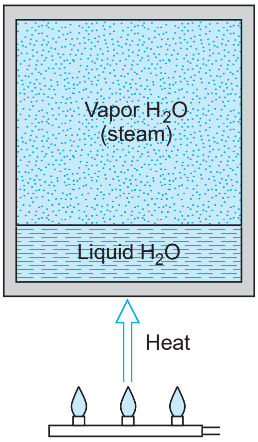

FIGURE 2.6 Heat transfer to H_2O.

Most complex molecules, such as typical polyatomic molecules, are usually three-dimensional in structure and have multiple vibrational modes, each of which contributes to the energy storage of the molecule. The more complicated the molecule is, the larger the number of degrees of freedom that exist for energy storage. The modes of energy storage and their evaluation are discussed in some detail in Appendix C for those interested in further development of the quantitative effects from a molecular viewpoint.

This general discussion can be summarized by referring to Fig. 2.6. Let heat be transferred to H_2O. During this process the temperature of the liquid and vapor (steam) will increase, and eventually all the liquid will become vapor. From the macroscopic point of view, we are concerned only with the energy that is transferred as heat, the change in properties such as temperature and pressure, and the total amount of energy (relative to some base) that the H_2O contains at any instant. Thus, questions about how energy is stored in the H_2O do not concern us. From a microscopic viewpoint, we are concerned about the way in which energy is stored in the molecules. We might be interested in developing a model of the molecule so that we can predict the amount of energy required to change the temperature a given amount. Although the focus in this book is on the macroscopic or classical viewpoint, it is helpful to keep in mind the microscopic or statistical perspective as well, as the relationship between the two helps us understand basic concepts such as energy.

In-Text Concept Questions

a. Make a control volume around the turbine in the steam power plant in Fig. 1.1 and list the flows of mass and energy located there.

b. Take a control volume around your kitchen refrigerator, indicate where the components shown in Fig. 1.6 are located, and show all energy transfers.

2.7 SPECIFIC VOLUME AND DENSITY

The specific volume of a substance is defined as the volume per unit mass and is given the symbol v. The density of a substance is defined as the mass per unit volume, and it is therefore the reciprocal of the specific volume. Density is designated by the symbol ρ. Specific volume and density are intensive properties.

The specific volume of a system in a gravitational field may vary from point to point. For example, if the atmosphere is considered a system, the specific volume increases as the elevation increases. Therefore, the definition of specific volume involves the specific volume of a substance at a point in a system.

Consider a small volume δV of a system, and let the mass be designated δm. The specific volume is defined by the relation

$$v = \lim_{\delta V \to \delta V'} \frac{\delta V}{\delta m}$$

where $\delta V'$ is the smallest volume for which the mass can be considered a continuum. Volumes smaller than this will lead to the recognition that mass is not evenly distributed in space but is concentrated in particles as molecules, atoms, electrons, etc. This is tentatively indicated in Fig. 2.7, where in the limit of a zero volume the specific volume may be infinite (the volume does not contain any mass) or very small (the volume is part of a nucleus).

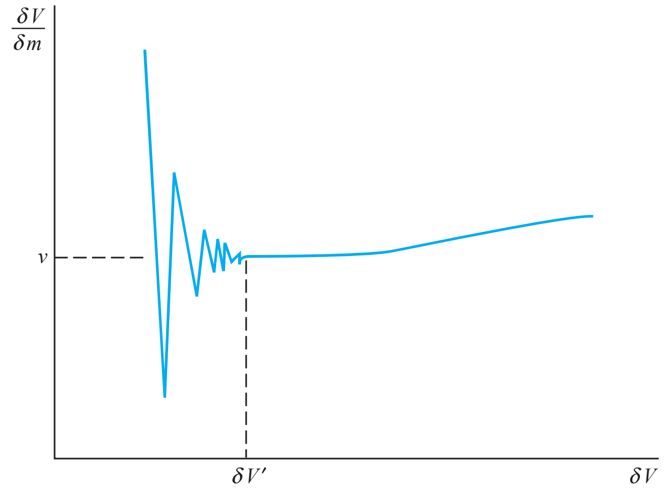

FIGURE 2.7 The continuum limit for the specific volume.

Thus, in a given system, we should speak of the specific volume or density at a point in the system and recognize that this may vary with elevation. However, most of the systems that we consider are relatively small, and the change in specific volume with elevation is not significant. Therefore, we can speak of one value of specific volume or density for the entire system.

In this book, the specific volume and density will be given either on a mass or a mole basis. A bar over the symbol (lowercase) will be used to designate the property on a mole basis. Thus, $\bar{v}$ will designate molal specific volume and $\bar{\rho}$ will designate molal density. In SI units, those for specific volume are m^3/kg and m^3/mol (or $m^3/kmol$); for density the corresponding units are kg/m^3 and mol/m^3 (or $kmol/m^3$). In English units, those for specific volume are ft^3/lbm and $ft^3/lb\ mol$; the corresponding units for density are lbm/ft^3 and $lb\ mol/ft^3$.

Although the SI unit for volume is the cubic meter, a commonly used volume unit is the liter (L), which is a special name given to a volume of 0.001 cubic meters, that is, $1\ L = 10^{-3}\ m^3$. The general ranges of density for some common solids, liquids, and gases are shown in Fig. 2.8. Specific values for various solids, liquids, and gases in SI units are listed in Tables A.3, A.4, and A.5, respectively, and in English units in Tables F.2, F.3, and F.4.

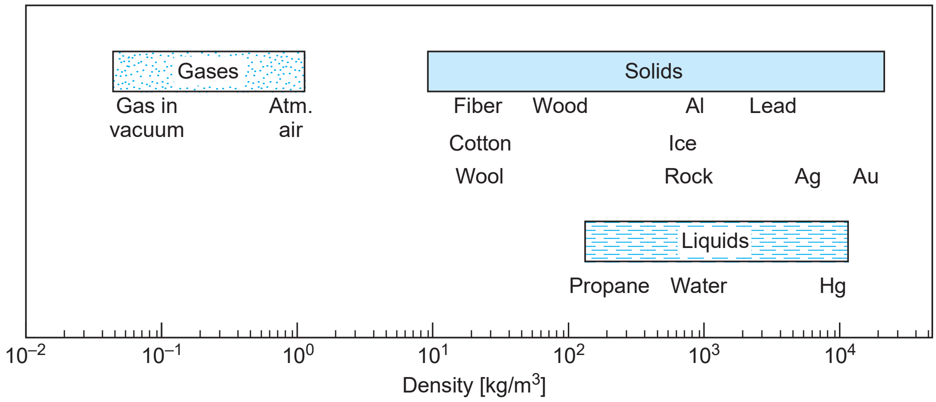

FIGURE 2.8 Density of common substances.

EXAMPLE 2.2 A 1 m^3 container, shown in Fig. 2.9, is filled with 0.12 m^3 of granite, 0.15 m^3 of sand, and 0.2 m^3 of liquid 25°C water; the rest of the volume, 0.53 m^3, is air with a density of 1.15 kg/m^3. Find the overall (average) specific volume and density.

Solution

From the definition of specific volume and density we have

$$v = V/m \quad \text{and} \quad \rho = m/V = 1/v$$

We need to find the total mass, taking density from Tables A.3 and A.4:

$$m_{\text{granite}} = \rho V_{\text{granite}} = 2750\ \text{kg/m}^3 \times 0.12\ \text{m}^3 = 330\ \text{kg}$$
$$m_{\text{sand}} = \rho_{\text{sand}}\ V_{\text{sand}} = 1500\ \text{kg/m}^3 \times 0.15\ \text{m}^3 = 225\ \text{kg}$$
$$m_{\text{water}} = \rho_{\text{water}}\ V_{\text{water}} = 997\ \text{kg/m}^3 \times 0.2\ \text{m}^3 = 199.4\ \text{kg}$$
$$m_{\text{air}} = \rho_{\text{air}}\ V_{\text{air}} = 1.15\ \text{kg/m}^3 \times 0.53\ \text{m}^3 = 0.61\ \text{kg}$$

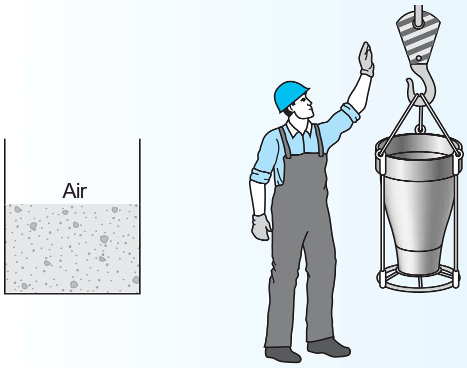

FIGURE 2.9 Sketch for Example 2.2.

Now the total mass becomes

$$m_{\text{tot}} = m_{\text{granite}} + m_{\text{sand}} + m_{\text{water}} + m_{\text{air}} = 755\ \text{kg}$$

and the specific volume and density can be calculated:

$$v = V_{\text{tot}}/m_{\text{tot}} = 1\ \text{m}^3/755\ \text{kg} = 0.001325\ \text{m}^3/\text{kg}$$
$$\rho = m_{\text{tot}}/V_{\text{tot}} = 755\ \text{kg}/1\ \text{m}^3 = 755\ \text{kg/m}^3$$

Remark: It is misleading to include air in the numbers for ρ and V, as the air is separate from the rest of the mass.

In-Text Concept Questions

c. Why do people float high in the water when swimming in the Dead Sea as compared with swimming in a freshwater lake?

d. The density of liquid water is $\rho = 1008 - T/2$ [kg/m^3] with T in °C. If the temperature increases, what happens to the density and specific volume?

2.8 PRESSURE

When dealing with liquids and gases, we ordinarily speak of pressure; for solids we speak of stresses. The pressure in a fluid at rest at a given point is the same in all directions, and we define pressure as the normal component of force per unit area. More specifically, if δA is a small area, $\delta A'$ is the smallest area over which we can consider the fluid a continuum, and δF_n is the component of force normal to δA, we define pressure, P, as

$$P = \lim_{\delta A \to \delta A'} \frac{\delta F_n}{\delta A}$$

where the lower limit corresponds to sizes as mentioned for the specific volume, shown in Fig. 2.7. The pressure P at a point in a fluid in equilibrium is the same in all directions. In a viscous fluid in motion, the variation in the state of stress with orientation becomes an important consideration. These considerations are beyond the scope of this book, and we will consider pressure only in terms of a fluid in equilibrium.

The unit for pressure in the International System is the force of one newton acting on a square meter area, which is called the pascal (Pa). That is,

$$1 \text{ Pa} = 1 \text{ N/m}^2$$

Two other units, not part of the International System, continue to be widely used. These are the bar, where

$$1 \text{ bar} = 10^5 \text{ Pa} = 0.1 \text{ MPa}$$

and the standard atmosphere, where

$$1 \text{ atm} = 101\,325 \text{ Pa} = 14.696 \text{ lbf/in.}^2$$

which is slightly larger than the bar. In this book, we will normally use the SI unit, the pascal, and especially the multiples of kilopascal and megapascal. The bar will be utilized often in the examples and problems, but the atmosphere will not be used, except in specifying certain reference points.

Consider a gas contained in a cylinder fitted with a movable piston, as shown in Fig. 2.10. The pressure exerted by the gas on all of its boundaries is the same, assuming that the gas is in an equilibrium state. This pressure is fixed by the external force acting on the piston, since there must be a balance of forces for the piston to remain stationary. Thus, the product of the pressure and the movable piston area must be equal to the external force. If the external force is now changed in either direction, the gas pressure inside must accordingly adjust, with appropriate movement of the piston, to establish a force balance at a new equilibrium state. As another example, if the gas in the cylinder is heated by an outside body, which tends to increase the gas pressure, the piston will move instead, such that the pressure remains equal to whatever value is required by the external force.

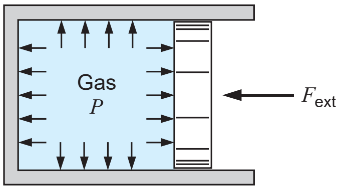

FIGURE 2.10 The balance of forces on a movable boundary relates to inside gas pressure.

EXAMPLE 2.3 The hydraulic piston/cylinder system shown in Fig. 2.11 has a cylinder diameter of $D =$ 0.1 m with a piston and rod mass of 25 kg. The rod has a diameter of 0.01 m with an outside atmospheric pressure of 101 kPa. The inside hydraulic fluid pressure is 250 kPa. How large a force can the rod push within the upward direction?

Solution

We will assume a static balance of forces on the piston (positive upward), so

$$F_{\text{net}} = ma = 0$$
$$= P_{\text{cyl}} A_{\text{cyl}} - P_0(A_{\text{cyl}} - A_{\text{rod}}) - F - m_p g$$

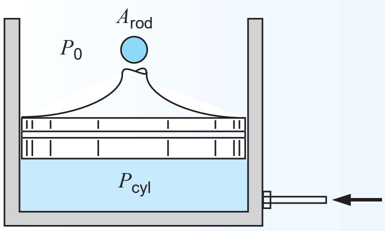

FIGURE 2.11 Sketch for Example 2.3.

Solve for F:

$$F = P_{\text{cyl}} A_{\text{cyl}} - P_0(A_{\text{cyl}} - A_{\text{rod}}) - m_p g$$

The areas are

$$A_{\text{cyl}} = \pi r^2 = \pi D^2/4 = \frac{\pi}{4} 0.1^2 \text{ m}^2 = 0.007\,854 \text{ m}^2$$

$$A_{\text{rod}} = \pi r^2 = \pi D^2/4 = \frac{\pi}{4} 0.01^2 \text{ m}^2 = 0.000\,078\,54 \text{ m}^2$$

So the force becomes

$$F = [250 \times 0.007\,854 - 101(0.007\,854 - 0.000\,078\,54)]1000 - 25 \times 9.81$$
$$= 1963.5 - 785.32 - 245.25$$
$$= 932.9 \text{ N}$$

Note that we must convert kPa to Pa to get units of N.

In most thermodynamic investigations we are concerned with absolute pressure. Most pressure and vacuum gauges, however, read the difference between the absolute pressure and the atmospheric pressure existing at the gauge. This is referred to as *gauge pressure*. It is shown graphically in Fig. 2.12, and the following examples illustrate the principles. Pressures below atmospheric and slightly above atmospheric, and pressure differences (for example, across an orifice in a pipe), are frequently measured with a manometer, which contains water, mercury, alcohol, oil, or other fluids.

Consider the column of fluid of height H standing above point B in the manometer shown in Fig. 2.13. The force acting downward at the bottom of the column is

$$P_0 A + mg = P_0 A + \rho A g H$$

where m is the mass of the fluid column, A is its cross-sectional area, and ρ is its density. This force must be balanced by the upward force at the bottom of the column, which is $P_B A$.

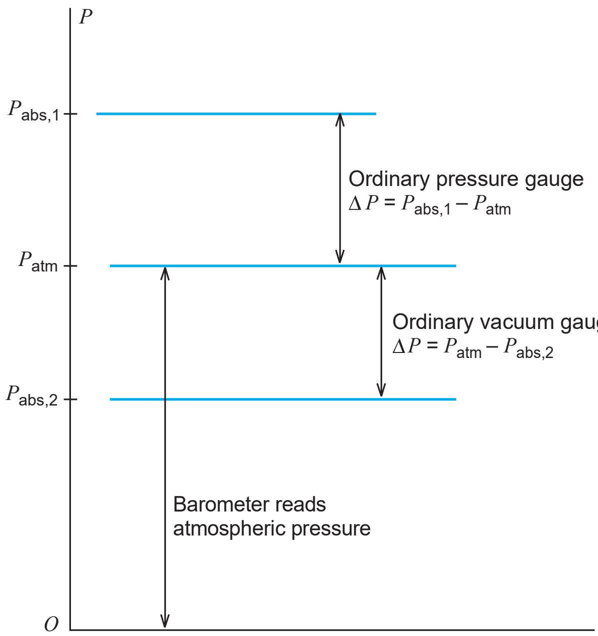

FIGURE 2.12 Illustration of terms used in pressure measurement.

Therefore,

$$P_B - P_0 = \rho g H$$

Since points A and B are at the same elevation in columns of the same fluid, their pressures must be equal (the fluid being measured in the vessel has a much lower density, such that its pressure P is equal to P_A). Overall,

$$\Delta P = P - P_0 = \rho g H \tag{2.2}$$

For distinguishing between absolute and gauge pressure in this book, the term *pascal* will always refer to absolute pressure. Any gauge pressure will be indicated as such.

Consider the barometer used to measure atmospheric pressure, as shown in Fig. 2.14. Since there is a near vacuum in the closed tube above the vertical column of fluid, usually mercury, the heigh of the fluid column gives the atmospheric pressure directly from Eq. 2.2:

$$P_{atm} = \rho g H_0 \tag{2.3}$$

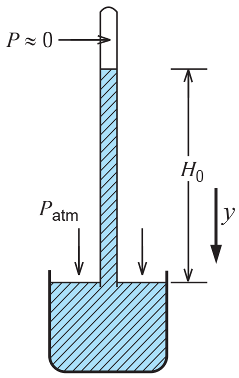

FIGURE 2.14 Barometer.

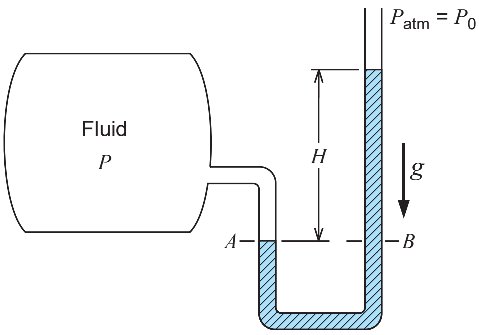

FIGURE 2.13 Example of pressure measurement using a column of fluid.

EXAMPLE 2.4 A mercury barometer located in a room at 25°C has a height of 750 mm. What is the atmospheric pressure in kPa?

Solution

The density of mercury at 25°C is found from Appendix Table A.4 to be 13 534 kg/m.[3] Using Eq. 2.3,

$$\begin{aligned} P_{\text{atm}} &= \rho g H_0 = 13\,534 \times 9.806\,65 \times 0.750/1000 \\ &= 99.54 \text{ kPa} \end{aligned}$$

EXAMPLE 2.5 A mercury (Hg) manometer is used to measure the pressure in a vessel as shown in Fig. 2.13. The mercury has a density of 13 590 kg/m^3, and the height difference between the two columns is measured to be 24 cm. We want to determine the pressure inside the vessel.

Solution

The manometer measures the gauge pressure as a pressure difference. From Eq. 2.2,

$$\begin{aligned} \Delta P = P_{\text{gauge}} &= \rho g H = 13\,590 \times 9.806\,65 \times 0.24 \\ &= 31\,985 \frac{\text{kg}}{\text{m}^3} \frac{\text{m}}{\text{s}^2} \text{m} = 31\,985 \text{ Pa} = 31.985 \text{ kPa} \\ &= 0.316 \text{ atm} \end{aligned}$$

To get the absolute pressure inside the vessel, we have

$$P_A = P_{\text{vessel}} = P_B = \Delta P + P_{\text{atm}}$$

We need to know the atmospheric pressure measured by a barometer (absolute pressure). Assume that this pressure is known to be 750 mm Hg. The absolute pressure in the vessel becomes

$$\begin{aligned} P_{\text{vessel}} &= \Delta P + P_{\text{atm}} = 31\,985 + 13\,590 \times 0.750 \times 9.806\,65 \\ &= 31\,985 + 99\,954 = 131\,940 \text{ Pa} = 1.302 \text{ atm} \end{aligned}$$

EXAMPLE 2.5E A mercury (Hg) manometer is used to measure the pressure in a vessel as shown in Fig. 2.13. The mercury has a density of 848 lbm/ft^3, and the height difference between the two columns is measured to be 9.5 in. We want to determine the pressure inside the vessel.

Solution

The manometer measures the gauge pressure as a pressure difference. From Eq. 2.2,

$$\begin{aligned} \Delta P = P_{\text{gauge}} &= \rho g H \\ &= 848 \frac{\text{lbm}}{\text{ft}^3} \times 32.174 \frac{\text{ft}}{\text{s}^2} \times 9.5 \text{ in.} \times \frac{1}{1728} \frac{\text{ft}^3}{\text{in.}^3} \times \left[\frac{1 \text{ lbf s}^2}{32.174 \text{ lbm ft}} \right] \\ &= 4.66 \text{ lbf/in.}^2 \end{aligned}$$

To get the absolute pressure inside the vessel, we have

$$P_A = P_{\text{vessel}} = P_0 = \Delta P + P_{\text{atm}}$$

We need to know the atmospheric pressure measured by a barometer (absolute pressure). Assume that this pressure is known to be 29.5 in. Hg. The absolute pressure in the vessel becomes

$$\begin{aligned} P_{\text{vessel}} &= \Delta P + P_{\text{atm}} \\ &= 848 \times 32.174 \times 29.5 \times \frac{1}{1728} \times \left(\frac{1}{32.174}\right) + 4.66 \\ &= 19.14 \text{ lbf/in.}^2 \end{aligned}$$

EXAMPLE 2.6

What is the pressure at the bottom of the 7.5-m-tall storage tank of fluid at 25°C shown in Fig. 2.15? Assume that the fluid is gasoline with atmospheric pressure 101 kPa on the top surface. Repeat the question for the liquid refrigerant R-134a when the top surface pressure is 1 MPa.

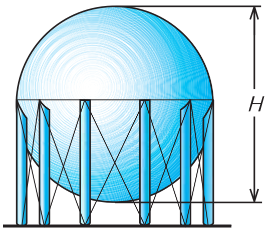

FIGURE 2.15 Sketch for Example 2.6.

Solution

The densities of the liquids are listed in Table A.4:

$$\rho_{\text{gasoline}} = 750 \text{ kg/m}^3; \quad \rho_{\text{R-134a}} = 1206 \text{ kg/m}^3$$

The pressure difference due to gravity is, from Eq. 2.2,

$$\Delta P = \rho g H$$

The total pressure is

$$P = P_{\text{top}} + \Delta P$$

For the gasoline we get

$$\Delta P = \rho g H = 750 \text{ kg/m}^3 \times 9.807 \text{ m/s}^2 \times 7.5 \text{ m} = 55\,164 \text{ Pa}$$

Now convert all pressures to kPa:

$$P = 101 + 55.164 = 156.2 \text{ kPa}$$

For the R-134a we get

$$\Delta P = \rho g H = 1206 \text{ kg/m}^3 \times 9.807 \text{ m/s}^2 \times 7.5 \text{ m} = 88\,704 \text{ Pa}$$

Now convert all pressures to kPa:

$$P = 1000 + 88.704 = 1089 \text{ kPa}$$

EXAMPLE 2.7

A piston/cylinder with a cross-sectional area of 0.01 m^2 is connected with a hydraulic line to another piston/cylinder with a cross-sectional area of 0.05 m^2. Assume that both chambers and the line are filled with hydraulic fluid of density 900 kg/m^3 and the larger second piston/cylinder is 6 m higher up in elevation. The telescope arm and the buckets have hydraulic piston/cylinders moving them, as seen in Fig. 2.16. With an outside atmospheric pressure of 100 kPa and a net force of 25 kN on the smallest piston, what is the balancing force on the second larger piston?

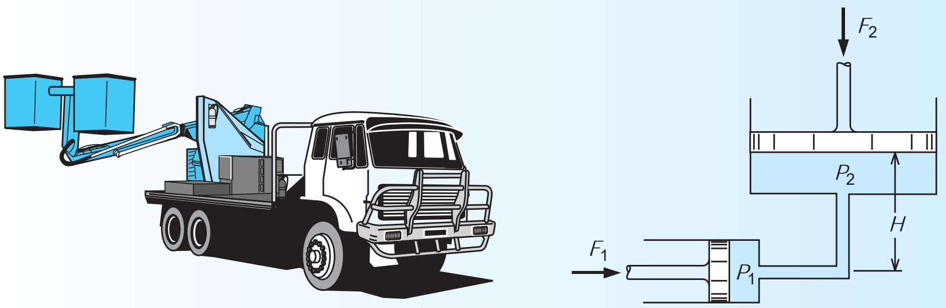

FIGURE 2.16 Sketch for Example 2.7.

Solution

When the fluid is stagnant and at the same elevation, we have the same pressure throughout the fluid. The force balance on the smaller piston is then related to the pressure (we neglect the rod area) as

$$F_1 + P_0 A_1 = P_1 A_1$$

from which the fluid pressure is

$$P_1 = P_0 + F_1/A_1 = 100\ \text{kPa} + 25\ \text{kN}/0.01\ \text{m}^2 = 2600\ \text{kPa}$$

The pressure at the higher elevation in piston/cylinder 2 is, from Eq. 2.2,

$$P_2 = P_1 - \rho g H = 2600\ \text{kPa} - 900\ \text{kg/m}^3 \times 9.81\ \text{m/s}^2 \times 6\ \text{m}/(1000\ \text{Pa/kPa})$$
$$= 2547\ \text{kPa}$$

where the second term is divided by 1000 to convert from Pa to kPa. Then the force balance on the second piston gives

$$F_2 + P_0 A_2 = P_2 A_2$$
$$F_2 = (P_2 - P_0) A_2 = (2547 - 100)\ \text{kPa} \times 0.05\ \text{m}^2 = 122.4\ \text{kN}$$

In-Text Concept Questions

e. A car tire gauge indicates 195 kPa; what is the air pressure inside?

f. Can I always neglect ΔP in the fluid above location A in Fig. 2.13? What circumstances does that depend on?

g. A U tube manometer has the left branch connected to a box with a pressure of 110 kPa and the right branch open. Which side has a higher column of fluid?

2.9 EQUALITY OF TEMPERATURE

Although temperature is a familiar property, defining it exactly is difficult. We are aware of temperature first of all as a sense of hotness or coldness when we touch an object. We also learn early that when a hot body and a cold body are brought into contact, the hot body becomes cooler and the cold body becomes warmer. If these bodies remain in contact for