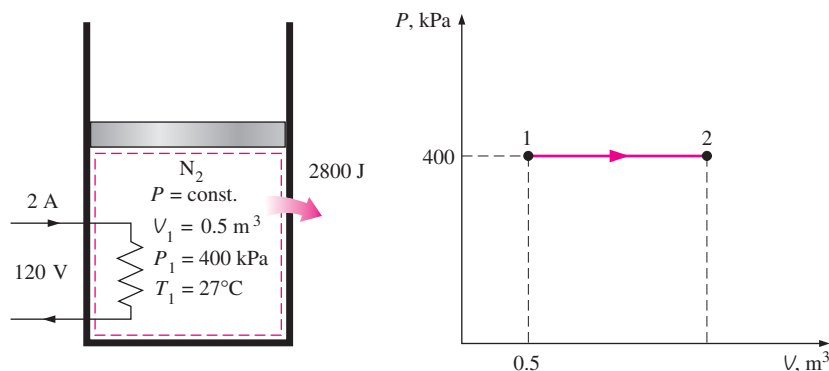
$$W_{e,\text{in}} - Q_{\text{out}} = \Delta H = m(h_2 - h_1) = mc_p(T_2 - T_1)$$

since  $\Delta U + W_b \equiv \Delta H$  for a closed system undergoing a quasi-equilibrium expansion or compression process at constant pressure. From Table A–2a,  $c_p = 1.039 \text{ kJ/kg} \cdot \text{K}$  for nitrogen at room temperature. The only unknown quantity in the previous equation is  $T_2$ , and it is found to be

$$72 \text{ kJ} - 2.8 \text{ kJ} = (2.245 \text{ kg})(1.039 \text{ kJ/kg} \cdot \text{K})(T_2 - 27^\circ\text{C})$$

$$T_2 = \mathbf{56.7^\circ\text{C}}$$

**Discussion** Note that we could also solve this problem by determining the boundary work and the internal energy change rather than the enthalpy change.



**FIGURE 4-31**  
Schematic and  $P$ - $V$  diagram for Example 4-9.

#### EXAMPLE 4-10 Heating of a Gas at Constant Pressure

A piston–cylinder device initially contains air at 150 kPa and 27°C. At this state, the piston is resting on a pair of stops, as shown in Fig. 4-32, and the enclosed volume is 400 L. The mass of the piston is such that a 350-kPa pressure is required to move it. The air is now heated until its volume has doubled. Determine (a) the final temperature, (b) the work done by the air, and (c) the total heat transferred to the air.

**Solution** Air in a piston–cylinder device with a set of stops is heated until its volume is doubled. The final temperature, work done, and the total heat transfer are to be determined.

**Assumptions** **1** Air is an ideal gas since it is at a high temperature and low pressure relative to its critical-point values. **2** The system is stationary and thus the kinetic and potential energy changes are zero,  $\Delta KE = \Delta PE = 0$  and  $\Delta E = \Delta U$ . **3** The volume remains constant until the piston starts moving, and the pressure remains constant afterwards. **4** There are no electrical, shaft, or other forms of work involved.

**Analysis** We take the contents of the cylinder as the *system* (Fig. 4-32). This is a *closed system* since no mass crosses the system boundary during the process. We observe that a piston–cylinder device typically involves a moving boundary and thus boundary work,  $W_b$ . Also, the boundary work is done by the system, and heat is transferred to the system.

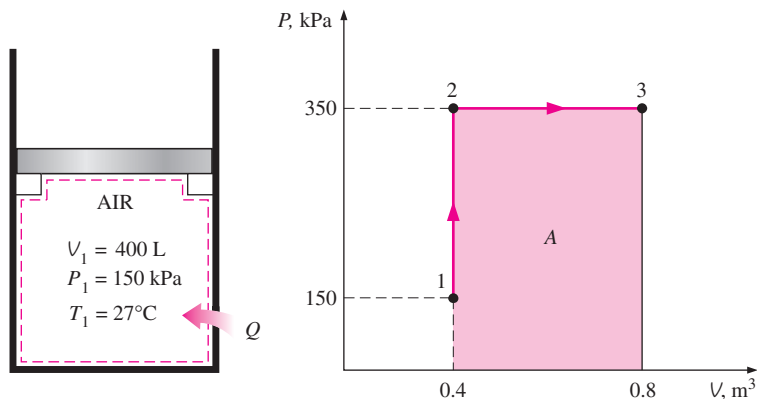
(a) The final temperature can be determined easily by using the ideal-gas relation between states 1 and 3 in the following form:

$$\frac{P_1 V_1}{T_1} = \frac{P_3 V_3}{T_3} \longrightarrow \frac{(150 \text{ kPa})(V_1)}{300 \text{ K}} = \frac{(350 \text{ kPa})(2V_1)}{T_3}$$

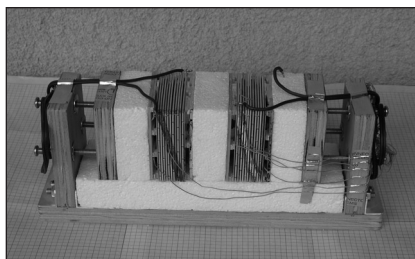
$$T_3 = \mathbf{1400 \text{ K}}$$

FIGURE 4–32

Schematic and  $P$ - $V$  diagram for Example 4–10.



## EXPERIMENT

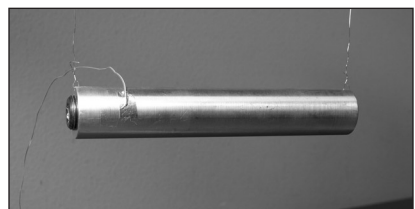


Use actual data from the experiment shown here to obtain the **specific heat** of aluminum. See end-of-chapter problem 4–189.

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## EXPERIMENT



Use actual data from the experiment shown here to obtain the **specific heat** of aluminum. See end-of-chapter problem 4–190.

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(b) The work done could be determined by integration, but for this case it is much easier to find it from the area under the process curve on a  $P$ - $V$  diagram, shown in Fig. 4–32:

$$A = (V_2 - V_1)P_2 = (0.4 \text{ m}^3)(350 \text{ kPa}) = 140 \text{ m}^3 \cdot \text{kPa}$$

Therefore,

$$W_{13} = 140 \text{ kJ}$$

The work is done by the system (to raise the piston and to push the atmospheric air out of the way), and thus it is work output.

(c) Under the stated assumptions and observations, the energy balance on the system between the initial and final states (process 1–3) can be expressed as

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

$$Q_{\text{in}} - W_{b,\text{out}} = \Delta U = m(u_3 - u_1)$$

The mass of the system can be determined from the ideal-gas relation:

$$m = \frac{P_1 V_1}{RT_1} = \frac{(150 \text{ kPa})(0.4 \text{ m}^3)}{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(300 \text{ K})} = 0.697 \text{ kg}$$

The internal energies are determined from the air table (Table A–17) to be

$$u_1 = u_{@ 300 \text{ K}} = 214.07 \text{ kJ/kg}$$

$$u_3 = u_{@ 1400 \text{ K}} = 1113.52 \text{ kJ/kg}$$

Thus,

$$Q_{\text{in}} - 140 \text{ kJ} = (0.697 \text{ kg})[(1113.52 - 214.07) \text{ kJ/kg}]$$

$$Q_{\text{in}} = 767 \text{ kJ}$$

**Discussion** The positive sign verifies that heat is transferred to the system.

## 4–5 ■ INTERNAL ENERGY, ENTHALPY, AND SPECIFIC HEATS OF SOLIDS AND LIQUIDS

A substance whose specific volume (or density) is constant is called an **incompressible substance**. The specific volumes of solids and liquids essentially remain constant during a process (Fig. 4–33). Therefore, liquids and solids can be approximated as incompressible substances without sacrificing much in accuracy. The constant-volume assumption should be taken to imply that the energy associated with the volume change is negligible compared with other forms of energy. Otherwise, this assumption would be ridiculous for studying the thermal stresses in solids (caused by volume change with temperature) or analyzing liquid-in-glass thermometers.

It can be mathematically shown that (see Chap. 12) the constant-volume and constant-pressure specific heats are identical for incompressible substances (Fig. 4–34). Therefore, for solids and liquids, the subscripts on  $c_p$  and  $c_v$  can be dropped, and both specific heats can be represented by a single symbol  $c$ . That is,

$$c_p = c_v = c \quad (4-32)$$

This result could also be deduced from the physical definitions of constant-volume and constant-pressure specific heats. Specific heat values for several common liquids and solids are given in Table A–3.

### Internal Energy Changes

Like those of ideal gases, the specific heats of incompressible substances depend on temperature only. Thus, the partial differentials in the defining equation of  $c_v$  can be replaced by ordinary differentials, which yield

$$du = c_v dT = c(T) dT \quad (4-33)$$

The change in internal energy between states 1 and 2 is then obtained by integration:

$$\Delta u = u_2 - u_1 = \int_1^2 c(T) dT \quad (\text{kJ/kg}) \quad (4-34)$$

The variation of specific heat  $c$  with temperature should be known before this integration can be carried out. For small temperature intervals, a  $c$  value at the average temperature can be used and treated as a constant, yielding

$$\Delta u \cong c_{\text{avg}}(T_2 - T_1) \quad (\text{kJ/kg}) \quad (4-35)$$

### Enthalpy Changes

Using the definition of enthalpy  $h = u + Pv$  and noting that  $v = \text{constant}$ , the differential form of the enthalpy change of incompressible substances can be determined by differentiation to be

$$dh = du + v dP + P d\overset{0}{v} = du + v dP \quad (4-36)$$

Integrating,

$$\Delta h = \Delta u + v \Delta P \cong c_{\text{avg}} \Delta T + v \Delta P \quad (\text{kJ/kg}) \quad (4-37)$$



INTERACTIVE  
TUTORIAL

SEE TUTORIAL CH. 4, SEC. 5 ON THE DVD.

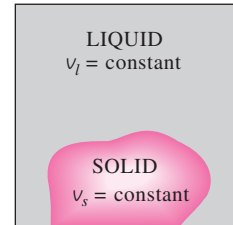


FIGURE 4–33

The specific volumes of incompressible substances remain constant during a process.

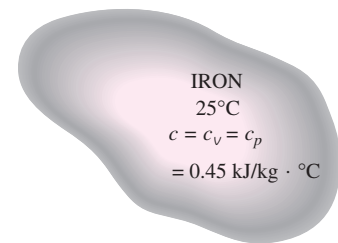


FIGURE 4–34

The  $c_v$  and  $c_p$  values of incompressible substances are identical and are denoted by  $c$ .

For *solids*, the term  $v \Delta P$  is insignificant and thus  $\Delta h = \Delta u \cong c_{\text{avg}} \Delta T$ . For *liquids*, two special cases are commonly encountered:

1. *Constant-pressure processes*, as in heaters ( $\Delta P = 0$ ):  $\Delta h = \Delta u \cong c_{\text{avg}} \Delta T$
2. *Constant-temperature processes*, as in pumps ( $\Delta T = 0$ ):  $\Delta h = v \Delta P$

For a process between states 1 and 2, the last relation can be expressed as  $h_2 - h_1 = v(P_2 - P_1)$ . By taking state 2 to be the compressed liquid state at a given  $T$  and  $P$  and state 1 to be the saturated liquid state at the same temperature, the enthalpy of the compressed liquid can be expressed as

$$h_{@P,T} \cong h_{f@T} + v_{f@T}(P - P_{\text{sat}@T}) \quad (4-38)$$

as discussed in Chap. 3. This is an improvement over the assumption that the enthalpy of the compressed liquid could be taken as  $h_f$  at the given temperature (that is,  $h_{@P,T} \cong h_{f@T}$ ). However, the contribution of the last term is often very small, and is neglected. (Note that at high temperature and pressures, Eq. 4–38 may overcorrect the enthalpy and result in a larger error than the approximation  $h \cong h_{f@T}$ .)

#### EXAMPLE 4–11 Enthalpy of Compressed Liquid

Determine the enthalpy of liquid water at 100°C and 15 MPa (a) by using compressed liquid tables, (b) by approximating it as a saturated liquid, and (c) by using the correction given by Eq. 4–38.

**Solution** The enthalpy of liquid water is to be determined exactly and approximately.

**Analysis** At 100°C, the saturation pressure of water is 101.42 kPa, and since  $P > P_{\text{sat}}$ , the water exists as a compressed liquid at the specified state.

(a) From compressed liquid tables, we read

$$\left. \begin{array}{l} P = 15 \text{ MPa} \\ T = 100^\circ\text{C} \end{array} \right\} h = \mathbf{430.39 \text{ kJ/kg}} \quad (\text{Table A-7})$$

This is the exact value.

(b) Approximating the compressed liquid as a saturated liquid at 100°C, as is commonly done, we obtain

$$h \cong h_{f@100^\circ\text{C}} = \mathbf{419.17 \text{ kJ/kg}}$$

This value is in error by about 2.6 percent.

(c) From Eq. 4–38,

$$\begin{aligned} h_{@P,T} &\cong h_{f@T} + v_{f@T}(P - P_{\text{sat}@T}) \\ &= (419.17 \text{ kJ/kg}) + (0.001 \text{ m}^3/\text{kg})[(15,000 - 101.42) \text{ kPa}] \left( \frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3} \right) \\ &= \mathbf{434.07 \text{ kJ/kg}} \end{aligned}$$

**Discussion** Note that the correction term reduced the error from 2.6 to about 1 percent in this case. However, this improvement in accuracy is often not worth the extra effort involved.

**EXAMPLE 4–12** Cooling of an Iron Block by Water

A 50-kg iron block at 80°C is dropped into an insulated tank that contains 0.5 m<sup>3</sup> of liquid water at 25°C. Determine the temperature when thermal equilibrium is reached.

**Solution** An iron block is dropped into water in an insulated tank. The final temperature when thermal equilibrium is reached is to be determined.

**Assumptions** **1** Both water and the iron block are incompressible substances. **2** Constant specific heats at room temperature can be used for water and the iron. **3** The system is stationary and thus the kinetic and potential energy changes are zero,  $\Delta KE = \Delta PE = 0$  and  $\Delta E = \Delta U$ . **4** There are no electrical, shaft, or other forms of work involved. **5** The system is well-insulated and thus there is no heat transfer.

**Analysis** We take the entire contents of the tank as the *system* (Fig. 4–35). This is a *closed system* since no mass crosses the system boundary during the process. We observe that the volume of a rigid tank is constant, and thus there is no boundary work. The energy balance on the system can be expressed as

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

$$0 = \Delta U$$

The total internal energy  $U$  is an extensive property, and therefore it can be expressed as the sum of the internal energies of the parts of the system. Then the total internal energy change of the system becomes

$$\Delta U_{\text{sys}} = \Delta U_{\text{iron}} + \Delta U_{\text{water}} = 0$$

$$[mc(T_2 - T_1)]_{\text{iron}} + [mc(T_2 - T_1)]_{\text{water}} = 0$$

The specific volume of liquid water at or about room temperature can be taken to be 0.001 m<sup>3</sup>/kg. Then the mass of the water is

$$m_{\text{water}} = \frac{V}{v} = \frac{0.5 \text{ m}^3}{0.001 \text{ m}^3/\text{kg}} = 500 \text{ kg}$$

The specific heats of iron and liquid water are determined from Table A–3 to be  $c_{\text{iron}} = 0.45 \text{ kJ/kg} \cdot ^\circ\text{C}$  and  $c_{\text{water}} = 4.18 \text{ kJ/kg} \cdot ^\circ\text{C}$ . Substituting these values into the energy equation, we obtain

$$(50 \text{ kg})(0.45 \text{ kJ/kg} \cdot ^\circ\text{C})(T_2 - 80^\circ\text{C}) + (500 \text{ kg})(4.18 \text{ kJ/kg} \cdot ^\circ\text{C})(T_2 - 25^\circ\text{C}) = 0$$

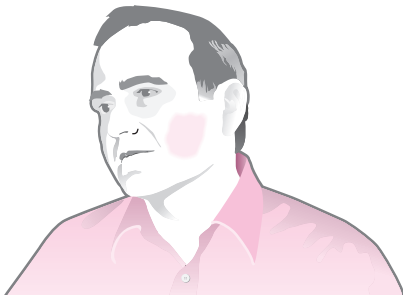
$$T_2 = \mathbf{25.6^\circ\text{C}}$$

Therefore, when thermal equilibrium is established, both the water and iron will be at 25.6°C.

**Discussion** The small rise in water temperature is due to its large mass and large specific heat.

**FIGURE 4–35**

Schematic for Example 4–12.



**FIGURE 4–36**  
Schematic for Example 4–13.

### EXAMPLE 4–13 Temperature Rise due to Slapping

If you ever slapped someone or got slapped yourself, you probably remember the burning sensation. Imagine you had the unfortunate occasion of being slapped by an angry person, which caused the temperature of the affected area of your face to rise by  $1.8^\circ\text{C}$  (ouch!). Assuming the slapping hand has a mass of  $1.2\text{ kg}$  and about  $0.150\text{ kg}$  of the tissue on the face and the hand is affected by the incident, estimate the velocity of the hand just before impact. Take the specific heat of the tissue to be  $3.8\text{ kJ/kg}\cdot^\circ\text{C}$ .

**Solution** The face of a person is slapped. For the specified temperature rise of the affected part, the impact velocity of the hand is to be determined.

**Assumptions** **1** The hand is brought to a complete stop after the impact. **2** The face takes the blow without significant movement. **3** No heat is transferred from the affected area to the surroundings, and thus the process is adiabatic. **4** No work is done on or by the system. **5** The potential energy change is zero,  $\Delta\text{PE} = 0$  and  $\Delta E = \Delta U + \Delta\text{KE}$ .

**Analysis** We analyze this incident in a professional manner without involving any emotions. First, we identify the system, draw a sketch of it, and state our observations about the specifics of the problem. We take the hand and the affected portion of the face as the *system* (Fig. 4–36). This is a *closed system* since it involves a fixed amount of mass (no mass transfer). We observe that the kinetic energy of the hand decreases during the process, as evidenced by a decrease in velocity from initial value to zero, while the internal energy of the affected area increases, as evidenced by an increase in the temperature. There seems to be no significant energy transfer between the system and its surroundings during this process.

Under the stated assumptions and observations, the energy balance on the system can be expressed as

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

$$0 = \Delta U_{\text{affected tissue}} + \Delta\text{KE}_{\text{hand}}$$

$$0 = (mc\Delta T)_{\text{affected tissue}} + [m(0 - V^2)/2]_{\text{hand}}$$

That is, the decrease in the kinetic energy of the hand must be equal to the increase in the internal energy of the affected area. Solving for the velocity and substituting the given quantities, the impact velocity of the hand is determined to be

$$V_{\text{hand}} = \sqrt{\frac{2(mc\Delta T)_{\text{affected tissue}}}{m_{\text{hand}}}}$$

$$= \sqrt{\frac{2(0.15\text{ kg})(3.8\text{ kJ/kg}\cdot^\circ\text{C})(1.8^\circ\text{C})}{1.2\text{ kg}} \left( \frac{1000\text{ m}^2/\text{s}^2}{1\text{ kJ/kg}} \right)}$$

$$= \mathbf{41.4\text{ m/s}} \text{ (or } 149\text{ km/h)}$$

**Discussion** Reconstruction of events such as this by making appropriate assumptions are commonly used in forensic engineering.

## TOPIC OF SPECIAL INTEREST\*

## Thermodynamic Aspects of Biological Systems

An important and exciting application area of thermodynamics is biological systems, which are the sites of rather complex and intriguing energy transfer and transformation processes. Biological systems are not in thermodynamic equilibrium, and thus they are not easy to analyze. Despite their complexity, biological systems are primarily made up of four simple elements: hydrogen, oxygen, carbon, and nitrogen. In the human body, hydrogen accounts for 63 percent, oxygen 25.5 percent, carbon 9.5 percent, and nitrogen 1.4 percent of all the atoms. The remaining 0.6 percent of the atoms comes from 20 other elements essential for life. By mass, about 72 percent of the human body is water.

The building blocks of living organisms are *cells*, which resemble miniature factories performing functions that are vital for the survival of organisms. A biological system can be as simple as a single cell. The human body contains about 100 trillion cells with an average diameter of 0.01 mm. The membrane of the cell is a semipermeable wall that allows some substances to pass through it while excluding others.

In a typical cell, thousands of chemical reactions occur every second during which some molecules are broken down and energy is released and some new molecules are formed. This high level of chemical activity in the cells, which maintains the human body at a temperature of 37°C while performing the necessary bodily tasks, is called **metabolism**. In simple terms, metabolism refers to the burning of foods such as carbohydrates, fat, and protein. The rate of metabolism in the resting state is called the *basal metabolic rate*, which is the rate of metabolism required to keep a body performing the necessary functions (such as breathing and blood circulation) at zero external activity level. The metabolic rate can also be interpreted as the energy consumption rate for a body. For an average male (30 years old, 70 kg, 1.8-m<sup>2</sup> body surface area), the basal metabolic rate is 84 W. That is, the body dissipates energy to the environment at a rate of 84 W, which means that the body is converting chemical energy of the food (or of the body fat if the person has not eaten) into thermal energy at a rate of 84 W (Fig. 4–37). The metabolic rate increases with the level of activity, and it may exceed 10 times the basal metabolic rate when a body is doing strenuous exercise. That is, two people doing heavy exercising in a room may be supplying more energy to the room than a 1-kW electrical resistance heater (Fig. 4–38). The fraction of sensible heat varies from about 40 percent in the case of heavy work to about 70 percent in the case of light work. The rest of the energy is rejected from the body by perspiration in the form of latent heat.

The basal metabolic rate varies with sex, body size, general health conditions, and so forth, and decreases considerably with age. This is one of the reasons people tend to put on weight in their late twenties and thirties even though they do not increase their food intake. The brain and the liver are the major sites of metabolic activity. These two organs are responsible for almost 50 percent of the basal metabolic rate of an adult human body although they constitute only about 4 percent of the body mass. In small children, it is remarkable that about half of the basal metabolic activity occurs in the brain alone.

\*This section can be skipped without a loss in continuity.



FIGURE 4–37

An average person dissipates energy to the surroundings at a rate of 84 W when resting.

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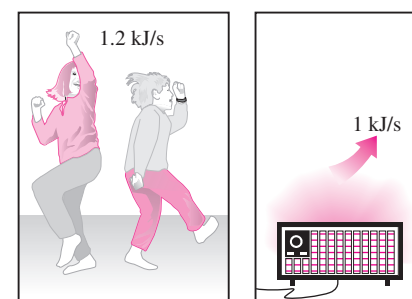


FIGURE 4–38

Two fast-dancing people supply more energy to a room than a 1-kW electric resistance heater.

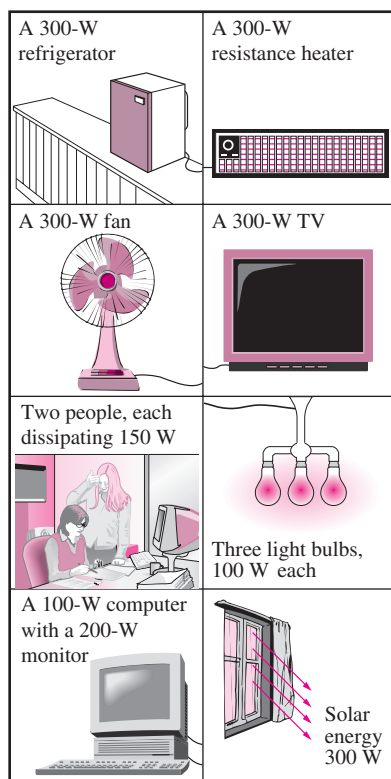


FIGURE 4-39

Some arrangements that supply a room the same amount of energy as a 300-W electric resistance heater.

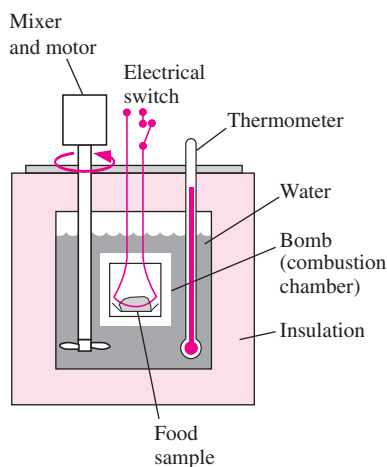


FIGURE 4-40

Schematic of a bomb calorimeter used to determine the energy content of food samples.

The biological reactions in cells occur essentially at constant temperature, pressure, and volume. The temperature of the cell tends to rise when some chemical energy is converted to heat, but this energy is quickly transferred to the circulatory system, which transports it to outer parts of the body and eventually to the environment through the skin.

The muscle cells function very much like an engine, converting the chemical energy into mechanical energy (work) with a conversion efficiency of close to 20 percent. When the body does no net work on the environment (such as moving some furniture upstairs), the entire work is also converted to heat. In that case, the entire chemical energy in the food released during metabolism in the body is eventually transferred to the environment. A TV set that consumes electricity at a rate of 300 W must reject heat to its environment at a rate of 300 W in steady operation regardless of what goes on in the set. That is, turning on a 300-W TV set or three 100-W light bulbs will produce the same heating effect in a room as a 300-W resistance heater (Fig. 4-39). This is a consequence of the conservation of energy principle, which requires that the energy input into a system must equal the energy output when the total energy content of a system remains constant during a process.

### Food and Exercise

The energy requirements of a body are met by the food we eat. The nutrients in the food are considered in three major groups: carbohydrates, proteins, and fats. *Carbohydrates* are characterized by having hydrogen and oxygen atoms in a 2:1 ratio in their molecules. The molecules of carbohydrates range from very simple (as in plain sugar) to very complex or large (as in starch). Bread and plain sugar are the major sources of carbohydrates. *Proteins* are very large molecules that contain carbon, hydrogen, oxygen, and nitrogen, and they are essential for the building and repairing of the body tissues. Proteins are made up of smaller building blocks called *amino acids*. Complete proteins such as meat, milk, and eggs have all the amino acids needed to build body tissues. Plant source proteins such as those in fruits, vegetables, and grains lack one or more amino acids, and are called incomplete proteins. *Fats* are relatively small molecules that consist of carbon, hydrogen, and oxygen. Vegetable oils and animal fats are major sources of fats. Most foods we eat contain all three nutrition groups at varying amounts. The typical average American diet consists of 45 percent carbohydrate, 40 percent fat, and 15 percent protein, although it is recommended that in a healthy diet less than 30 percent of the calories should come from fat.

The energy content of a given food is determined by burning a small sample of the food in a device called a *bomb calorimeter*, which is basically a well-insulated rigid tank (Fig. 4-40). The tank contains a small combustion chamber surrounded by water. The food is ignited and burned in the combustion chamber in the presence of excess oxygen, and the energy released is transferred to the surrounding water. The energy content of the food is calculated on the basis of the conservation of energy principle by measuring the temperature rise of the water. The carbon in the food is converted into  $\text{CO}_2$  and hydrogen into  $\text{H}_2\text{O}$  as the food burns. The same chemical reactions occur in the body, and thus the same amount of energy is released.

Using dry (free of water) samples, the average energy contents of the three basic food groups are determined by bomb calorimeter measurements to be

18.0 MJ/kg for carbohydrates, 22.2 MJ/kg for proteins, and 39.8 MJ/kg for fats. These food groups are not entirely metabolized in the human body, however. The fraction of metabolizable energy contents are 95.5 percent for carbohydrates, 77.5 percent for proteins, and 97.7 percent for fats. That is, the fats we eat are almost entirely metabolized in the body, but close to one quarter of the protein we eat is discarded from the body unburned. This corresponds to 4.1 Calories/g for proteins and carbohydrates and 9.3 Calories/g for fats (Fig. 4–41) commonly seen in nutrition books and on food labels. The energy contents of the foods we normally eat are much lower than the values above because of the large water content (water adds bulk to the food but it cannot be metabolized or burned, and thus it has no energy value). Most vegetables, fruits, and meats, for example, are mostly water. The average metabolizable energy contents of the three basic food groups are 4.2 MJ/kg for carbohydrates, 8.4 MJ/kg for proteins, and 33.1 MJ/kg for fats. Note that 1 kg of natural fat contains almost 8 times the metabolizable energy of 1 kg of natural carbohydrates. Thus, a person who fills his stomach with fatty foods is consuming much more energy than a person who fills his stomach with carbohydrates such as bread or rice.

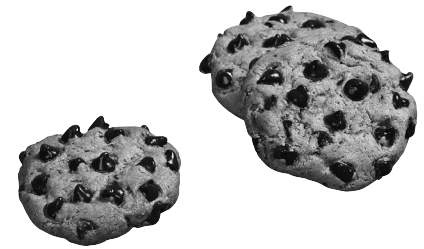
The metabolizable energy content of foods is usually expressed by nutritionists in terms of the capitalized *Calories*. One Calorie is equivalent to one *kilocalorie* (1000 calories), which is equivalent to 4.1868 kJ. That is,

$$1 \text{ Cal (Calorie)} = 1000 \text{ calories} = 1 \text{ kcal (kilocalorie)} = 4.1868 \text{ kJ}$$

The calorie notation often causes confusion since it is not always followed in the tables or articles on nutrition. When the topic is food or fitness, a calorie normally means a kilocalorie whether it is capitalized or not.

The **daily calorie needs** of people vary greatly with age, gender, the state of health, the activity level, the body weight, and the composition of the body as well as other factors. A small person needs fewer calories than a larger person of the same sex and age. An average man needs about 2400 to 2700 Calories a day. The daily need of an average woman varies from 1800 to 2200 Calories. The daily calorie needs are about 1600 for sedentary women and some older adults; 2000 for sedentary men and most older adults; 2200 for most children, teenage girls, and active women; 2800 for teenage boys, active men, and some very active women; and above 3000 for very active men. The *average* value of calorie intake is usually taken to be 2000 Calories per day. The daily calorie needs of a person can be determined by multiplying the body weight in pounds (which is 2.205 times the body weight in kg) by 11 for a sedentary person, 13 for a moderately active person, 15 for a moderate exerciser or physical laborer, and 18 for an extremely active exerciser or physical laborer. The extra calories a body consumes are usually stored as fat, which serves as the spare energy of the body for use when the energy intake of the body is less than the needed amount.

Like other natural fat, 1 kg of human body fat contains about 33.1 MJ of metabolizable energy. Therefore, a starving person (zero energy intake) who uses up 2200 Calories (9211 kJ) a day can meet his daily energy intake requirements by burning only  $9211/33,100 = 0.28$  kg of body fat. So it is no surprise that people are known to survive over 100 days without eating. (They still need to drink water, however, to replenish the water lost through the lungs and the skin to avoid the dehydration that may occur in just a few



**FIGURE 4–41**

Evaluating the calorie content of one serving of chocolate chip cookies (values are for Chips Ahoy cookies made by Nabisco).

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days.) Although the desire to get rid of the excess fat in a thin world may be overwhelming at times, starvation diets are not recommended because the body soon starts to consume its own muscle tissue in addition to fat. A healthy diet should involve regular exercise while allowing a reasonable amount of calorie intake.

The average metabolizable energy contents of various foods and the energy consumption during various activities are given in Tables 4–1 and 4–2. Considering that no two hamburgers are alike, and that no two people walk exactly the same way, there is some uncertainty in these values, as you would expect. Therefore, you may encounter somewhat different values in other books or magazines for the same items.

The rates of energy consumption listed in Table 4–2 during some activities are for a 68-kg adult. The energy consumed for smaller or larger adults can be determined using the proportionality of the metabolism rate and the body size. For example, the rate of energy consumption by a 68-kg bicyclist is listed in Table 4–2 to be 639 Calories/h. Then the rate of energy consumption by a 50-kg bicyclist is

$$(50 \text{ kg}) \frac{639 \text{ Cal/h}}{68 \text{ kg}} = 470 \text{ Cal/h}$$

For a 100-kg person, it would be 940 Cal/h.

The thermodynamic analysis of the human body is rather complicated since it involves mass transfer (during breathing, perspiring, etc.) as well as energy transfer. As such, it should be treated as an open system. However, the energy transfer with mass is difficult to quantify. Therefore, the human body is often modeled as a closed system for simplicity by treating energy transported with mass as just energy transfer. For example, eating is modeled as the transfer of energy into the human body in the amount of the metabolizable energy content of the food.

### Dieting

Most diets are based on *calorie counting*; that is, the conservation of energy principle: a person who consumes more calories than his or her body burns

**TABLE 4–1**

Approximate metabolizable energy content of some common foods

(1 Calorie = 4.1868 kJ =  
3.968 Btu)

Food	Calories	Food	Calories	Food	Calories
Apple (one, medium)	70	Fish sandwich	450	Milk (skim, 200 ml)	76
Baked potato (plain)	250	French fries (regular)	250	Milk (whole, 200 ml)	136
Baked potato with cheese	550	Hamburger	275	Peach (one, medium)	65
Bread (white, one slice)	70	Hot dog	300	Pie (one $\frac{1}{8}$ slice, 23 cm diameter)	300
Butter (one teaspoon)	35	Ice cream (100 ml, 10% fat)	110	Pizza (large, cheese, one $\frac{1}{8}$ slice)	350
Cheeseburger	325	Lettuce salad with French dressing	150		
Chocolate candy bar (20 g)	105				
Cola (200 ml)	87				
Egg (one)	80				

will gain weight whereas a person who consumes less calories than his or her body burns will lose weight. Yet, people who eat whatever they want whenever they want without gaining any weight are living proof that the calorie-counting technique alone does not work in dieting. Obviously there is more to dieting than keeping track of calories. It should be noted that the phrases *weight gain* and *weight loss* are misnomers. The correct phrases should be *mass gain* and *mass loss*. A man who goes to space loses practically all of his weight but none of his mass. When the topic is food and fitness, *weight* is understood to mean *mass*, and weight is expressed in mass units.

Researchers on nutrition proposed several theories on dieting. One theory suggests that some people have very “food efficient” bodies. These people need fewer calories than other people do for the same activity, just like a fuel-efficient car needing less fuel for traveling a given distance. It is interesting that we want our cars to be fuel efficient but we do not want the same high efficiency for our bodies. One thing that frustrates the dieters is that the body interprets dieting as *starvation* and starts using the energy reserves of the body more stringently. Shifting from a normal 2000-Calorie daily diet to an 800-Calorie diet without exercise is observed to lower the basal metabolic rate by 10 to 20 percent. Although the metabolic rate returns to normal once the dieting stops, extended periods of low-calorie dieting without adequate exercise may result in the loss of considerable muscle tissue together with fat. With less muscle tissue to burn calories, the metabolic rate of the body declines and stays below normal even after a person starts eating normally. As a result, the person regains the weight he or she has lost in the form of fat, plus more. The basal metabolic rate remains about the same in people who exercise while dieting.

Regular moderate exercise is part of any healthy dieting program for good reason: it builds or preserves muscle tissue that burns calories much faster than the fat tissue does. It is interesting that aerobic exercise continues burning calories for several hours after the workout, raising the overall metabolic rate considerably.

Another theory suggests that people with *too many fat cells* developed during childhood or adolescence are much more likely to gain weight. Some people believe that the fat content of the bodies is controlled by the setting of a “fat control” mechanism, much like the temperature of a house is controlled by the thermostat setting.

Some people put the blame for weight problems simply on the *genes*. Considering that 80 percent of the children of overweight parents are also overweight, heredity may indeed play an important role in the way a body stores fat. Researchers from the University of Washington and the Rockefeller University have identified a gene, called the RIIbeta, that seems to control the rate of metabolism. The body tries to keep the body fat at a particular level, called the **set point**, that differs from person to person (Fig. 4–42). This is done by *speeding up* the metabolism and thus burning extra calories much faster when a person tends to gain weight and by *slowing down* the metabolism and thus burning calories at a slower rate when a person tends to lose weight. Therefore, a person who just became slim burns fewer calories than does a person of the same size who has always been slim. Even exercise does not seem to change that. Then to keep the weight off, the newly slim

TABLE 4–2

Approximate energy consumption of a 68-kg adult during some activities (1 Calorie = 4.1868 kJ = 3.968 Btu)

Activity	Calories/h
Basal metabolism	72
Basketball	550
Bicycling (21 km/h)	639
Cross-country skiing (13 km/h)	936
Driving a car	180
Eating	99
Fast dancing	600
Fast running (13 km/h)	936
Jogging (8 km/h)	540
Swimming (fast)	860
Swimming (slow)	288
Tennis (advanced)	480
Tennis (beginner)	288
Walking (7.2 km/h)	432
Watching TV	72

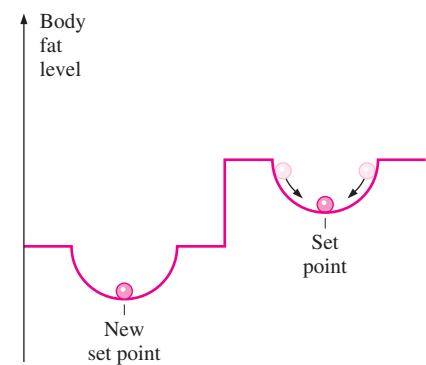


FIGURE 4–42

The body tends to keep the body fat level at a *set point* by speeding up metabolism when a person splurges and by slowing it down when the person starves.

person should consume no more calories than he or she can burn. Note that in people with high metabolic rates, the body dissipates the extra calories as body heat instead of storing them as fat, and thus there is no violation of the conservation of energy principle.

In some people, a *genetic flaw* is believed to be responsible for the extremely low rates of metabolism. Several studies concluded that losing weight for such people is nearly impossible. That is, obesity is a biological phenomenon. However, even such people will not gain weight unless they eat more than their body can burn. They just must learn to be content with little food to remain slim, and forget about ever having a normal “eating” life. For most people, genetics determine the range of normal weights. A person may end up at the high or low end of that range, depending on eating and exercise habits. This also explains why some genetically identical twins are not so identical when it comes to body weight. *Hormone imbalance* is also believed to cause excessive weight gain or loss.

Based on his experience, the first author of this book has also developed a diet called the “*sensible diet*.” It consists of two simple rules: eat *whatever* you want *whenever* you want *as much as* you want provided that (1) you do not eat unless you are hungry and (2) you stop eating before you get stuffed. In other words, *listen to your body and don’t impose on it*. Don’t expect to see this unscientific diet advertised anywhere since there is nothing to be sold and thus no money to be made. Also, it is not as easy as it sounds since food is at the center stage of most leisure activities in social life, and eating and drinking have become synonymous with having a good time. However, it is comforting to know that the human body is quite forgiving of occasional impositions.

Being *overweight* is associated with a long list of health risks from high blood pressure to some forms of cancer, especially for people who have a weight-related medical condition such as diabetes, hypertension, and heart disease. Therefore, people often wonder if their weight is in the proper range. Well, the answer to this question is not written in stone, but if you cannot see your toes or you can pinch your love handles more than an inch, you don’t need an expert to tell you that you went over your range. On the other hand, some people who are obsessed with the weight issue try to lose more weight even though they are actually underweight. Therefore, it is useful to have a scientific criterion to determine physical fitness. The range of healthy weight for adults is usually expressed in terms of the **body mass index** (BMI), defined, in SI units, as

$$\text{BMI} = \frac{W(\text{kg})}{H^2(\text{m}^2)} \quad \text{with} \quad \begin{array}{ll} \text{BMI} < 19 & \text{underweight} \\ 19 \leq \text{BMI} \leq 25 & \text{healthy weight} \\ \text{BMI} > 25 & \text{overweight} \end{array} \quad (4-39)$$

where  $W$  is the weight (actually, the mass) of the person in kg and  $H$  is the height in m. Therefore, a BMI of 25 is the upper limit for the healthy weight and a person with a BMI of 27 is 8 percent overweight. It can be shown that the formula above is equivalent in English units to  $\text{BMI} = 705 W/H^2$  where  $W$  is in pounds and  $H$  is in inches. The proper range of weight for adults of various heights is given in Table 4–3 in both SI and English units.

**TABLE 4–3**

The range of healthy weight for adults of various heights (Source: National Institute of Health)

	English Units		SI Units	
Height, in.	Healthy weight, lbm*	Height, m	Healthy weight, kg*	
58	91–119	1.45	40–53	
60	97–127	1.50	43–56	
62	103–136	1.55	46–60	
64	111–146	1.60	49–64	
66	118–156	1.65	52–68	
68	125–165	1.70	55–72	
70	133–175	1.75	58–77	
72	140–185	1.80	62–81	
74	148–195	1.85	65–86	
76	156–205	1.90	69–90	

\*The upper and lower limits of healthy range correspond to mass body indexes of 19 and 25, respectively.

**EXAMPLE 4-14** Burning Off Lunch Calories

A 90-kg man had two hamburgers, a regular serving of french fries, and a 200-ml Coke for lunch (Fig. 4-43). Determine how long it will take for him to burn the lunch calories off (a) by watching TV and (b) by fast swimming. What would your answers be for a 45-kg man?

**Solution** A man had lunch at a restaurant. The times it will take for him to burn the lunch calories by watching TV and by fast swimming are to be determined.

**Assumptions** The values in Tables 4-1 and 4-2 are applicable for food and exercise.

**Analysis** (a) We take the human body as our *system* and treat it as a *closed system* whose energy content remains unchanged during the process. Then the conservation of energy principle requires that the energy input into the body must be equal to the energy output. The net energy input in this case is the metabolizable energy content of the food eaten. It is determined from Table 4-1 to be

$$\begin{aligned} E_{\text{in}} &= 2 \times E_{\text{hamburger}} + E_{\text{fries}} + E_{\text{cola}} \\ &= 2 \times 275 + 250 + 87 \\ &= 887 \text{ Cal} \end{aligned}$$

The rate of energy output for a 68-kg man watching TV is given in Table 4-2 to be 72 Calories/h. For a 90-kg man it becomes

$$E_{\text{out}} = (90 \text{ kg}) \frac{72 \text{ Cal/h}}{68 \text{ kg}} = 95.3 \text{ Cal/h}$$

Therefore, it will take

$$\Delta t = \frac{887 \text{ Cal}}{95.3 \text{ Cal/h}} = \mathbf{9.3 \text{ h}}$$

to burn the lunch calories off by watching TV.

(b) It can be shown in a similar manner that it takes only **47 min** to burn the lunch calories off by fast swimming.

**Discussion** The 45-kg man is half as large as the 90-kg man. Therefore, expending the same amount of energy takes twice as long in each case: **18.6 h** by watching TV and **94 min** by fast swimming.

**FIGURE 4-43**

A typical lunch discussed in Example 4-14.

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**EXAMPLE 4-15** Losing Weight by Switching to Fat-Free Chips

The fake fat olestra passes through the body undigested, and thus adds zero calorie to the diet. Although foods cooked with olestra taste pretty good, they may cause abdominal discomfort and the long-term effects are unknown. A 1-oz (28.3-g) serving of regular potato chips has 10 g of fat and 150 Calories, whereas 1 oz of the so-called fat-free chips fried in olestra has only 75 Calories. Consider a person who eats 1 oz of regular potato chips every day at lunch without gaining or losing any weight. Determine how much weight this person will lose in one year if he or she switches to fat-free chips (Fig. 4-44).

**FIGURE 4-44**

Schematic for Example 4-15.

**Solution** A person switches from regular potato chips to fat-free ones. The weight the person loses in one year is to be determined.

**Assumptions** Exercising and other eating habits remain the same.

**Analysis** The person who switches to the fat-free chips consumes 75 fewer Calories a day. Then the annual reduction in calories consumed becomes

$$E_{\text{reduced}} = (75 \text{ Cal/day})(365 \text{ day/year}) = 27,375 \text{ Cal/year}$$

The metabolizable energy content of 1 kg of body fat is 33,100 kJ. Therefore, assuming the deficit in the calorie intake is made up by burning body fat, the person who switches to fat-free chips will lose

$$m_{\text{fat}} = \frac{E_{\text{reduced}}}{\text{Energy content of fat}} = \frac{27,375 \text{ Cal}}{33,100 \text{ kJ/kg}} \left( \frac{4.1868 \text{ kJ}}{1 \text{ Cal}} \right) = 3.46 \text{ kg}$$

(about 7.6 pounds) of body fat that year.

## SUMMARY

Work is the energy transferred as a force acts on a system through a distance. The most common form of mechanical work is the *boundary work*, which is the work associated with the expansion and compression of substances. On a  $P$ - $V$  diagram, the area under the process curve represents the boundary work for a quasi-equilibrium process. Various forms of boundary work are expressed as follows:

(1) General 
$$W_b = \int_1^2 P dV$$

(2) Isobaric process

$$W_b = P_0(V_2 - V_1) \quad (P_1 = P_2 = P_0 = \text{constant})$$

(3) Polytropic process

$$W_b = \frac{P_2 V_2 - P_1 V_1}{1 - n} \quad (n \neq 1) \quad (PV^n = \text{constant})$$

(4) Isothermal process of an ideal gas

$$W_b = P_1 V_1 \ln \frac{V_2}{V_1} = mRT_0 \ln \frac{V_2}{V_1} \quad (PV = mRT_0 = \text{constant})$$

The first law of thermodynamics is essentially an expression of the conservation of energy principle, also called the energy balance. The general energy balances for *any system* undergoing *any process* can be expressed as

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

It can also be expressed in the *rate form* as

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

Taking heat transfer *to* the system and work done *by* the system to be positive quantities, the energy balance for a closed system can also be expressed as

$$Q - W = \Delta U + \Delta \text{KE} + \Delta \text{PE} \quad (\text{kJ})$$

where

$$W = W_{\text{other}} + W_b$$

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

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

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

For a *constant-pressure process*,  $W_b + \Delta U = \Delta H$ . Thus,

$$Q - W_{\text{other}} = \Delta H + \Delta \text{KE} + \Delta \text{PE} \quad (\text{kJ})$$

The amount of energy needed to raise the temperature of a unit mass of a substance by one degree is called the *specific heat at constant volume*  $c_v$  for a constant-volume process and the *specific heat at constant pressure*  $c_p$  for a constant-pressure process. They are defined as

$$c_v = \left( \frac{\partial u}{\partial T} \right)_v \quad \text{and} \quad c_p = \left( \frac{\partial h}{\partial T} \right)_p$$

For ideal gases  $u$ ,  $h$ ,  $c_v$ , and  $c_p$  are functions of temperature alone. The  $\Delta u$  and  $\Delta h$  of ideal gases are expressed as

$$\Delta u = u_2 - u_1 = \int_1^2 c_v(T) dT \cong c_{v,\text{avg}}(T_2 - T_1)$$

$$\Delta h = h_2 - h_1 = \int_1^2 c_p(T) dT \cong c_{p,\text{avg}}(T_2 - T_1)$$

For ideal gases,  $c_v$  and  $c_p$  are related by

$$c_p = c_v + R \quad (\text{kJ/kg} \cdot \text{K})$$

where  $R$  is the gas constant. The *specific heat ratio*  $k$  is defined as

$$k = \frac{c_p}{c_v}$$

For *incompressible substances* (liquids and solids), both the constant-pressure and constant-volume specific heats are identical and denoted by  $c$ :

$$c_p = c_v = c \quad (\text{kJ/kg} \cdot \text{K})$$

The  $\Delta u$  and  $\Delta h$  of incompressible substances are given by

$$\Delta u = \int_1^2 c(T) dT \cong c_{\text{avg}}(T_2 - T_1) \quad (\text{kJ/kg})$$

$$\Delta h = \Delta u + v\Delta P \quad (\text{kJ/kg})$$

## REFERENCES AND SUGGESTED READINGS

1. ASHRAE *Handbook of Fundamentals*. SI version. Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., 1993.
2. ASHRAE *Handbook of Refrigeration*. SI version. Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., 1994.

## PROBLEMS\*

### Moving Boundary Work

**4-1C** On a  $P$ - $v$  diagram, what does the area under the process curve represent?

**4-2C** Is the boundary work associated with constant-volume systems always zero?

**4-3C** An ideal gas at a given state expands to a fixed final volume first at constant pressure and then at constant temperature. For which case is the work done greater?

**4-4C** Show that  $1 \text{ kPa} \cdot \text{m}^3 = 1 \text{ kJ}$ .

**4-5** The volume of 1 kg of helium in a piston-cylinder device is initially  $5 \text{ m}^3$ . Now helium is compressed to  $3 \text{ m}^3$

while its pressure is maintained constant at 200 kPa. Determine the initial and final temperatures of helium as well as the work required to compress it, in kJ.

**4-6** Calculate the total work, in kJ, for process 1-3 shown in Fig. P4-6 when the system consists of 2 kg of nitrogen.

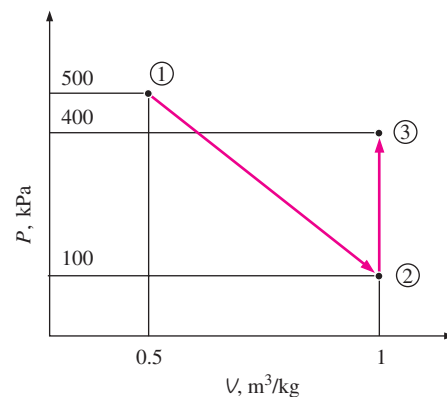


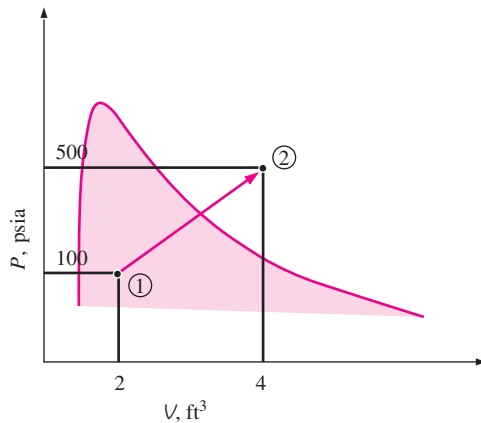


FIGURE P4-6

\*Problems designated by a "C" are concept questions, and students are encouraged to answer them all. Problems designated by an "E" are in English units, and the SI users can ignore them. Problems with the  icon are solved using EES, and complete solutions together with parametric studies are included on the enclosed DVD. Problems with the  icon are comprehensive in nature, and are intended to be solved with a computer, preferably using the EES software that accompanies this text.

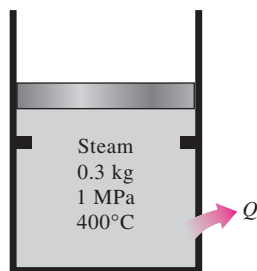
**4-7E** Calculate the total work, in Btu, produced by the process of Fig. P4-7E.



**FIGURE P4-7E**

**4-8** A piston–cylinder device initially contains  $0.07 \text{ m}^3$  of nitrogen gas at  $130 \text{ kPa}$  and  $120^\circ\text{C}$ . The nitrogen is now expanded polytropically to a state of  $100 \text{ kPa}$  and  $100^\circ\text{C}$ . Determine the boundary work done during this process.

**4-9** A piston–cylinder device with a set of stops initially contains  $0.3 \text{ kg}$  of steam at  $1.0 \text{ MPa}$  and  $400^\circ\text{C}$ . The location of the stops corresponds to 60 percent of the initial volume. Now the steam is cooled. Determine the compression work if the final state is (a)  $1.0 \text{ MPa}$  and  $250^\circ\text{C}$  and (b)  $500 \text{ kPa}$ . (c) Also determine the temperature at the final state in part (b).

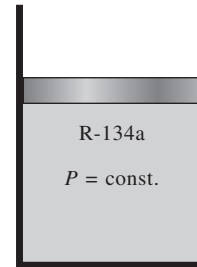


**FIGURE P4-9**


**4-10** A piston–cylinder device initially contains  $0.07 \text{ m}^3$  of nitrogen gas at  $130 \text{ kPa}$  and  $120^\circ\text{C}$ . The nitrogen is now expanded to a pressure of  $100 \text{ kPa}$  polytropically with a polytropic exponent whose value is equal to the specific heat ratio (called *isentropic expansion*). Determine the final temperature and the boundary work done during this process.

**4-11** A mass of  $5 \text{ kg}$  of saturated water vapor at  $300 \text{ kPa}$  is heated at constant pressure until the temperature reaches  $200^\circ\text{C}$ . Calculate the work done by the steam during this process. *Answer: 165.9 kJ*

**4-12** A frictionless piston–cylinder device initially contains  $200 \text{ L}$  of saturated liquid refrigerant-134a. The piston is free to move, and its mass is such that it maintains a pressure of  $900 \text{ kPa}$  on the refrigerant. The refrigerant is now heated until its temperature rises to  $70^\circ\text{C}$ . Calculate the work done during this process. *Answer: 5571 kJ*




**FIGURE P4-12**


**4-13**  Reconsider Prob. 4-12. Using EES (or other) software, investigate the effect of pressure on the work done. Let the pressure vary from  $400$  to  $1200 \text{ kPa}$ . Plot the work done versus the pressure, and discuss the results. Explain why the plot is not linear. Also plot the process described in Prob. 4-12 on the  $P$ - $v$  diagram.

**4-14E** A frictionless piston–cylinder device contains  $16 \text{ lbm}$  of superheated water vapor at  $40 \text{ psia}$  and  $600^\circ\text{F}$ . Steam is now cooled at constant pressure until 70 percent of it, by mass, condenses. Determine the work done during this process.

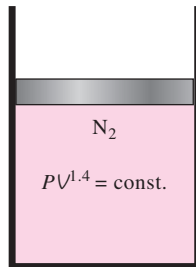
**4-15** A mass of  $2.4 \text{ kg}$  of air at  $150 \text{ kPa}$  and  $12^\circ\text{C}$  is contained in a gas-tight, frictionless piston–cylinder device. The air is now compressed to a final pressure of  $600 \text{ kPa}$ . During the process, heat is transferred from the air such that the temperature inside the cylinder remains constant. Calculate the work input during this process. *Answer: 272 kJ*

**4-16E** During an expansion process, the pressure of a gas changes from  $15$  to  $100 \text{ psia}$  according to the relation  $P = aV + b$ , where  $a = 5 \text{ psia/ft}^3$  and  $b$  is a constant. If the initial volume of the gas is  $7 \text{ ft}^3$ , calculate the work done during the process. *Answer: 181 Btu*


**4-17**  During some actual expansion and compression processes in piston–cylinder devices, the gases have been observed to satisfy the relationship  $PV^n = C$ , where  $n$  and  $C$  are constants. Calculate the work done when a gas expands from  $150 \text{ kPa}$  and  $0.03 \text{ m}^3$  to a final volume of  $0.2 \text{ m}^3$  for the case of  $n = 1.3$ .


**4-18**  Reconsider Prob. 4-17. Using the EES (or other) software, plot the process described in the problem on a  $P$ - $V$  diagram, and investigate the effect of the polytropic exponent  $n$  on the boundary work. Let the polytropic exponent vary from 1.1 to 1.6. Plot the boundary work versus the polytropic exponent, and discuss the results.

**4-19** A frictionless piston–cylinder device contains 2 kg of nitrogen at 100 kPa and 300 K. Nitrogen is now compressed slowly according to the relation  $PV^{1.4} = \text{constant}$  until it reaches a final temperature of 360 K. Calculate the work input during this process. *Answer: 89 kJ*



**FIGURE P4-19**

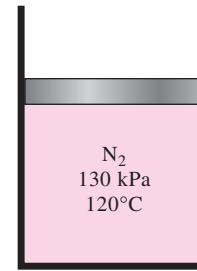
**4-20**  The equation of state of a gas is given as  $\bar{v}(P + 10/\bar{v}^2) = R_u T$ , where the units of  $\bar{v}$  and  $P$  are  $\text{m}^3/\text{kmol}$  and kPa, respectively. Now 0.5 kmol of this gas is expanded in a quasi-equilibrium manner from 2 to 4  $\text{m}^3$  at a constant temperature of 300 K. Determine (a) the unit of the quantity 10 in the equation and (b) the work done during this isothermal expansion process.

**4-21**  Reconsider Prob. 4-20. Using the integration feature of the EES software, calculate the work done, and compare your result with the “hand-calculated” result obtained in Prob. 4-20. Plot the process described in the problem on a  $P$ - $v$  diagram.

**4-22** Carbon dioxide contained in a piston–cylinder device is compressed from 0.3 to 0.1  $\text{m}^3$ . During the process, the pressure and volume are related by  $P = aV^{-2}$ , where  $a = 8 \text{ kPa} \cdot \text{m}^6$ . Calculate the work done on the carbon dioxide during this process. *Answer: 53.3 kJ*

**4-23** Determine the boundary work done by a gas during an expansion process if the pressure and volume values at various states are measured to be 300 kPa, 1 L; 290 kPa, 1.1 L; 270 kPa, 1.2 L; 250 kPa, 1.4 L; 220 kPa, 1.7 L; and 200 kPa, 2 L.

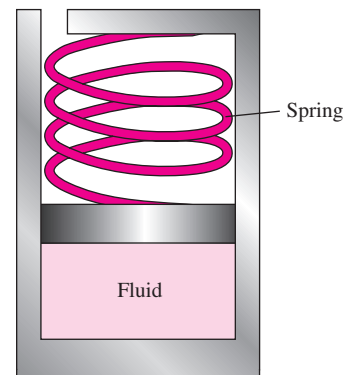
**4-24** A piston–cylinder device initially contains 0.25 kg of nitrogen gas at 130 kPa and 120°C. The nitrogen is now expanded isothermally to a pressure of 100 kPa. Determine the boundary work done during this process. *Answer: 7.65 kJ*



**FIGURE P4-24**

**4-25** A piston–cylinder device contains 0.15 kg of air initially at 2 MPa and 350°C. The air is first expanded isothermally to 500 kPa, then compressed polytropically with a polytropic exponent of 1.2 to the initial pressure, and finally compressed at the constant pressure to the initial state. Determine the boundary work for each process and the net work of the cycle.

**4-26** 1-kg of water that is initially at 90°C with a quality of 10 percent occupies a spring-loaded piston–cylinder device, such as that in Fig. P4-26. This device is now heated until the pressure rises to 800 kPa and the temperature is 250°C. Determine the total work produced during this process, in kJ. *Answer: 24.5 kJ*



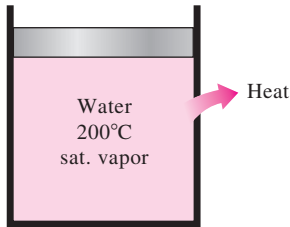
**FIGURE P4-26**

**4-27** 0.5-kg water that is initially at 1 MPa and 10 percent quality occupies a spring-loaded piston–cylinder device. This device is now cooled until the water is a saturated liquid at 100°C. Calculate the total work produced during this process, in kJ.

**4-28** Argon is compressed in a polytropic process with  $n = 1.2$  from 120 kPa and 30°C to 1200 kPa in a piston–cylinder device. Determine the final temperature of the argon.

**Closed System Energy Analysis**

**4–29** Saturated water vapor at 200°C is isothermally condensed to a saturated liquid in a piston–cylinder device. Calculate the heat transfer and the work done during this process, in kJ/kg. *Answers: 1940 kJ/kg, 196 kJ/kg*

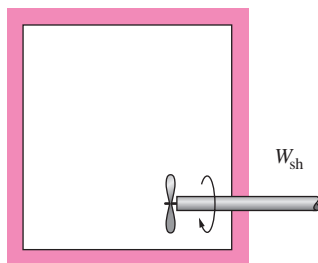

**FIGURE P4–29**

**4–30E** A closed system undergoes a process in which there is no internal energy change. During this process, the system produces  $1.6 \times 10^6$  ft · lbf of work. Calculate the heat transfer for this process, in Btu.

**4–31** Complete each line of the table below on the basis of the conservation of energy principle for a closed system.

$Q_{in}$ kJ	$W_{out}$ kJ	$E_1$ kJ	$E_2$ kJ	$m$ kg	$e_2 - e_1$ kJ/kg
280	—	1020	860	3	—
–350	130	550	—	5	—
—	260	300	—	2	–150
300	—	750	500	1	—
—	–200	—	300	2	–100

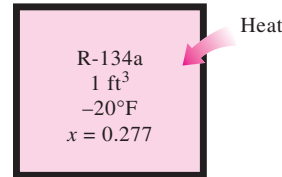
**4–32** A substance is contained in a well-insulated rigid container that is equipped with a stirring device, as shown in Fig. P4–32. Determine the change in the internal energy of this substance when 15 kJ of work is applied to the stirring device.


**FIGURE P4–32**

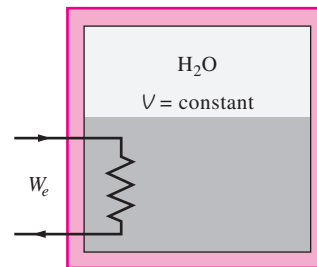
**4–33** A rigid container equipped with a stirring device contains 1.5 kg of motor oil. Determine the rate of specific


energy increase when heat is transferred to the oil at a rate of 1 W, and 1.5 W of power is applied to the stirring device.

**4–34E** A rigid 1-ft<sup>3</sup> vessel contains R-134a originally at –20°F and 27.7 percent quality. The refrigerant is then heated until its temperature is 100°F. Calculate the heat transfer required to do this. *Answer: 84.7 Btu*


**FIGURE P4–34E**

**4–35** A well-insulated rigid tank contains 5 kg of a saturated liquid–vapor mixture of water at 100 kPa. Initially, three-quarters of the mass is in the liquid phase. An electric resistor placed in the tank is connected to a 110-V source, and a current of 8 A flows through the resistor when the switch is turned on. Determine how long it will take to vaporize all the liquid in the tank. Also, show the process on a  $T$ - $v$  diagram with respect to saturation lines.


**FIGURE P4–35**

**4–36**  Reconsider Prob. 4–35. Using EES (or other) software, investigate the effect of the initial mass of water on the length of time required to completely vaporize the liquid. Let the initial mass vary from 1 to 10 kg. Plot the vaporization time against the initial mass, and discuss the results.

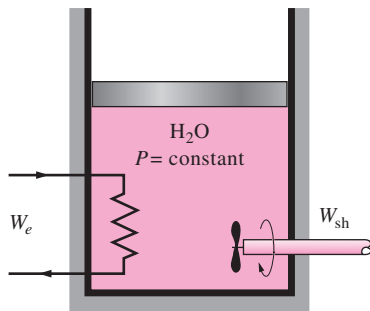
**4–37** A piston–cylinder device contains 5 kg of refrigerant-134a at 800 kPa and 70°C. The refrigerant is now cooled at constant pressure until it exists as a liquid at 15°C. Determine the amount of heat loss and show the process on a  $T$ - $v$  diagram with respect to saturation lines. *Answer: 1173 kJ*

**4–38E** A piston–cylinder device contains 0.5 lbm of water initially at 120 psia and 2 ft<sup>3</sup>. Now 200 Btu of heat is transferred to the water while its pressure is held constant. Deter-


mine the final temperature of the water. Also, show the process on a  $T$ - $v$  diagram with respect to saturation lines.

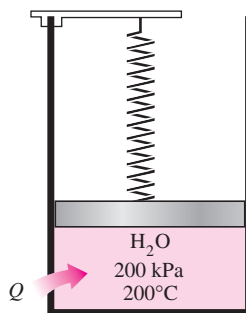
**4-39** An insulated piston-cylinder device contains 5 L of saturated liquid water at a constant pressure of 175 kPa. Water is stirred by a paddle wheel while a current of 8 A flows for 45 min through a resistor placed in the water. If one-half of the liquid is evaporated during this constant-pressure process and the paddle-wheel work amounts to 400 kJ, determine the voltage of the source. Also, show the process on a  $P$ - $v$  diagram with respect to saturation lines.

*Answer: 224 V*




**FIGURE P4-39**

**4-40**  A piston-cylinder device initially contains steam at 200 kPa, 200°C, and 0.5 m<sup>3</sup>. At this state, a linear spring ( $F \propto x$ ) is touching the piston but exerts no force on it. Heat is now slowly transferred to the steam, causing the pressure and the volume to rise to 500 kPa and 0.6 m<sup>3</sup>, respectively. Show the process on a  $P$ - $v$  diagram with respect to saturation lines and determine (a) the final temperature, (b) the work done by the steam, and (c) the total heat transferred. *Answers: (a) 1132°C, (b) 35 kJ, (c) 808 kJ*

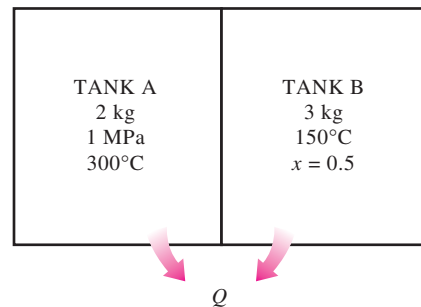


**FIGURE P4-40**

**4-41**  Reconsider Prob. 4-40. Using EES (or other) software, investigate the effect of the initial temperature of steam on the final temperature, the work done,

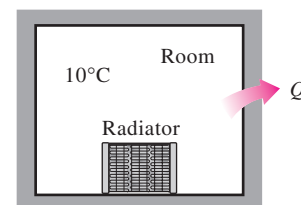
and the total heat transfer. Let the initial temperature vary from 150 to 250°C. Plot the final results against the initial temperature, and discuss the results.

**4-42** Two tanks (Tank A and Tank B) are separated by a partition. Initially Tank A contains 2-kg steam at 1 MPa and 300°C while Tank B contains 3-kg saturated liquid-vapor mixture at 150°C with a vapor mass fraction of 50 percent. Now the partition is removed and the two sides are allowed to mix until the mechanical and thermal equilibrium are established. If the pressure at the final state is 300 kPa, determine (a) the temperature and quality of the steam (if mixture) at the final state and (b) the amount of heat lost from the tanks.



**FIGURE P4-42**

**4-43** A 30-L electrical radiator containing heating oil is placed in a 50-m<sup>3</sup> room. Both the room and the oil in the radiator are initially at 10°C. The radiator with a rating of 1.8 kW is now turned on. At the same time, heat is lost from the room at an average rate of 0.35 kJ/s. After some time, the average temperature is measured to be 20°C for the air in the room, and 50°C for the oil in the radiator. Taking the density and the specific heat of the oil to be 950 kg/m<sup>3</sup> and 2.2 kJ/kg · °C, respectively, determine how long the heater is kept on. Assume the room is well-sealed so that there are no air leaks.



**FIGURE P4-43**

**4-44** 2-kg of saturated liquid water at 150°C is heated at constant pressure in a piston-cylinder device until it is saturated vapor. Determine the heat transfer required for this process.

**4-45** Steam at 75 kPa and 13 percent quality is contained in a spring-loaded piston–cylinder device, as shown in Fig. P4-45, with an initial volume of 2 m<sup>3</sup>. Steam is now heated until its volume is 5 m<sup>3</sup> and its pressure is 300 kPa. Determine the heat transferred to and the work produced by the steam during this process.

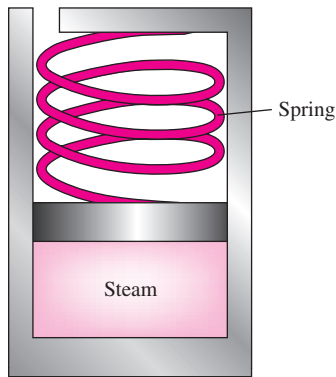


FIGURE P4-45

**4-46** Refrigerant-134a at 600 kPa and 150°C is contained in a spring-loaded piston–cylinder device with an initial volume of 0.3 m<sup>3</sup>. The refrigerant is now cooled until its temperature is -30°C and its volume is 0.1 m<sup>3</sup>. Determine the heat transferred to and the work produced by the refrigerant during this process. *Answers:* 1849 kJ heat out, 68.4 kJ work in

**4-47E** Saturated R-134a vapor at 100°F is condensed at constant pressure to a saturated liquid in a closed piston–cylinder system. Calculate the heat transfer and work done during this process, in Btu/lbm.

**4-48** 2-kg of saturated liquid R-134a with an initial temperature of -10°C is contained in a well-insulated, weighted piston–cylinder device. This device contains an electrical resistor, as shown in Fig. P4-48, to which 10 volts are applied causing a current of 2 amperes to flow through the resistor.

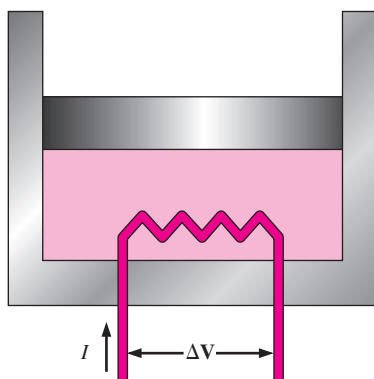


FIGURE P4-48

Determine the time required for the refrigerant to be converted to a saturated vapor, and the final temperature.

### Specific Heats, $\Delta u$ , and $\Delta h$ of Ideal Gases

**4-49C** Is the relation  $\Delta u = mc_{v,avg}\Delta T$  restricted to constant-volume processes only, or can it be used for any kind of process of an ideal gas?

**4-50C** Is the relation  $\Delta h = mc_{p,avg}\Delta T$  restricted to constant-pressure processes only, or can it be used for any kind of process of an ideal gas?

**4-51C** Show that for an ideal gas  $\bar{c}_p = \bar{c}_v + R_u$ .

**4-52C** Is the energy required to heat air from 295 to 305 K the same as the energy required to heat it from 345 to 355 K? Assume the pressure remains constant in both cases.

**4-53C** In the relation  $\Delta u = mc_v\Delta T$ , what is the correct unit of  $c_v$ —kJ/kg·°C or kJ/kg·K?

**4-54C** A fixed mass of an ideal gas is heated from 50 to 80°C at a constant pressure of (a) 1 atm and (b) 3 atm. For which case do you think the energy required will be greater? Why?

**4-55C** A fixed mass of an ideal gas is heated from 50 to 80°C at a constant volume of (a) 1 m<sup>3</sup> and (b) 3 m<sup>3</sup>. For which case do you think the energy required will be greater? Why?

**4-56C** When undergoing a given temperature change, which of the two gases—air or oxygen—experiences the largest change in its (a) enthalpy,  $h$  and (b) internal energy,  $u$ ?

**4-57** A mass of 10-g of nitrogen is contained in the spring-loaded piston–cylinder device shown in Fig. P4-57. The spring constant is 1 kN/m, and the piston diameter is 10 cm. When the spring exerts no force against the piston, the nitrogen is at 120 kPa and 27°C. The device is now heated until its volume is 10 percent greater than the original volume. Determine the change in the specific internal energy and enthalpy of the nitrogen. *Answers:* 46.8 kJ/kg, 65.5 kJ/kg

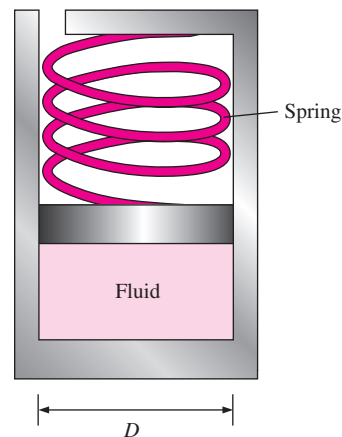


FIGURE P4-57

**4-58E** What is the change in the internal energy, in Btu/lbm, of air as its temperature changes from 100 to 200°F? Is there any difference if the temperature were to change from 0 to 100°F?

**4-59** The temperature of 2 kg of neon is increased from 20°C to 180°C. Calculate the change in the total internal energy of the neon, in kJ. Would the internal energy change be any different if the neon were replaced with argon?

**4-60** Calculate the change in the enthalpy of argon, in kJ/kg, when it is cooled from 400 to 100°C. If neon had undergone this same change of temperature, would its enthalpy change have been any different?

**4-61** Neon is compressed from 100 kPa and 20°C to 500 kPa in an isothermal compressor. Determine the change in the specific volume and specific enthalpy of neon caused by this compression.

**4-62E** Determine the enthalpy change  $\Delta h$  of oxygen, in Btu/lbm, as it is heated from 800 to 1500 R, using (a) the empirical specific heat equation as a function of temperature (Table A-2Ec), (b) the  $c_p$  value at the average temperature (Table A-2Eb), and (c) the  $c_p$  value at room temperature (Table A-2Ea).

*Answers: (a) 170.1 Btu/lbm, (b) 178.5 Btu/lbm, (c) 153.3 Btu/lbm*

**4-63** Determine the internal energy change  $\Delta u$  of hydrogen, in kJ/kg, as it is heated from 200 to 800 K, using (a) the empirical specific heat equation as a function of temperature (Table A-2c), (b) the  $c_v$  value at the average temperature (Table A-2b), and (c) the  $c_v$  value at room temperature (Table A-2a).

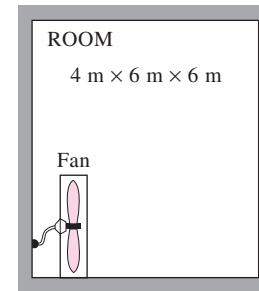
### Closed-System Energy Analysis: Ideal Gases

**4-64C** Is it possible to compress an ideal gas isothermally in an adiabatic piston-cylinder device? Explain.

**4-65E** A rigid tank contains 20 lbm of air at 50 psia and 80°F. The air is now heated until its pressure doubles. Determine (a) the volume of the tank and (b) the amount of heat transfer. *Answers: (a) 80 ft<sup>3</sup>, (b) 1898 Btu*

**4-66** A 4-m  $\times$  5-m  $\times$  6-m room is to be heated by a baseboard resistance heater. It is desired that the resistance heater be able to raise the air temperature in the room from 7 to 23°C within 15 min. Assuming no heat losses from the room and an atmospheric pressure of 100 kPa, determine the required power of the resistance heater. Assume constant specific heats at room temperature. *Answer: 1.91 kW*

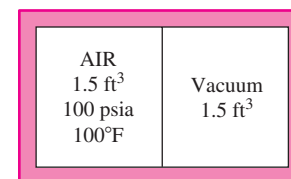
**4-67** A student living in a 4-m  $\times$  6-m  $\times$  6-m dormitory room turns on her 150-W fan before she leaves the room on a summer day, hoping that the room will be cooler when she comes back in the evening. Assuming all the doors and windows are tightly closed and disregarding any heat transfer through the walls and the windows, determine the temperature in the room when she comes back 10 h later. Use specific heat values at room temperature, and assume the



**FIGURE P4-67**

room to be at 100 kPa and 15°C in the morning when she leaves. *Answer: 58.2°C*

**4-68E** A 3-ft<sup>3</sup> adiabatic rigid container is divided into two equal volumes by a thin membrane, as shown in Fig. P4-68E. Initially, one of these chambers is filled with air at 100 psia and 100°F while the other chamber is evacuated. Determine the internal energy change of the air when the membrane is ruptured. Also determine the final air pressure in the container.

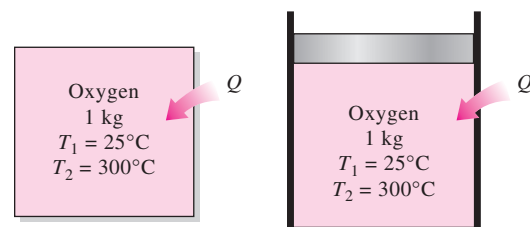


**FIGURE P4-68E**

**4-69** Nitrogen in a rigid vessel is cooled by rejecting 100 kJ/kg of heat. Determine the internal energy change of the nitrogen, in kJ/kg.

**4-70E** Nitrogen at 100 psia and 300°F in a rigid container is cooled until its pressure is 50 psia. Determine the work done and the heat transferred during this process, in Btu/lbm. *Answers: 0 Btu/lbm, 67.3 Btu/lbm*

**4-71** 1-kg of oxygen is heated from 25 to 300°C. Determine the amount of heat transfer required when this is done during a (a) constant-volume process and (b) isobaric process.

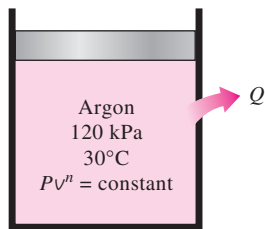


**FIGURE P4-71**

**4-72** A closed system containing 2-kg of air undergoes an isothermal process from 600 kPa and 200°C to 80 kPa. Determine the initial volume of this system, the work done, and the heat transfer during this process. *Answers:* 0.453 m<sup>3</sup>, 547 kJ, 547 kJ

**4-73** A piston–cylinder device containing argon gas as the system undergoes an isothermal process from 200 kPa and 100°C to 50 kPa. During the process, 1500 kJ of heat is transferred to the system. Determine the mass of this system and the amount of work produced.

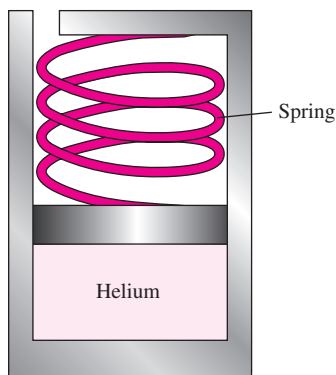
**4-74** Argon is compressed in a polytropic process with  $n = 1.2$  from 120 kPa and 30°C to 1200 kPa in a piston–cylinder device. Determine the work produced and heat transferred during this compression process, in kJ/kg.



**FIGURE P4-74**

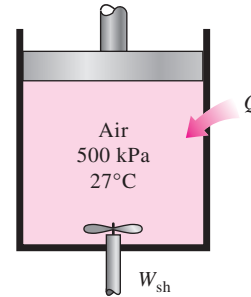
**4-75E** A piston–cylinder device containing carbon-dioxide gas undergoes an isobaric process from 15 psia and 80°F to 200°F. Determine the work and the heat transfer associated with this process, in Btu/lbm. *Answers:* 5.42 Btu/lbm, 24.4 Btu/lbm

**4-76** A spring-loaded piston–cylinder device contains 5 kg of helium as the system, as shown in Fig. P4-76. This system is heated from 100 kPa and 20°C to 800 kPa and 160°C. Determine the heat transferred to and work produced by this system.



**FIGURE P4-76**

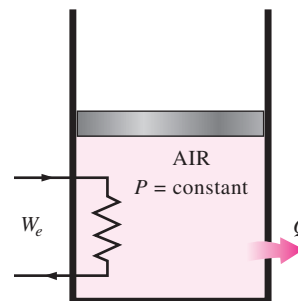
**4-77** Air is contained in a variable-load piston device equipped with a paddle wheel. Initially, air is at 500 kPa and 27°C. The paddle wheel is now turned by an external electric motor until 50 kJ/kg of work has been transferred to air. During this process, heat is transferred to maintain a constant air temperature while allowing the gas volume to triple. Calculate the required amount of heat transfer, in kJ/kg. *Answer:* 122 kJ/kg



**FIGURE P4-77**

**4-78** A piston–cylinder device whose piston is resting on top of a set of stops initially contains 0.5 kg of helium gas at 100 kPa and 25°C. The mass of the piston is such that 500 kPa of pressure is required to raise it. How much heat must be transferred to the helium before the piston starts rising? *Answer:* 1857 kJ


**4-79** A mass of 15 kg of air in a piston–cylinder device is heated from 25 to 77°C by passing current through a resistance heater inside the cylinder. The pressure inside the cylinder is held constant at 300 kPa during the process, and a heat loss of 60 kJ occurs. Determine the electric energy supplied, in kWh. *Answer:* 0.235 kWh



**FIGURE P4-79**

**4-80** An insulated piston–cylinder device initially contains 0.3 m<sup>3</sup> of carbon dioxide at 200 kPa and 27°C. An electric switch is turned on, and a 110-V source supplies current to a resistance heater inside the cylinder for a period of 10 min. The pressure is held constant during the process, while the volume is doubled. Determine the current that passes through the resistance heater.

**4–81** A piston–cylinder device contains 0.8 kg of nitrogen initially at 100 kPa and 27°C. The nitrogen is now compressed slowly in a polytropic process during which  $PV^{1.3} = \text{constant}$  until the volume is reduced by one-half. Determine the work done and the heat transfer for this process.

**4–82**  Reconsider Prob. 4–81. Using EES (or other) software, plot the process described in the problem on a  $P$ - $V$  diagram, and investigate the effect of the polytropic exponent  $n$  on the boundary work and heat transfer. Let the polytropic exponent vary from 1.1 to 1.6. Plot the boundary work and the heat transfer versus the polytropic exponent, and discuss the results.

**4–83** A room is heated by a baseboard resistance heater. When the heat losses from the room on a winter day amount to 6500 kJ/h, the air temperature in the room remains constant even though the heater operates continuously. Determine the power rating of the heater, in kW.

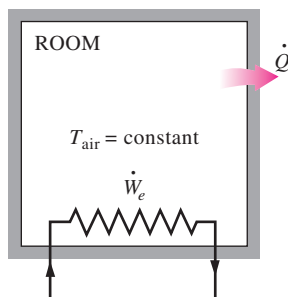



FIGURE P4–83

**4–84** A piston–cylinder device, whose piston is resting on a set of stops, initially contains 3 kg of air at 200 kPa and 27°C. The mass of the piston is such that a pressure of 400 kPa is required to move it. Heat is now transferred to the air until its volume doubles. Determine the work done by the air and the total heat transferred to the air during this process. Also show the process on a  $P$ - $v$  diagram. *Answers: 516 kJ, 2674 kJ*

**4–85**  A piston–cylinder device, with a set of stops on the top, initially contains 3 kg of air at 200 kPa and 27°C. Heat is now transferred to the air, and the piston rises until it hits the stops, at which point the volume is twice the initial volume. More heat is transferred until the pressure inside the cylinder also doubles. Determine the work done and the amount of heat transfer for this process. Also, show the process on a  $P$ - $v$  diagram.

### Closed-System Energy Analysis: Solids and Liquids

**4–86** A 1-kg block of iron is heated from 20°C to 80°C. What is the change in the iron's total internal energy and enthalpy?

**4–87E** The state of liquid water is changed from 50 psia and 50°F to 2000 psia and 100°F. Determine the change in the

internal energy and enthalpy of water on the basis of the (a) compressed liquid tables, (b) incompressible substance approximation and property tables, and (c) specific-heat model.

**4–88E** During a picnic on a hot summer day, all the cold drinks disappeared quickly, and the only available drinks were those at the ambient temperature of 75°F. In an effort to cool a 12-fluid-oz drink in a can, a person grabs the can and starts shaking it in the iced water of the chest at 32°F. Using the properties of water for the drink, determine the mass of ice that will melt by the time the canned drink cools to 45°F.

**4–89** Consider a 1000-W iron whose base plate is made of 0.5-cm-thick aluminum alloy 2024-T6 ( $\rho = 2770 \text{ kg/m}^3$  and  $c_p = 875 \text{ J/kg} \cdot ^\circ\text{C}$ ). The base plate has a surface area of 0.03 m<sup>2</sup>. Initially, the iron is in thermal equilibrium with the ambient air at 22°C. Assuming 85 percent of the heat generated in the resistance wires is transferred to the plate, determine the minimum time needed for the plate temperature to reach 140°C.



FIGURE P4–89

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**4–90** Stainless steel ball bearings ( $\rho = 8085 \text{ kg/m}^3$  and  $c_p = 0.480 \text{ kJ/kg} \cdot ^\circ\text{C}$ ) having a diameter of 1.2 cm are to be quenched in water at a rate of 800 per minute. The balls leave the oven at a uniform temperature of 900°C and are exposed to air at 25°C for a while before they are dropped into the water. If the temperature of the balls drops to 850°C prior to quenching, determine the rate of heat transfer from the balls to the air.

**4–91** Carbon steel balls ( $\rho = 7833 \text{ kg/m}^3$  and  $c_p = 0.465 \text{ kJ/kg} \cdot ^\circ\text{C}$ ) 8 mm in diameter are annealed by heating them first to 900°C in a furnace, and then allowing them to cool slowly to 100°C in ambient air at 35°C. If 2500 balls are to be annealed per hour, determine the total rate of heat transfer from the balls to the ambient air. *Answer: 542 W*

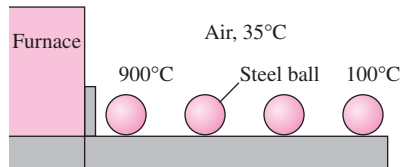



FIGURE P4-91

**4-92** An electronic device dissipating 30 W has a mass of 20 g and a specific heat of  $850 \text{ J/kg} \cdot ^\circ\text{C}$ . The device is lightly used, and it is on for 5 min and then off for several hours, during which it cools to the ambient temperature of  $25^\circ\text{C}$ . Determine the highest possible temperature of the device at the end of the 5-min operating period. What would your answer be if the device were attached to a 0.2-kg aluminum heat sink? Assume the device and the heat sink to be nearly isothermal.

**4-93**  Reconsider Prob. 4-92. Using EES (or other) software, investigate the effect of the mass of the heat sink on the maximum device temperature. Let the mass of heat sink vary from 0 to 1 kg. Plot the maximum temperature against the mass of heat sink, and discuss the results.

**4-94** An ordinary egg can be approximated as a 5.5-cm-diameter sphere. The egg is initially at a uniform temperature of  $8^\circ\text{C}$  and is dropped into boiling water at  $97^\circ\text{C}$ . Taking the properties of the egg to be  $\rho = 1020 \text{ kg/m}^3$  and  $c_p = 3.32 \text{ kJ/kg} \cdot ^\circ\text{C}$ , determine how much heat is transferred to the egg by the time the average temperature of the egg rises to  $80^\circ\text{C}$ .

**4-95E** In a production facility, 1.2-in-thick 2-ft  $\times$  2-ft square brass plates ( $\rho = 532.5 \text{ lbm/ft}^3$  and  $c_p = 0.091 \text{ Btu/lbm} \cdot ^\circ\text{F}$ ) that are initially at a uniform temperature of  $75^\circ\text{F}$  are heated by passing them through an oven at  $1300^\circ\text{F}$  at a rate of 300 per minute. If the plates remain in the oven until their average temperature rises to  $1000^\circ\text{F}$ , determine the rate of heat transfer to the plates in the furnace.

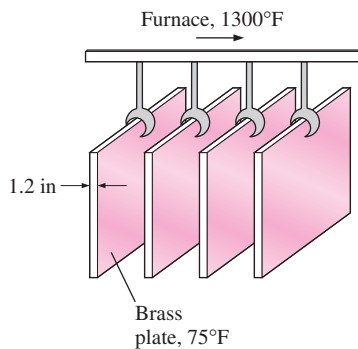


FIGURE P4-95E

**4-96** Long cylindrical steel rods ( $\rho = 7833 \text{ kg/m}^3$  and  $c_p = 0.465 \text{ kJ/kg} \cdot ^\circ\text{C}$ ) of 10-cm diameter are heat-treated by draw-

ing them at a velocity of 3 m/min through an oven maintained at  $900^\circ\text{C}$ . If the rods enter the oven at  $30^\circ\text{C}$  and leave at a mean temperature of  $700^\circ\text{C}$ , determine the rate of heat transfer to the rods in the oven.

### Special Topic: Biological Systems

**4-97C** What is metabolism? What is basal metabolic rate? What is the value of basal metabolic rate for an average man?

**4-98C** For what is the energy released during metabolism in humans used?

**4-99C** Is the metabolizable energy content of a food the same as the energy released when it is burned in a bomb calorimeter? If not, how does it differ?

**4-100C** Is the number of prospective occupants an important consideration in the design of heating and cooling systems of classrooms? Explain.

**4-101C** What do you think of a diet program that allows for generous amounts of bread and rice provided that no butter or margarine is added?

**4-102** Consider two identical rooms, one with a 2-kW electric resistance heater and the other with three couples fast dancing. In which room will the air temperature rise faster?

**4-103** Consider two identical 80-kg men who are eating identical meals and doing identical things except that one of them jogs for 30 min every day while the other watches TV. Determine the weight difference between the two in a month. *Answer: 1.045 kg*

**4-104** Consider a classroom that is losing heat to the outdoors at a rate of 20,000 kJ/h. If there are 30 students in class, each dissipating sensible heat at a rate of 100 W, determine if it is necessary to turn the heater in the classroom on to prevent the room temperature from dropping.

**4-105** A 68-kg woman is planning to bicycle for an hour. If she is to meet her entire energy needs while bicycling by eating 30-g chocolate candy bars, determine how many candy bars she needs to take with her.

**4-106** A 55-kg man gives in to temptation and eats an entire 1-L box of ice cream. How long does this man need to jog to burn off the calories he consumed from the ice cream? *Answer: 2.52 h*

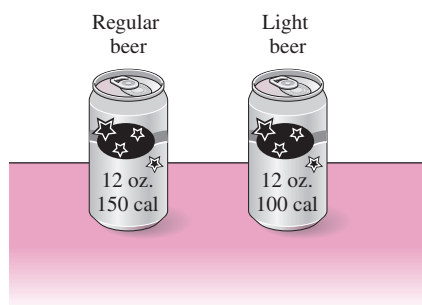
**4-107** Consider a man who has 20 kg of body fat when he goes on a hunger strike. Determine how long he can survive on his body fat alone.

**4-108** Consider two identical 50-kg women, Candy and Wendy, who are doing identical things and eating identical food except that Candy eats her baked potato with four teaspoons of butter while Wendy eats hers plain every evening. Determine the difference in the weights of Candy and Wendy after one year. *Answer: 6.5 kg*

**4-109** A woman who used to drink about one liter of regular cola every day switches to diet cola (zero calorie) and

starts eating two slices of apple pie every day. Is she now consuming fewer or more calories?

**4-110** A 12-oz serving of a regular beer contains 13 g of alcohol and 13 g of carbohydrates, and thus 150 Calories. A 12-oz serving of a light beer contains 11 g of alcohol and 5 g of carbohydrates, and thus 100 Calories. An average person burns 700 Calories per hour while exercising on a treadmill. Determine how long it will take to burn the calories from a 12-oz can of (a) regular beer and (b) light beer on a treadmill.



**FIGURE P4-110**

**4-111** A 5-oz serving of a Bloody Mary contains 14 g of alcohol and 5 g of carbohydrates, and thus 116 Calories. A 2.5-oz serving of a martini contains 22 g of alcohol and a negligible amount of carbohydrates, and thus 156 Calories. An average person burns 600 Calories per hour while exercising on a cross-country ski machine. Determine how long it will take to burn the calories from one serving of (a) a Bloody Mary and (b) a martini on this cross-country ski machine.

**4-112E** A 176-pound man and a 132-pound woman went to Burger King for lunch. The man had a BK Big Fish sandwich (720 Cal), medium french fries (400 Cal), and a large Coke (225 Cal). The woman had a basic hamburger (330 Cal), medium french fries (400 Cal), and a diet Coke (0 Cal). After lunch, they start shoveling snow and burn calories at a rate of 360 Cal/h for the woman and 480 Cal/h for the man. Determine how long each one of them needs to shovel snow to burn off the lunch calories.

**4-113** Consider two friends who go to Burger King every day for lunch. One of them orders a Double Whopper sandwich, large fries, and a large Coke (total Calories = 1600) while the other orders a Whopper Junior, small fries, and a small Coke (total Calories = 800) every day. If these two friends are very much alike otherwise and they have the same metabolic rate, determine the weight difference between these two friends in a year.

**4-114E** A 150-pound person goes to Hardee's for dinner and orders a regular roast beef (270 Cal) and a big roast beef (410 Cal) sandwich together with a 12-oz can of Pepsi (150 Cal). A 150-pound person burns 400 Calories per hour while climbing stairs. Determine how long this person needs to climb stairs to burn off the dinner calories.

**4-115** A person eats a McDonald's Big Mac sandwich (530 Cal), a second person eats a Burger King Whopper sandwich (640 Cal), and a third person eats 50 olives with regular french fries (350 Cal) for lunch. Determine who consumes the most calories. An olive contains about 5 Calories.

**4-116** A 100-kg man decides to lose 5 kg without cutting down his intake of 3000 Calories a day. Instead, he starts fast swimming, fast dancing, jogging, and biking each for an hour every day. He sleeps or relaxes the rest of the day. Determine how long it will take him to lose 5 kg.

**4-117E** The range of healthy weight for adults is usually expressed in terms of the *body mass index* (BMI), defined, in SI units, as

$$\text{BMI} = \frac{W(\text{kg})}{H^2(\text{m}^2)}$$

where  $W$  is the weight (actually, the mass) of the person in kg and  $H$  is the height in m, and the range of healthy weight is  $19 \leq \text{BMI} \leq 25$ . Convert the previous formula to English units such that the weight is in pounds and the height in inches. Also, calculate your own BMI, and if it is not in the healthy range, determine how many pounds (or kg) you need to gain or lose to be fit.

**4-118** The body mass index (BMI) of a 1.7-m tall woman who normally has 3 large slices of cheese pizza and a 400-ml Coke for lunch is 30. She now decides to change her lunch to 2 slices of pizza and a 200-ml Coke. Assuming that the deficit in the calorie intake is made up by burning body fat, determine how long it will take for the BMI of this person to drop to 25. Use the data in the text for calories and take the metabolizable energy content of 1 kg of body fat to be 33,100 kJ.

*Answer: 262 days*

**4-119** Many fast food restaurants offer supersizing your burger, fries, and soda at a bargain price, but supersizing may cost you up to 1000 extra calories. Determine how much extra weight supersizing once a day can cause a person to gain per month.

### Review Problems

**4-120** Which of the two gases—neon or air—requires the least amount of work when compressed in a closed system from  $P_1$  to  $P_2$  using a polytropic process with  $n = 1.5$ ?

**4-121** 10-kg of nitrogen is heated from 20°C to 250°C. Determine the total amount of heat required when this is done in (a) a constant-volume process and (b) an isobaric process.

**4-122E** Air in the amount of 1 lbm is contained in a well-insulated, rigid vessel equipped with a stirring paddle wheel. The initial state of this air is 30 psia and 40°F. How much work, in Btu, must be transferred to the air with the paddle wheel to raise the air pressure to 50 psia? Also, what is the final temperature of air?

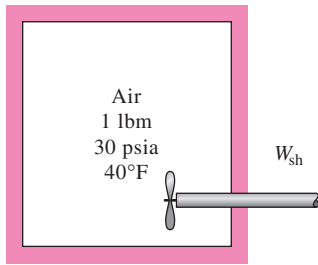


FIGURE P4-122E

**4-123** Does the concept of a specific heat property (either at constant volume or constant pressure) have a meaning for substances that are undergoing a phase change? Why or why not?

**4-124** A rigid tank contains a gas mixture with a specific heat of  $c_v = 0.748 \text{ kJ/kg} \cdot \text{K}$ . The mixture is cooled from 200 kPa and 200°C until its pressure is 100 kPa. Determine the heat transfer during this process, in kJ/kg.

**4-125** A well-insulated rigid vessel contains 3 kg of saturated liquid water at 40°C. The vessel also contains an electrical resistor that draws 10 amperes when 50 volts are applied. Determine the final temperature in the vessel after the resistor has been operating for 30 minutes. *Answer: 119°C*

**4-126** Derive a general expression for the work produced by an ideal gas as it undergoes a polytropic process in a closed system from initial state 1 to final state 2. Your result should be in terms of the initial pressure and temperature and the final pressure as well as the gas constant  $R$  and the polytropic exponent  $n$ .

**4-127** A frictionless piston–cylinder device initially contains air at 200 kPa and  $0.2 \text{ m}^3$ . At this state, a linear spring ( $F \propto x$ ) is touching the piston but exerts no force on it. The air is now heated to a final state of  $0.5 \text{ m}^3$  and 800 kPa. Determine (a) the total work done by the air and (b) the work done against the spring. Also, show the process on a  $P$ - $v$  diagram. *Answers: (a) 150 kJ, (b) 90 kJ*

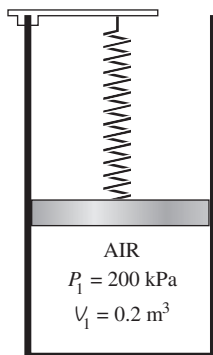


FIGURE P4-127

**4-128** A mass of 5 kg of saturated liquid–vapor mixture of water is contained in a piston–cylinder device at 125 kPa. Initially, 2 kg of the water is in the liquid phase and the rest is in the vapor phase. Heat is now transferred to the water, and the piston, which is resting on a set of stops, starts moving when the pressure inside reaches 300 kPa. Heat transfer continues until the total volume increases by 20 percent. Determine (a) the initial and final temperatures, (b) the mass of liquid water when the piston first starts moving, and (c) the work done during this process. Also, show the process on a  $P$ - $v$  diagram.

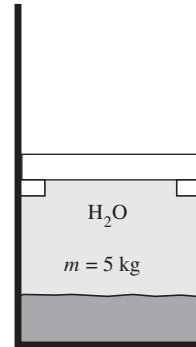



FIGURE P4-128

**4-129E** A spherical balloon contains 10 lbm of air at 30 psia and 800 R. The balloon material is such that the pressure inside is always proportional to the square of the diameter. Determine the work done when the volume of the balloon doubles as a result of heat transfer. *Answer: 715 Btu*

**4-130E**  Reconsider Prob. 4-129E. Using the integration feature of the EES software, determine the work done. Compare the result with your “hand-calculated” result.

**4-131** A mass of 12 kg of saturated refrigerant-134a vapor is contained in a piston–cylinder device at 240 kPa. Now 300 kJ of heat is transferred to the refrigerant at constant pressure while a 110-V source supplies current to a resistor within the

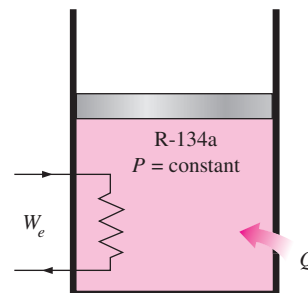
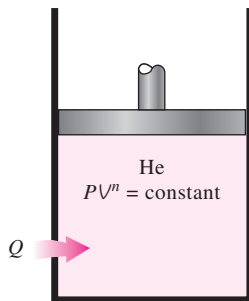


FIGURE P4-131

cylinder for 6 min. Determine the current supplied if the final temperature is 70°C. Also, show the process on a  $T$ - $v$  diagram with respect to the saturation lines. *Answer: 12.8 A*

**4–132** A mass of 0.2 kg of saturated refrigerant-134a is contained in a piston–cylinder device at 200 kPa. Initially, 75 percent of the mass is in the liquid phase. Now heat is transferred to the refrigerant at constant pressure until the cylinder contains vapor only. Show the process on a  $P$ - $v$  diagram with respect to saturation lines. Determine (a) the volume occupied by the refrigerant initially, (b) the work done, and (c) the total heat transfer.

**4–133** A piston–cylinder device contains helium gas initially at 150 kPa, 20°C, and 0.5 m<sup>3</sup>. The helium is now compressed in a polytropic process ( $PV^n = \text{constant}$ ) to 400 kPa and 140°C. Determine the heat loss or gain during this process. *Answer: 11.2 kJ loss*



**FIGURE P4–133**

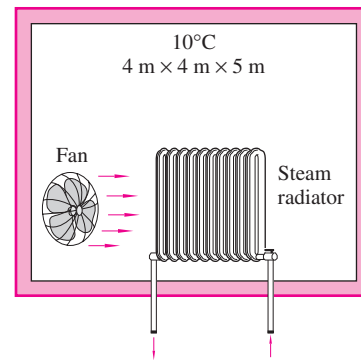
**4–134** Nitrogen gas is expanded in a polytropic process with  $n = 1.35$  from 2 MPa and 1200 K to 120 kPa in a piston–cylinder device. How much work is produced and heat is transferred during this expansion process, in kJ/kg?

**4–135** Which of the two gases—neon or air—produces the greatest amount of work when expanded from  $P_1$  to  $P_2$  in a closed system polytropic process with  $n = 1.2$ ?

**4–136** A frictionless piston–cylinder device and a rigid tank initially contain 12 kg of an ideal gas each at the same temperature, pressure, and volume. It is desired to raise the temperatures of both systems by 15°C. Determine the amount of extra heat that must be supplied to the gas in the cylinder which is maintained at constant pressure to achieve this result. Assume the molar mass of the gas is 25.

**4–137** A passive solar house that is losing heat to the outdoors at an average rate of 50,000 kJ/h is maintained at 22°C at all times during a winter night for 10 h. The house is to be heated by 50 glass containers each containing 20 L of water that is heated to 80°C during the day by absorbing solar energy. A thermostat-controlled 15-kW back-up electric resistance heater turns on whenever necessary to keep the house at

22°C. (a) How long did the electric heating system run that night? (b) How long would the electric heater run that night if the house incorporated no solar heating? *Answers: (a) 4.77 h, (b) 9.26 h*



**FIGURE P4–137**

**4–138** An 1800-W electric resistance heating element is immersed in 40 kg of water initially at 20°C. Determine how long it will take for this heater to raise the water temperature to 80°C.

**4–139** One ton (1000 kg) of liquid water at 80°C is brought into a well-insulated and well-sealed 4-m × 5-m × 6-m room initially at 22°C and 100 kPa. Assuming constant specific heats for both air and water at room temperature, determine the final equilibrium temperature in the room. *Answer: 78.6°C*

**4–140** A 4-m × 5-m × 6-m room is to be heated by one ton (1000 kg) of liquid water contained in a tank that is placed in the room. The room is losing heat to the outside at an average rate of 8000 kJ/h. The room is initially at 20°C and 100 kPa and is maintained at an average temperature of 20°C at all times. If the hot water is to meet the heating requirements of this room for a 24-h period, determine the minimum temperature of the water when it is first brought into the room. Assume constant specific heats for both air and water at room temperature.

**4–141** The energy content of a certain food is to be determined in a bomb calorimeter that contains 3 kg of water by burning a 2-g sample of it in the presence of 100 g of air in the reaction chamber. If the water temperature rises by 3.2°C when equilibrium is established, determine the energy content of the food, in kJ/kg, by neglecting the thermal energy stored in the reaction chamber and the energy supplied by the mixer. What is a rough estimate of the error involved in neglecting the thermal energy stored in the reaction chamber? *Answer: 20,060 kJ/kg*

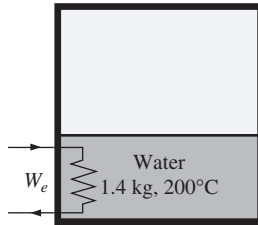



FIGURE P4-141

**4-142** A 68-kg man whose average body temperature is  $39^\circ\text{C}$  drinks 1 L of cold water at  $3^\circ\text{C}$  in an effort to cool down. Taking the average specific heat of the human body to be  $3.6 \text{ kJ/kg}\cdot^\circ\text{C}$ , determine the drop in the average body temperature of this person under the influence of this cold water.

**4-143** A 0.2-L glass of water at  $20^\circ\text{C}$  is to be cooled with ice to  $5^\circ\text{C}$ . Determine how much ice needs to be added to the water, in grams, if the ice is at (a)  $0^\circ\text{C}$  and (b)  $-8^\circ\text{C}$ . Also determine how much water would be needed if the cooling is to be done with cold water at  $0^\circ\text{C}$ . The melting temperature and the heat of fusion of ice at atmospheric pressure are  $0^\circ\text{C}$  and  $333.7 \text{ kJ/kg}$ , respectively, and the density of water is  $1 \text{ kg/L}$ .

**4-144**  Reconsider Prob. 4-143. Using EES (or other) software, investigate the effect of the initial temperature of the ice on the final mass required. Let the ice temperature vary from  $-20$  to  $0^\circ\text{C}$ . Plot the mass of ice against the initial temperature of ice, and discuss the results.

**4-145** One kilogram of carbon dioxide is compressed from 1 MPa and  $200^\circ\text{C}$  to 3 MPa in a piston–cylinder device arranged to execute a polytropic process  $PV^{1.5} = \text{constant}$ . Determine the final temperature treating the carbon dioxide as (a) an ideal gas and (b) a van der Waals gas. *Answers: (a) 682.1 K, (b) 680.9 K*

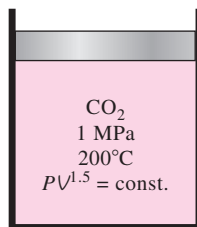


FIGURE P4-145

**4-146** Two adiabatic chambers,  $2 \text{ m}^3$  each, are interconnected by a valve, as shown in Fig. P4-146, with one chamber containing oxygen at 1000 kPa and  $127^\circ\text{C}$  and the other chamber evacuated. The valve is now opened until the oxygen fills both chambers and both tanks have the same pressure. Determine the total internal energy change and the final pressure in the tanks.

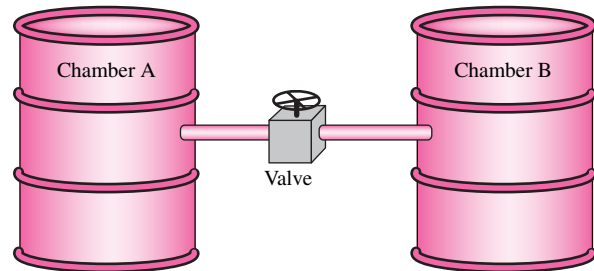


FIGURE P4-146

**4-147** A rigid tank containing  $0.4 \text{ m}^3$  of air at 400 kPa and  $30^\circ\text{C}$  is connected by a valve to a piston–cylinder device with zero clearance. The mass of the piston is such that a pressure of 200 kPa is required to raise the piston. The valve is now opened slightly, and air is allowed to flow into the cylinder until the pressure in the tank drops to 200 kPa. During this process, heat is exchanged with the surroundings such that the entire air remains at  $30^\circ\text{C}$  at all times. Determine the heat transfer for this process.

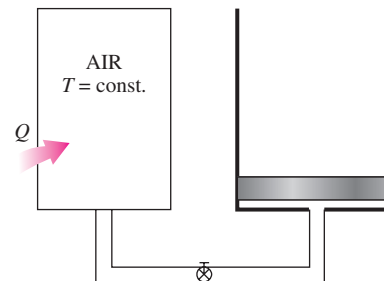


FIGURE P4-147

**4-148** A well-insulated  $4\text{-m} \times 4\text{-m} \times 5\text{-m}$  room initially at  $10^\circ\text{C}$  is heated by the radiator of a steam heating system. The radiator has a volume of 15 L and is filled with superheated vapor at 200 kPa and  $200^\circ\text{C}$ . At this moment both the inlet and the exit valves to the radiator are closed. A 120-W fan is used to distribute the air in the room. The pressure of the steam is observed to drop to 100 kPa after 30 min as a result of heat transfer to the room. Assuming constant specific heats

for air at room temperature, determine the average temperature of air in 30 min. Assume the air pressure in the room remains constant at 100 kPa.

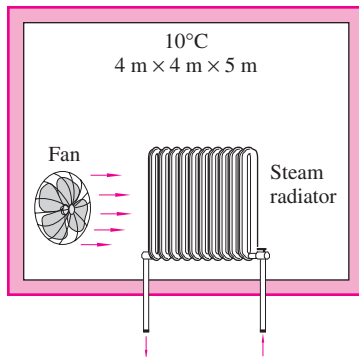


FIGURE P4-148

**4-149** Consider a well-insulated horizontal rigid cylinder that is divided into two compartments by a piston that is free to move but does not allow either gas to leak into the other side. Initially, one side of the piston contains 1 m<sup>3</sup> of N<sub>2</sub> gas at 500 kPa and 80°C while the other side contains 1 m<sup>3</sup> of He gas at 500 kPa and 25°C. Now thermal equilibrium is established in the cylinder as a result of heat transfer through the piston. Using constant specific heats at room temperature, determine the final equilibrium temperature in the cylinder. What would your answer be if the piston were not free to move?

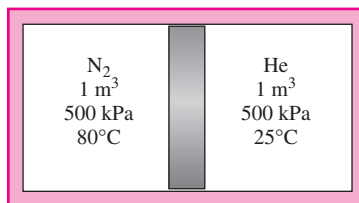



FIGURE P4-149

**4-150** Repeat Prob. 4-149 by assuming the piston is made of 5 kg of copper initially at the average temperature of the two gases on both sides. *Answer: 56°C*

**4-151**  Reconsider Prob. 4-150. Using EES (or other) software, investigate the effect of the mass of the copper piston on the final equilibrium temperature. Let the mass of piston vary from 1 to 10 kg. Plot the final temperature against the mass of piston, and discuss the results.

**4-152** An insulated piston-cylinder device initially contains 1.4-kg saturated liquid water at 200°C. Now an electric resistor

placed in the tank is turned on for 20 min until the volume quadruples. Determine (a) the volume of the tank, (b) the final temperature, and (c) the electrical power rating of the resistor.

*Answers: (a) 0.00648 m<sup>3</sup>, (b) 200°C, (c) 0.00623 kW*

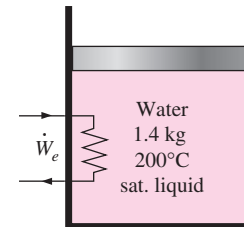


FIGURE P4-152

**4-153** A vertical 12-cm diameter piston-cylinder device contains an ideal gas at the ambient conditions of 1 bar and 24°C. Initially, the inner face of the piston is 20 cm from the base of the cylinder. Now an external shaft connected to the piston exerts a force corresponding to a boundary work input of 0.1 kJ. The temperature of the gas remains constant during the process. Determine (a) the amount of heat transfer, (b) the final pressure in the cylinder, and (c) the distance that the piston is displaced.

**4-154** A piston-cylinder device initially contains 0.15-kg steam at 3.5 MPa, superheated by 5°C. Now the steam loses heat to the surroundings and the piston moves down, hitting a set of stops at which point the cylinder contains saturated liquid water. The cooling continues until the cylinder contains water at 200°C. Determine (a) the final pressure and the quality (if mixture), (b) the boundary work, (c) the amount of heat transfer when the piston first hits the stops, (d) and the total heat transfer.

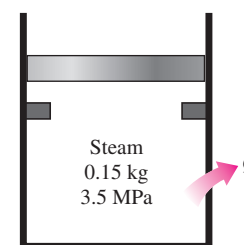


FIGURE P4-154

**4-155** An insulated rigid tank is divided into two compartments of different volumes. Initially, each compartment contains the same ideal gas at identical pressure but at different temperatures and masses. The wall separating the two compartments is removed and the two gases are allowed to mix.



of  $0.1 \text{ m}^3$ . The work done on the gas during this compression process is

- (a) 746 kJ (b) 0 kJ  
(c) 420 kJ (d) 998 kJ  
(e) 1890 kJ

**4-163** A well-sealed room contains 60 kg of air at 200 kPa and  $25^\circ\text{C}$ . Now solar energy enters the room at an average rate of  $0.8 \text{ kJ/s}$  while a 120-W fan is turned on to circulate the air in the room. If heat transfer through the walls is negligible, the air temperature in the room in 30 min will be

- (a)  $25.6^\circ\text{C}$  (b)  $49.8^\circ\text{C}$   
(c)  $53.4^\circ\text{C}$  (d)  $52.5^\circ\text{C}$   
(e)  $63.4^\circ\text{C}$

**4-164** A 2-kW baseboard electric resistance heater in a vacant room is turned on and kept on for 15 min. The mass of the air in the room is 75 kg, and the room is tightly sealed so that no air can leak in or out. The temperature rise of air at the end of 15 min is

- (a)  $8.5^\circ\text{C}$  (b)  $12.4^\circ\text{C}$   
(c)  $24.0^\circ\text{C}$  (d)  $33.4^\circ\text{C}$   
(e)  $54.8^\circ\text{C}$

**4-165** A room contains 60 kg of air at 100 kPa and  $15^\circ\text{C}$ . The room has a 250-W refrigerator (the refrigerator consumes 250 W of electricity when running), a 120-W TV, a 1-kW electric resistance heater, and a 50-W fan. During a cold winter day, it is observed that the refrigerator, the TV, the fan, and the electric resistance heater are running continuously but the air temperature in the room remains constant. The rate of heat loss from the room that day is

- (a) 3312 kJ/h (b) 4752 kJ/h  
(c) 5112 kJ/h (d) 2952 kJ/h  
(e) 4680 kJ/h

**4-166** A piston-cylinder device contains 5 kg of air at 400 kPa and  $30^\circ\text{C}$ . During a quasi-equilibrium isothermal expansion process, 15 kJ of boundary work is done by the system, and 3 kJ of paddle-wheel work is done on the system. The heat transfer during this process is

- (a) 12 kJ (b) 18 kJ  
(c) 2.4 kJ (d) 3.5 kJ  
(e) 60 kJ

**4-167** A container equipped with a resistance heater and a mixer is initially filled with 3.6 kg of saturated water vapor at  $120^\circ\text{C}$ . Now the heater and the mixer are turned on; the steam is compressed; and there is heat loss to the surrounding air. At the end of the process, the temperature and pressure of steam in the container are measured to be  $300^\circ\text{C}$  and 0.5 MPa. The net energy transfer to the steam during this process is

- (a) 274 kJ (b) 914 kJ  
(c) 1213 kJ (d) 988 kJ  
(e) 1291 kJ

**4-168** A 6-pack canned drink is to be cooled from  $25^\circ\text{C}$  to  $3^\circ\text{C}$ . The mass of each canned drink is 0.355 kg. The drinks can be treated as water, and the energy stored in the aluminum can itself is negligible. The amount of heat transfer from the 6 canned drinks is

- (a) 33 kJ (b) 37 kJ  
(c) 47 kJ (d) 196 kJ  
(e) 223 kJ

**4-169** A glass of water with a mass of 0.45 kg at  $20^\circ\text{C}$  is to be cooled to  $0^\circ\text{C}$  by dropping ice cubes at  $0^\circ\text{C}$  into it. The latent heat of fusion of ice is  $334 \text{ kJ/kg}$ , and the specific heat of water is  $4.18 \text{ kJ/kg} \cdot ^\circ\text{C}$ . The amount of ice that needs to be added is

- (a) 56 g (b) 113 g  
(c) 124 g (d) 224 g  
(e) 450 g

**4-170** A 2-kW electric resistance heater submerged in 5-kg water is turned on and kept on for 10 min. During the process, 300 kJ of heat is lost from the water. The temperature rise of water is

- (a)  $0.4^\circ\text{C}$  (b)  $43.1^\circ\text{C}$   
(c)  $57.4^\circ\text{C}$  (d)  $71.8^\circ\text{C}$   
(e)  $180.0^\circ\text{C}$

**4-171** 3 kg of liquid water initially at  $12^\circ\text{C}$  is to be heated at  $95^\circ\text{C}$  in a teapot equipped with a 1200-W electric heating element inside. The specific heat of water can be taken to be  $4.18 \text{ kJ/kg} \cdot ^\circ\text{C}$ , and the heat loss from the water during heating can be neglected. The time it takes to heat water to the desired temperature is

- (a) 4.8 min (b) 14.5 min  
(c) 6.7 min (d) 9.0 min  
(e) 18.6 min

**4-172** An ordinary egg with a mass of 0.1 kg and a specific heat of  $3.32 \text{ kJ/kg} \cdot ^\circ\text{C}$  is dropped into boiling water at  $95^\circ\text{C}$ . If the initial temperature of the egg is  $5^\circ\text{C}$ , the maximum amount of heat transfer to the egg is

- (a) 12 kJ (b) 30 kJ  
(c) 24 kJ (d) 18 kJ  
(e) infinity

**4-173** An apple with an average mass of 0.18 kg and average specific heat of  $3.65 \text{ kJ/kg} \cdot ^\circ\text{C}$  is cooled from  $22^\circ\text{C}$  to  $5^\circ\text{C}$ . The amount of heat transferred from the apple is

- (a) 0.85 kJ (b) 62.1 kJ  
(c) 17.7 kJ (d) 11.2 kJ  
(e) 7.1 kJ

**4-174** The specific heat at constant pressure for an ideal gas is given by  $c_p = 0.9 + (2.7 \times 10^{-4})T$  ( $\text{kJ/kg} \cdot \text{K}$ ) where  $T$  is in kelvin. The change in the enthalpy for this ideal gas undergoing a process in which the temperature changes from 27 to  $127^\circ\text{C}$  is most nearly

- (a) 90 kJ/kg            (b) 92.1 kJ/kg  
 (c) 99.5 kJ/kg        (d) 108.9 kJ/kg  
 (e) 105.2 kJ/kg

**4-175** The specific heat at constant volume for an ideal gas is given by  $c_v = 0.7 + (2.7 \times 10^{-4})T$  (kJ/kg · K) where  $T$  is in kelvin. The change in the internal energy for this ideal gas undergoing a process in which the temperature changes from 27 to 127°C is most nearly

- (a) 70 kJ/kg            (b) 72.1 kJ/kg  
 (c) 79.5 kJ/kg        (d) 82.1 kJ/kg  
 (e) 84.0 kJ/kg

**4-176** A piston–cylinder device contains an ideal gas. The gas undergoes two successive cooling processes by rejecting heat to the surroundings. First the gas is cooled at constant pressure until  $T_2 = \frac{3}{4}T_1$ . Then the piston is held stationary while the gas is further cooled to  $T_3 = \frac{1}{2}T_1$ , where all temperatures are in K.

- The ratio of the final volume to the initial volume of the gas is
 

(a) 0.25                    (b) 0.50  
 (c) 0.67                    (d) 0.75  
 (e) 1.0
- The work done on the gas by the piston is
 

(a)  $RT_1/4$             (b)  $c_v T_1/2$   
 (c)  $c_p T_1/2$             (d)  $(c_v + c_p)T_1/4$   
 (e)  $c_v(T_1 + T_2)/2$
- The total heat transferred from the gas is
 

(a)  $RT_1/4$             (b)  $c_v T_1/2$   
 (c)  $c_p T_1/2$             (d)  $(c_v + c_p)T_1/4$   
 (e)  $c_v(T_1 + T_3)/2$

**4-177** Saturated steam vapor is contained in a piston–cylinder device. While heat is added to the steam, the piston is held stationary, and the pressure and temperature become 1.2 MPa and 700°C, respectively. Additional heat is added to the steam until the temperature rises to 1200°C, and the piston moves to maintain a constant pressure.

- The initial pressure of the steam is most nearly
 

(a) 250 kPa                (b) 500 kPa  
 (c) 750 kPa                (d) 1000 kPa  
 (e) 1250 kPa
- The work done by the steam on the piston is most nearly
 

(a) 230 kJ/kg            (b) 1100 kJ/kg  
 (c) 2140 kJ/kg          (d) 2340 kJ/kg  
 (e) 840 kJ/kg
- The total heat transferred to the steam is most nearly
 

(a) 230 kJ/kg            (b) 1100 kJ/kg  
 (c) 2140 kJ/kg          (d) 2340 kJ/kg  
 (e) 840 kJ/kg

### Design, Essay, and Experiment Problems

**4-178** Compressed gases and phase-changing liquids are used to store energy in rigid containers. What are the advan-

tages and disadvantages of each substance as a means of storing energy?

**4-179** Someone has suggested that the device shown in Fig. P4-179 be used to move the maximum force  $F$  against the spring, which has a spring constant of  $k$ . This is accomplished by changing the temperature of the liquid–vapor mixture in the container. You are to design such a device to close sun-blocking window shutters that require a maximum force of 0.5 lbf. The piston must move 6 inches to close these shutters completely. You elect to use R-134a as the working fluid and arrange the liquid–vapor mixture container such that the temperature changes from 70°F when shaded from the sun to 100°F when exposed to the full sun. Select the sizes of the various components in this system to do this task. Also select the necessary spring constant and the amount of R-134a to be used.

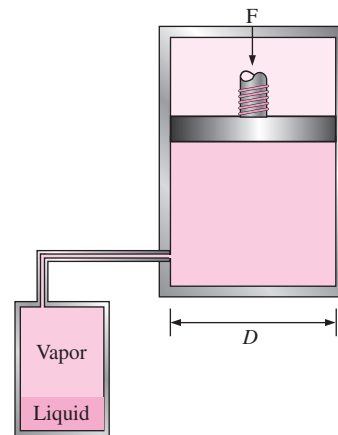


FIGURE P4-179

**4-180** Design an experiment complete with instrumentation to determine the specific heats of a liquid using a resistance heater. Discuss how the experiment will be conducted, what measurements need to be taken, and how the specific heats will be determined. What are the sources of error in your system? How can you minimize the experimental error? How would you modify this system to determine the specific heat of a solid?

**4-181** You are asked to design a heating system for a swimming pool that is 2 m deep, 25 m long, and 25 m wide. Your client desires that the heating system be large enough to raise the water temperature from 20 to 30°C in 3 h. The rate of heat loss from the water to the air at the outdoor design conditions is determined to be 960 W/m<sup>2</sup>, and the heater must also be able to maintain the pool at 30°C at those conditions. Heat losses to the ground are expected to be small and can be disregarded. The heater considered is a natural gas furnace

whose efficiency is 80 percent. What heater size (in kW input) would you recommend to your client?

**4–182** It is claimed that fruits and vegetables are cooled by 6°C for each percentage point of weight loss as moisture during vacuum cooling. Using calculations, demonstrate if this claim is reasonable.

**4–183** A 1982 U.S. Department of Energy article (FS #204) states that a leak of one drip of hot water per second can cost \$1.00 per month. Making reasonable assumptions about the drop size and the unit cost of energy, determine if this claim is reasonable.

**4–184** *Polytropic Expansion of Air Experiment* The expansion on compression of a gas can be described by the *polytropic relation*  $p\nu^n = c$ , where  $p$  is *pressure*,  $\nu$  is *specific volume*,  $c$  is a *constant* and the exponent  $n$  depends on the *thermodynamic process*. In our experiment compressed air in a steel pressure vessel is discharged to the atmosphere while temperature and pressure measurements of the air inside the vessel are recorded. These measurements, along with the first law of thermodynamics, are used to produce the polytropic exponent  $n$  for the process. Obtain the polytropic exponent  $n$  for the process using the video clip, the complete write-up, and the data provided on the DVD accompanying this book.

**4–185** *First Law of Thermodynamics—Lead Smashing Experiment* The *first law of thermodynamics* is verified with a lead smashing experiment. A small piece of lead, instrumented with a thermocouple, is smashed with two steel cylinders. The cylinders are suspended by nylon chords and swing as pendulums from opposite directions, simultaneously striking the lead. The loss in gravitational potential energy of the cylinders is equated to the rise in internal energy of the lead. Verify the first law of thermodynamics using the video clip, the complete write-up, and the data provided on the DVD accompanying this book.

**4–186** *First Law of Thermodynamics—Friction Bearing Experiment* The *first law of thermodynamics* is verified with a friction bearing experiment. A copper friction bearing is attached to one end of a wood shaft that is driven in rotation with a falling weight turning a pulley attached to the shaft. Friction causes the bearing to heat up. Data reduction analysis accounts for gravitational potential energy, elastic potential energy, translational and rotational kinetic energy, internal energy, and heat loss from the bearing. Verify the first law of thermodynamics using the video clip, the complete write-up, and the data provided on the DVD accompanying this book.

**4–187** *First Law of Thermodynamics—Copper Cold Working Experiment* The *first law of thermodynamics* is verified again, but this time with a copper hinge calorimeter that is “worked” by a swinging pendulum, which causes a rise in the

hinge temperature. The loss in potential energy of the pendulum is equated to the rise in internal energy of the hinge, plus the heat unavoidably transferred into the hinge clamps. Verify the first law of thermodynamics using the video clip, the complete write-up, and the data provided on the DVD accompanying this book.

**4–188** *First Law of Thermodynamics—Bicycle Braking Experiment* The *first law of thermodynamics* is verified yet again—this time with a bicycle. A bicycle front caliper brake is removed and replaced with a lever-mounted, *copper calorimeter friction pad*. The calorimeter friction pad rubs on the front tire, heats up, brings the bicycle to a stop, and verifies the first law of thermodynamics. Used in the data reduction analysis are *aerodynamics drag* and *rolling friction*, which are obtained using bicycle coast-down data read into a cassette audio recorder by the bicycle rider. Verify the first law of thermodynamics using the video clip, the complete write-up, and the data provided on the DVD accompanying this book.

**4–189** *Specific Heat of Aluminum—Electric Calorimeter Experiment* The *specific heat of aluminum* is obtained with an electric calorimeter. The design consists of two individual calorimeters—each an assembly of 13 aluminum plates with electric resistance heater wires laced in-between the plates. The exterior surfaces of both calorimeters and the surrounding insulation are identical. However, the interior plates are different—one calorimeter has *solid* interior plates and the other has *perforated* interior plates. By initially adjusting the electrical power into each calorimeter the temperature-versus-time curves for each calorimeter are matched. This curve match allows cancellation of the unknown heat loss from each calorimeter and cancellation of the unknown heater thermal capacity to deliver an accurate specific heat value. Obtain the specific heat of aluminum using the video clip, the complete write-up, and the data provided on the DVD accompanying this book.

**4–190** *Specific Heat of Aluminum—Transient Cooling Experiment* The *specific heat of aluminum* is obtained with an entirely different experiment than the one described in Prob. 4–189. In the present experiment a hollow, aluminum cylinder *calorimeter* is fitted with a plug forming a watertight cavity. The calorimeter is heated with a hair drier and then allowed to cool in still air. Two tests are performed: one with water in the cavity and one without water in the cavity. Transient temperature measurements from the two tests give different cooling rates characterized with *Trendlines* in EXCEL. These *Trendlines* are used to compute the aluminum specific heat. Obtain the specific heat of aluminum using the video clip, the complete write-up, and the data provided on the DVD accompanying this book.

