

Also, there are about  $3 \times 10^{16}$  molecules of oxygen in the tiny volume of  $1 \text{ mm}^3$  at 1 atm pressure and  $20^\circ\text{C}$  (Fig. 2-3). The continuum model is applicable as long as the characteristic length of the system (such as its diameter) is much larger than the mean free path of the molecules. At very low pressure, e.g., at very high elevations, the mean free path may become large (for example, it is about 0.1 m for atmospheric air at an elevation of 100 km). For such cases the **rarefied gas flow theory** should be used, and the impact of individual molecules should be considered. In this text we limit our consideration to substances that can be modeled as a continuum. Quantitatively, a dimensionless number called the Knudsen number  $\text{Kn} = \lambda/L$  is defined, where  $\lambda$  is the mean free path of the fluid molecules and  $L$  is some characteristic length scale of the fluid flow. If  $\text{Kn}$  is very small (typically less than about 0.01), the fluid medium can be approximated as a continuum medium.

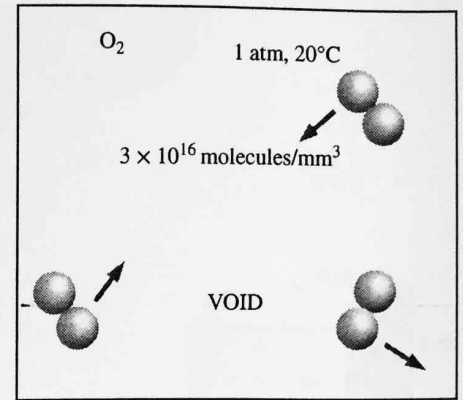


FIGURE 2-3

Despite the relatively large gaps between molecules, a gas can usually be treated as a continuum because of the very large number of molecules even in an extremely small volume.

## 2-2 ■ DENSITY AND SPECIFIC GRAVITY

**Density** is defined as *mass per unit volume* (Fig. 2-4). That is,

$$\text{Density:} \quad \rho = \frac{m}{V} \quad (\text{kg/m}^3) \quad (2-1)$$

The reciprocal of density is the **specific volume**  $\nu$ , which is defined as *volume per unit mass*. That is,  $\nu = V/m = 1/\rho$ . For a differential volume element of mass  $\delta m$  and volume  $\delta V$ , density can be expressed as  $\rho = \delta m/\delta V$ .

The density of a substance, in general, depends on temperature and pressure. The density of most gases is proportional to pressure and inversely proportional to temperature. Liquids and solids, on the other hand, are essentially incompressible substances, and the variation of their density with pressure is usually negligible. At  $20^\circ\text{C}$ , for example, the density of water changes from  $998 \text{ kg/m}^3$  at 1 atm to  $1003 \text{ kg/m}^3$  at 100 atm, a change of just 0.5 percent. The density of liquids and solids depends more strongly on temperature than it does on pressure. At 1 atm, for example, the density of water changes from  $998 \text{ kg/m}^3$  at  $20^\circ\text{C}$  to  $975 \text{ kg/m}^3$  at  $75^\circ\text{C}$ , a change of 2.3 percent, which can still be neglected in many engineering analyses.

Sometimes the density of a substance is given relative to the density of a well-known substance. Then it is called **specific gravity**, or **relative density**, and is defined as *the ratio of the density of a substance to the density of some standard substance at a specified temperature* (usually water at  $4^\circ\text{C}$ , for which  $\rho_{\text{H}_2\text{O}} = 1000 \text{ kg/m}^3$ ). That is,

$$\text{Specific gravity:} \quad \text{SG} = \frac{\rho}{\rho_{\text{H}_2\text{O}}} \quad (2-2)$$

Note that the specific gravity of a substance is a dimensionless quantity. However, in SI units, the numerical value of the specific gravity of a substance is exactly equal to its density in  $\text{g/cm}^3$  or  $\text{kg/L}$  (or 0.001 times the density in  $\text{kg/m}^3$ ) since the density of water at  $4^\circ\text{C}$  is  $1 \text{ g/cm}^3 = 1 \text{ kg/L} = 1000 \text{ kg/m}^3$ . The specific gravity of mercury at  $20^\circ\text{C}$ , for example, is 13.6. Therefore, its density at  $20^\circ\text{C}$  is  $13.6 \text{ g/cm}^3 = 13.6 \text{ kg/L} = 13,600 \text{ kg/m}^3$ . The specific gravities of some substances at  $20^\circ\text{C}$  are given in Table 2-1. Note that substances with specific gravities less than 1 are lighter than water, and thus they would float on water (if immiscible).

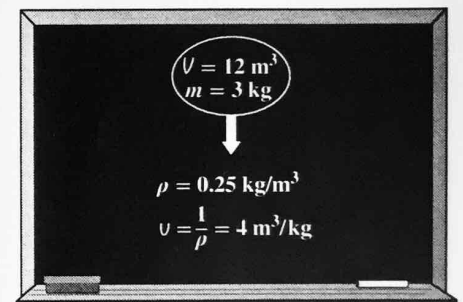


FIGURE 2-4

Density is mass per unit volume; specific volume is volume per unit mass.

TABLE 2-1

The specific gravity of some substances at  $20^\circ\text{C}$  and 1 atm unless stated otherwise

Substance	SG
Water	1.0
Blood (at $37^\circ\text{C}$ )	1.06
Seawater	1.025
Gasoline	0.68
Ethyl alcohol	0.790
Mercury	13.6
Balsa wood	0.17
Dense oak wood	0.93
Gold	19.3
Bones	1.7–2.0
Ice (at $0^\circ\text{C}$ )	0.916
Air	0.001204

The weight of a unit volume of a substance is called **specific weight** or **weight density** and is expressed as

$$\text{Specific weight: } \gamma_s = \rho g \quad (\text{N/m}^3) \quad (2-3)$$

where  $g$  is the gravitational acceleration.

Recall from Chap. 1 that the densities of liquids are essentially constant, and thus they can often be approximated as being incompressible substances during most processes without sacrificing much in accuracy.

## Density of Ideal Gases

Property tables provide very accurate and precise information about the properties, but sometimes it is convenient to have some simple relations among the properties that are sufficiently general and reasonably accurate. Any equation that relates the pressure, temperature, and density (or specific volume) of a substance is called an **equation of state**. The simplest and best-known equation of state for substances in the gas phase is the **ideal-gas equation of state**, expressed as

$$P\upsilon = RT \quad \text{or} \quad P = \rho RT \quad (2-4)$$

where  $P$  is the absolute pressure,  $\upsilon$  is the specific volume,  $T$  is the thermodynamic (absolute) temperature,  $\rho$  is the density, and  $R$  is the gas constant. The gas constant  $R$  is different for each gas and is determined from  $R = R_u/M$ , where  $R_u$  is the **universal gas constant** whose value is  $R_u = 8.314 \text{ kJ/kmol}\cdot\text{K} = 1.986 \text{ Btu/lbmol}\cdot\text{R}$ , and  $M$  is the *molar mass* (also called *molecular weight*) of the gas. The values of  $R$  and  $M$  for several substances are given in Table A-1.

The thermodynamic temperature scale in the SI is the **Kelvin scale**, and the temperature unit on this scale is the **kelvin**, designated by K. In the English system, it is the **Rankine scale**, and the temperature unit on this scale is the **rankine**, R. Various temperature scales are related to each other by

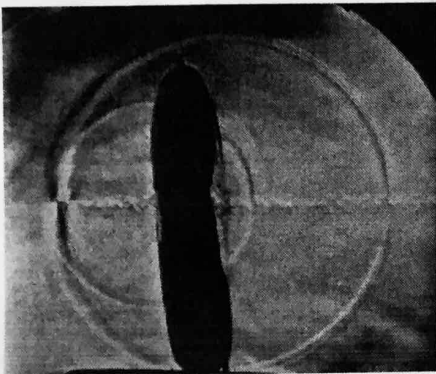
$$T(\text{K}) = T(^{\circ}\text{C}) + 273.15 = T(\text{R})/1.8 \quad (2-5)$$

$$T(\text{R}) = T(^{\circ}\text{F}) + 459.67 = 1.8 T(\text{K}) \quad (2-6)$$

It is common practice to round the constants 273.15 and 459.67 to 273 and 460, respectively, but we do not encourage this practice.

Equation 2-4, the ideal-gas equation of state, is also called simply the **ideal-gas relation**, and a gas that obeys this relation is called an **ideal gas**. For an ideal gas of volume  $\upsilon$ , mass  $m$ , and number of moles  $N = m/M$ , the ideal-gas equation of state can also be written as  $P\upsilon = mRT$  or  $P\upsilon = NR_u T$ . For a fixed mass  $m$ , writing the ideal-gas relation twice and simplifying, the properties of an ideal gas at two different states are related to each other by  $P_1\upsilon_1/T_1 = P_2\upsilon_2/T_2$ .

An ideal gas is a hypothetical substance that obeys the relation  $P\upsilon = RT$ . It has been experimentally observed that the ideal-gas relation closely approximates the  $P$ - $\upsilon$ - $T$  behavior of real gases at low densities. At low pressures and high temperatures, the density of a gas decreases and the gas behaves like an ideal gas (Fig. 2-5). In the range of practical interest, many familiar



**FIGURE 2-5**

Air behaves as an ideal gas, even at very high speeds. In this schlieren image, a bullet traveling at about the speed of sound bursts through both sides of a balloon, forming two expanding shock waves. The turbulent wake of the bullet is also visible.

© G.S. Settles, Gas Dynamics Lab, Penn State University. Used with permission.

gases such as air, nitrogen, oxygen, hydrogen, helium, argon, neon, and carbon dioxide and even heavier gases such as krypton can be treated as ideal gases with negligible error (often less than 1 percent). Dense gases such as water vapor in steam power plants and refrigerant vapor in refrigerators, air conditioners, and heat pumps, however, should not be treated as ideal gases since they usually exist at a state near saturation.

### EXAMPLE 2-1 Density, Specific Gravity, and Mass of Air in a Room

- Determine the density, specific gravity, and mass of the air in a room whose dimensions are 4 m × 5 m × 6 m at 100 kPa and 25°C (Fig. 2-6).

**SOLUTION** The density, specific gravity, and mass of the air in a room are to be determined.

**Assumptions** At specified conditions, air can be treated as an ideal gas.

**Properties** The gas constant of air is  $R = 0.287 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K}$ .

**Analysis** The density of the air is determined from the ideal-gas relation  $P = \rho RT$  to be

$$\rho = \frac{P}{RT} = \frac{100 \text{ kPa}}{(0.287 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(25 + 273.15) \text{ K}} = 1.17 \text{ kg/m}^3$$

Then the specific gravity of the air becomes

$$\text{SG} = \frac{\rho}{\rho_{\text{H}_2\text{O}}} = \frac{1.17 \text{ kg/m}^3}{1000 \text{ kg/m}^3} = 0.00117$$

Finally, the volume and the mass of the air in the room are

$$\begin{aligned} V &= (4 \text{ m})(5 \text{ m})(6 \text{ m}) = 120 \text{ m}^3 \\ m &= \rho V = (1.17 \text{ kg/m}^3)(120 \text{ m}^3) = 140 \text{ kg} \end{aligned}$$

**Discussion** Note that we converted the temperature to (absolute) unit K from (relative) unit °C before using it in the ideal-gas relation.

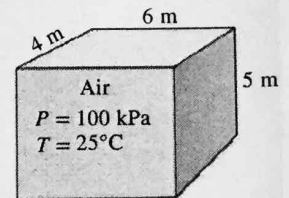


FIGURE 2-6 Schematic for Example 2-1.

## 2-3 ■ VAPOR PRESSURE AND CAVITATION

It is well-established that temperature and pressure are dependent properties for pure substances during phase-change processes, and there is one-to-one correspondence between temperature and pressure. At a given pressure, the temperature at which a pure substance changes phase is called the **saturation temperature**  $T_{\text{sat}}$ . Likewise, at a given temperature, the pressure at which a pure substance changes phase is called the **saturation pressure**  $P_{\text{sat}}$ . At an absolute pressure of 1 standard atmosphere (1 atm or 101.325 kPa), for example, the saturation temperature of water is 100°C. Conversely, at a temperature of 100°C, the saturation pressure of water is 1 atm.

The **vapor pressure**  $P_v$  of a pure substance is defined as *the pressure exerted by its vapor in phase equilibrium with its liquid at a given temperature* (Fig. 2-7).  $P_v$  is a property of the pure substance, and turns out to be identical to the saturation pressure  $P_{\text{sat}}$  of the liquid ( $P_v = P_{\text{sat}}$ ). We must be

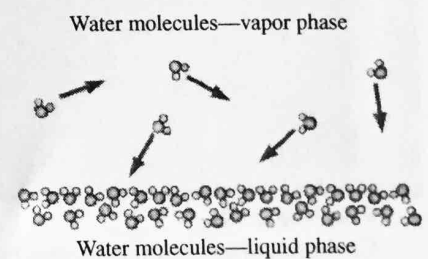


FIGURE 2-7

The vapor pressure (saturation pressure) of a pure substance (e.g., water) is the pressure exerted by its vapor molecules when the system is in phase equilibrium with its liquid molecules at a given temperature.



### EXAMPLE 2-2 Danger of Cavitation in a Propeller

- The analysis of a propeller that operates in water at 20°C shows that the pressure at the tips of the propeller drops to 2 kPa at high speeds. Determine if there is a danger of cavitation for this propeller.

**SOLUTION** The minimum pressure in a propeller is given. It is to be determined if there is a danger of cavitation.

**Properties** The vapor pressure of water at 20°C is 2.34 kPa (Table 2-2).

**Analysis** To avoid cavitation, the pressure everywhere in the flow should remain above the vapor (or saturation) pressure at the given temperature, which is

$$P_v = P_{\text{sat}@20^\circ\text{C}} = 2.34 \text{ kPa}$$

The pressure at the tip of the propeller is 2 kPa, which is less than the vapor pressure. Therefore, **there is a danger of cavitation for this propeller.**

**Discussion** Note that the vapor pressure increases with increasing temperature, and thus there is a greater danger of cavitation at higher fluid temperatures.

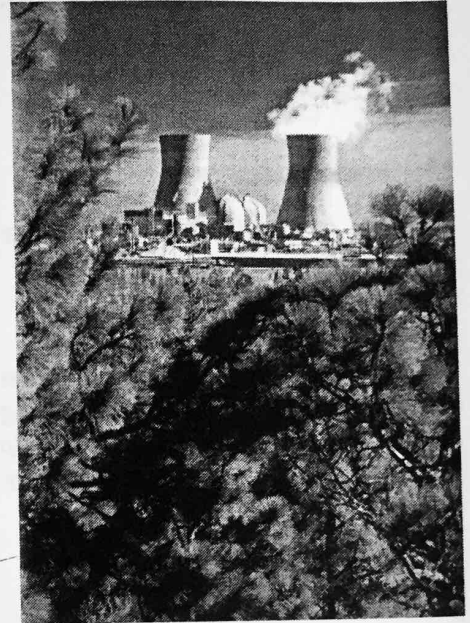
## 2-4 ■ ENERGY AND SPECIFIC HEATS

Energy can exist in numerous forms such as thermal, mechanical, kinetic, potential, electrical, magnetic, chemical, and nuclear (Fig. 2-9) and their sum constitutes the **total energy**  $E$  (or  $e$  on a unit mass basis) of a system. The forms of energy related to the molecular structure of a system and the degree of the molecular activity are referred to as the *microscopic energy*. The sum of all microscopic forms of energy is called the **internal energy** of a system, and is denoted by  $U$  (or  $u$  on a unit mass basis).

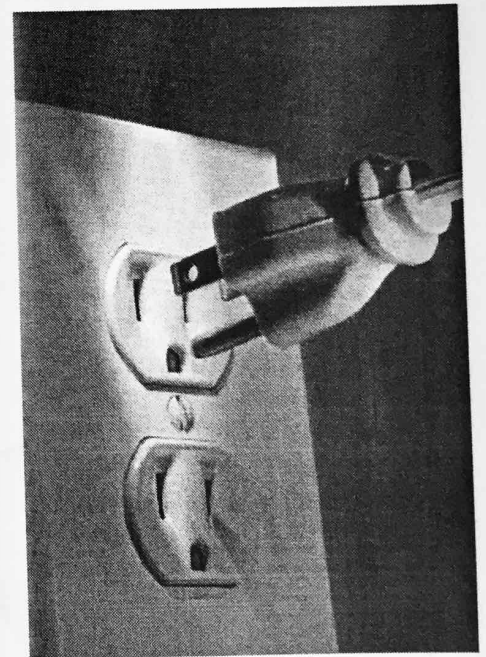
The *macroscopic* energy of a system is related to motion and the influence of some external effects such as gravity, magnetism, electricity, and surface tension. The energy that a system possesses as a result of its motion is called **kinetic energy**. When all parts of a system move with the same velocity, the kinetic energy per unit mass is expressed as  $ke = V^2/2$  where  $V$  denotes the velocity of the system relative to some fixed reference frame. The energy that a system possesses as a result of its elevation in a gravitational field is called **potential energy** and is expressed on a per-unit mass basis as  $pe = gz$  where  $g$  is the gravitational acceleration and  $z$  is the elevation of the center of gravity of the system relative to some arbitrarily selected reference plane.

In daily life, we frequently refer to the sensible and latent forms of internal energy as **heat**, and we talk about the heat content of bodies. In engineering, however, those forms of energy are usually referred to as **thermal energy** to prevent any confusion with *heat transfer*.

The international unit of energy is the *joule* (J) or *kilojoule* (1 kJ = 1000 J). A joule is 1 N times 1 m. In the English system, the unit of energy is the *British thermal unit* (Btu), which is defined as the energy needed to raise the temperature of 1 lbm of water at 68°F by 1°F. The magnitudes of kJ and Btu are almost identical (1 Btu = 1.0551 kJ). Another well-known unit of energy is the *calorie* (1 cal = 4.1868 J), which is defined as the energy needed to raise the temperature of 1 g of water at 14.5°C by 1°C.



(a)



(b)

**FIGURE 2-9**

At least six different forms of energy are encountered in bringing power from a nuclear plant to your home, nuclear, thermal, mechanical, kinetic, magnetic, and electrical.

(a) © Creatas/PunchStock RF

(b) Comstock Images/Jupiterimages RF