some time, they usually appear to have the same hotness or coldness. However, we also realize that our sense of hotness or coldness is very unreliable. Sometimes very cold bodies may seem hot, and bodies of different materials that are at the same temperature appear to be at different temperatures.

Because of these difficulties in defining temperature, we define equality of temperature. Consider two blocks of copper, one hot and the other cold, each of which is in contact with a mercury-in-glass thermometer. If these two blocks of copper are brought into thermal communication, we observe that the electrical resistance of the hot block decreases with time and that of the cold block increases with time. After a period of time has elapsed, however, no further changes in resistance are observed. Similarly, when the blocks are first brought in thermal communication, the length of a side of the hot block decreases with time but the length of a side of the cold block increases with time. After a period of time, no further change in length of either block is perceived. In addition, the mercury column of the thermometer in the hot block drops at first and that in the cold block rises, but after a period of time no further changes in height are observed. We may say, therefore, that two bodies have equality of temperature if, when they are in thermal communication, no change in any observable property occurs.

2.10 THE ZEROTH LAW OF THERMODYNAMICS

Now consider the same two blocks of copper and another thermometer. Let one block of copper be brought into contact with the thermometer until equality of temperature is established, and then remove it. Then let the second block of copper be brought into contact with the thermometer. Suppose that no change in the mercury level of the thermometer occurs during this operation with the second block. We then can say that both blocks are in thermal equilibrium with the given thermometer.

The zeroth law of thermodynamics states that when two bodies have equality of temperature with a third body, they in turn have equality of temperature with each other. This seems obvious to us because we are so familiar with this experiment. Because the principle is not derivable from other laws, and because it precedes the first and second laws of thermodynamics in the logical presentation of thermodynamics, it is called the zeroth law of thermodynamics. This law is really the basis of temperature measurement. Every time a body has equality of temperature with the thermometer, we can say that the body has the temperature we read on the thermometer. The problem remains of how to relate temperatures that we might read on different mercury thermometers or obtain from different temperature-measuring devices, such as thermocouples and resistance thermometers. This observation suggests the need for a standard scale for temperature measurements.

2.11 TEMPERATURE SCALES

Two scales are commonly used for measuring temperature, namely, the Fahrenheit (after Gabriel Fahrenheit, 1686–1736) and the Celsius. The Celsius scale was formerly called the centigrade scale but is now designated the Celsius scale after Anders Celsius (1701–1744), the Swedish astronomer who devised this scale.

The Fahrenheit temperature scale is used with the English Engineering system of units and the Celsius scale with the SI unit system. Until 1954 both of these scales were based on two fixed, easily duplicated points: the ice point and the steam point. The temperature of the ice point is defined as the temperature of a mixture of ice and water that is in equilibrium with saturated air at a pressure of 1 atm. The temperature of the steam point is the temperature of water and steam, which are in equilibrium at a pressure of 1 atm. On the Fahrenheit scale these two points are assigned the numbers 32 and 212, respectively, and on the Celsius scale the points are 0 and 100, respectively. Why Fahrenheit chose these numbers is an interesting story. In searching for an easily reproducible point, Fahrenheit selected the temperature of the human body and assigned it the number 96. He assigned the number 0 to the temperature of a certain mixture of salt, ice, and salt solution. On this scale the ice point was approximately 32. When this scale was slightly revised and fixed in terms of the ice point and steam point, the normal temperature of the human body was found to be 98.6 F.

In this book the symbols F and °C will denote the Fahrenheit and Celsius scales, respectively (the Celsius scale symbol includes the degree symbol since the letter C alone denotes Coulomb, the unit of electrical charge in the SI system of units). The symbol T will refer to temperature on all temperature scales.

At the tenth CGPM in 1954, the Celsius scale was redefined in terms of a single fixed point and the ideal-gas temperature scale. The single fixed point is the triple point of water (the state in which the solid, liquid, and vapor phases of water exist together in equilibrium). The magnitude of the degree is defined in terms of the ideal-gas temperature scale, which is discussed in Chapter 7. The essential features of this new scale are a single fixed point and a definition of the magnitude of the degree. The triple point of water is assigned the value of 0.01°C. On this scale the steam point is experimentally found to be 100.00°C. Thus, there is essential agreement between the old and new temperature scales.

We have not yet considered an absolute scale of temperature. The possibility of such a scale comes from the second law of thermodynamics and is discussed in Chapter 7. On the basis of the second law of thermodynamics, a temperature scale that is independent of any thermometric substance can be defined. This absolute scale is usually referred to as the *thermodynamic scale of temperature.* However, it is difficult to use this scale directly; therefore, a more practical scale, the International Temperature Scale, which closely represents the thermodynamic scale, has been adopted.

The absolute scale related to the Celsius scale is the Kelvin scale (after William Thomson, 1824–1907, who is also known as Lord Kelvin), and is designated K (without the degree symbol). The relation between these scales is

$$\mathrm{K} = {}^\circ\mathrm{C} + 273.15 \tag{2.4}$$

In 1967, the CGPM defined the kelvin as 1/273.16 of the temperature at the triple point of water. The Celsius scale is now defined by this equation instead of by its earlier definition.

The absolute scale related to the Fahrenheit scale is the Rankine scale and is designated R. The relation between these scales is

$$\mathrm{R} = \mathrm{F} + 459.67 \tag{2.5}$$

A number of empirically based temperature scales, to standardize temperature measurement and calibration, have been in use during the last 70 years. The most recent of these is the International Temperature Scale of 1990, or ITS-90. It is based on a number of fixed and easily reproducible points that are assigned definite numerical values of temperature, and on specified formulas relating temperature to the readings on certain temperature-measuring instruments for the purpose of interpolation between the defining fixed points. Details of the

ITS-90 are not considered further in this book. This scale is a practical means for establishing measurements that conform closely to the absolute thermodynamic temperature scale.

2.12 ENGINEERING APPLICATIONS

Pressure is used in applications for process control or limit control for safety reasons. In most cases, this is the gauge pressure. For instance a storage tank has a pressure indicator to show how close it is to being full, but it may also have a pressure-sensitive safety valve that will open and let material escape if the pressure exceeds a preset value. An air tank with a compressor on top is shown in Fig. 2.17; as a portable unit, it is used to drive air tools, such as nailers. A pressure gauge will activate a switch to start the compressor when the pressure drops below a preset value, and it will disengage the compressor when a preset high value is reached.

Tire pressure gauges, shown in Fig. 2.18, are connected to the valve stem on the tire. Some gauges have a digital readout. The tire pressure is important for the safety and durability of automobile tires. Too low a pressure causes large deflections and the tire may overheat; too high a pressure leads to excessive wear in the center.

A spring-loaded pressure relief valve is shown in Fig. 2.19. With the cap the spring can be compressed to make the valve open at a higher pressure, or the opposite. This valve is used for pneumatic systems.

When a throttle plate in an intake system for an automotive engine restricts the flow (Fig. 2.20), it creates a vacuum behind it that is measured by a pressure gauge sending a signal to the computer control. The smallest absolute pressure (highest vacuum) occurs when the engine idles and the highest pressure (smallest vacuum) occurs when the engine is at full throttle. In Fig. 2.20, the throttle is shown completely closed.

A pressure difference, ΔP, can be used to measure flow velocity indirectly, as shown schematically in Fig. 2.21 (this effect is felt when you hold your hand out of a car window, with a higher pressure on the side facing forward and a lower pressure on the other side,

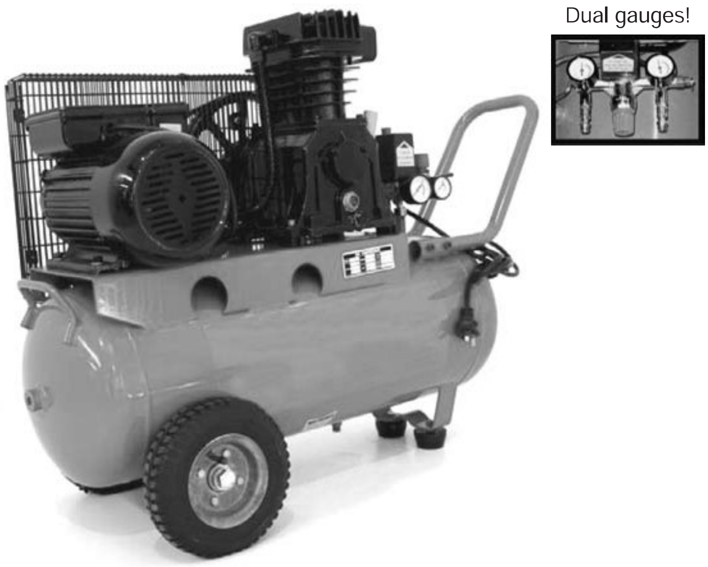

FIGURE 2.17 Air compressor with tank.

FIGURE 2.18
Automotive tire pressure gauges.

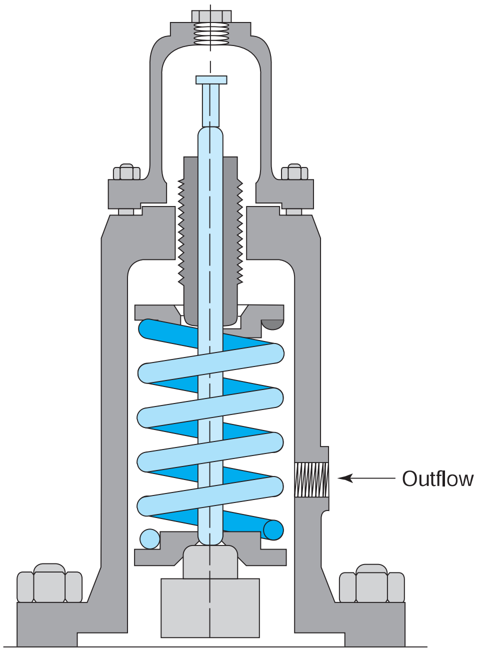

FIGURE 2.19
Schematic of a pressure relief valve.

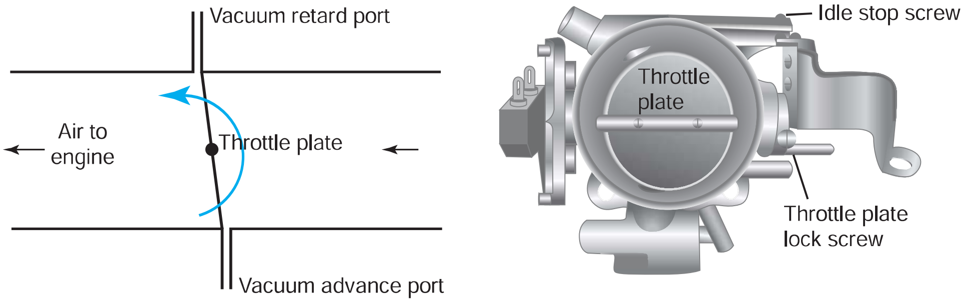

FIGURE 2.20
Automotive engine intake throttle.

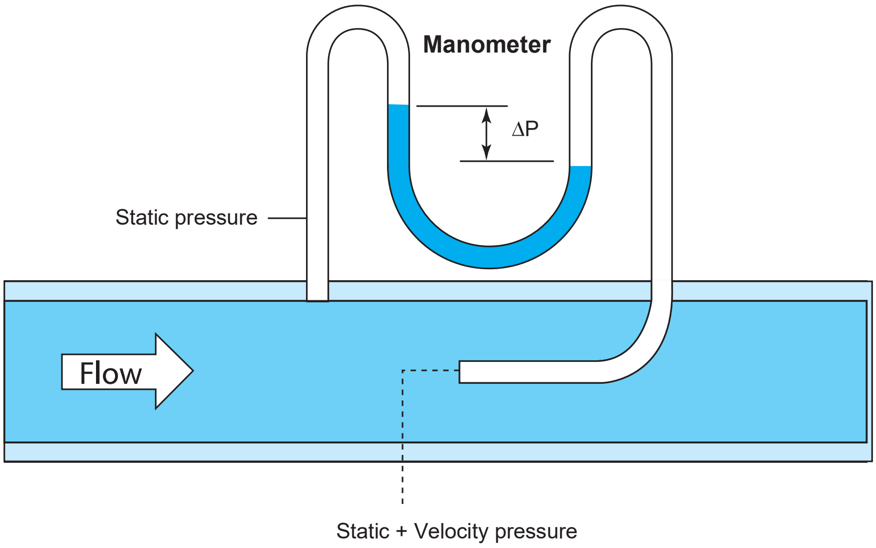

FIGURE 2.21 Schematic of flow velocity measurement.

giving a net force on your hand). The engineering analysis of such processes is developed and presented in Chapter 9. In a speedboat, a small pipe has its end pointing forward, feeling the higher pressure due to the relative velocity between the boat and the water. The other end goes to a speedometer transmitting the pressure signal to an indicator.

An aneroid barometer, shown in Fig. 2.22, measures the absolute pressure used for weather predictions. It consists of a thin metal capsule or bellows that expands or contracts with atmospheric pressure. Measurement is by a mechanical pointer or by a change in electrical capacitance with distance between two plates.

Numerous types of devices are used to measure temperature. Perhaps the most familiar of these is the liquid-in-glass thermometer, in which the liquid is commonly mercury. Since the density of the liquid decreases with temperature, the height of the liquid column rises accordingly. Other liquids are also used in such thermometers, depending on the range of temperature to be measured.

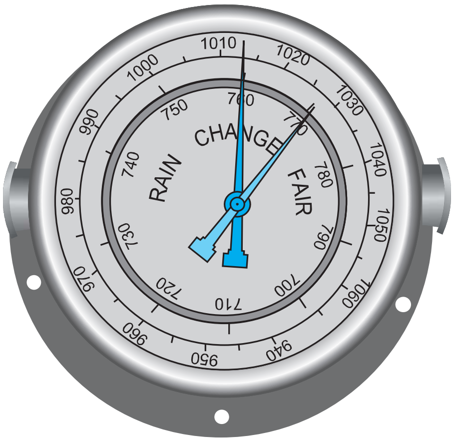

FIGURE 2.22 Aneroid barometer.

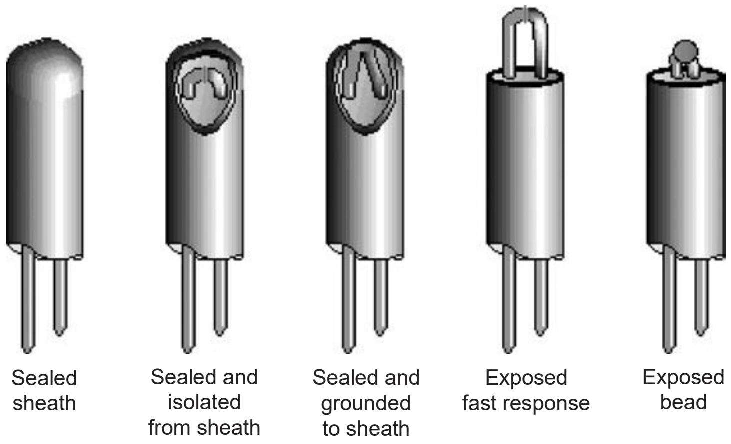

FIGURE 2.23
Thermocouples.

Two types of devices commonly used in temperature measurement are thermocouples and thermistors, examples of which are shown in Figs. 2.23 and 2.24, respectively. A thermocouple consists of a pair of junctions of two dissimilar metals that creates an electrical potential (voltage) that increases with the temperature difference between the junctions. One junction is maintained at a known reference temperature (for example, in an ice bath), such that the voltage measured indicates the temperature of the other junction. Different material combinations are used for different temperature ranges, and the size of the junction is kept small to have a short response time. Thermistors change their electrical resistance with temperature, so if a known current is passed through the thermistor, the voltage across it becomes proportional to the resistance. The output signal is improved if this is arranged in an electrical bridge that provides input to an instrument. The small signal from these sensors is amplified and scaled so that a meter can show the temperature or the signal can

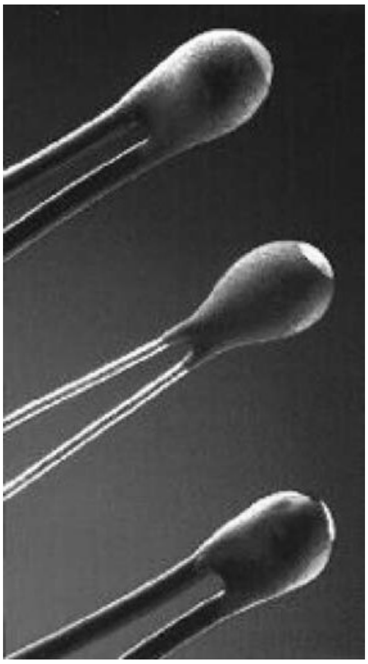

FIGURE 2.24
Thermistors.

be sent to a computer or a control system. High-precision temperature measurements are made in a similar manner using a platinum resistance thermometer. A large portion of the ITS-90 (13.8033 K to 1234.93 K) is measured in such a manner. Higher temperatures are determined from visible-spectrum radiation intensity observations.

It is also possible to measure temperature indirectly by certain pressure measurements. If the vapor pressure, discussed in Chapter 3, is accurately known as a function of temperature, then this value can be used to indicate the temperature. Also, under certain conditions, a constant-volume gas thermometer, discussed in Chapter 7, can be used to determine temperature by a series of pressure measurements.

SUMMARY

We introduce a thermodynamic system as a control volume, which for a fixed mass is a control mass. Such a system can be isolated, exchanging neither mass, momentum, nor energy with its surroundings. A closed system versus an open system refers to the ability of mass exchange with the surroundings. If properties for a substance change, the state changes and a process occurs. When a substance has gone through several processes, returning to the same initial state, it has completed a cycle.

Basic units for thermodynamic and physical properties are mentioned, and most are covered in Table A.1. Thermodynamic properties such as density ρ, specific volume v, pressure P, and temperature T are introduced together with units for these properties. Properties are classified as intensive, independent of mass (like v), or extensive, proportional to mass (like V). Students should already be familiar with other concepts from physics such as force F, velocity $\mathbf{V}$, and acceleration a. Application of Newton's law of motion leads to the variation of static pressure in a column of fluid and the measurements of pressure (absolute and gauge) by barometers and manometers. The normal temperature scale and the absolute temperature scale are introduced.

You should have learned a number of skills and acquired abilities from studying this chapter that will allow you to

- Define (choose) a control volume (C.V.) around some matter; sketch the content and identify storage locations for mass; and identify mass and energy flows crossing the C.V. surface.
- Know properties P, T, v, and ρ and their units.
- Know how to look up conversion of units in Table A.1.
- Know that energy is stored as kinetic, potential, or internal (in molecules).
- Know that energy can be transferred.
- Know the difference between (v, ρ) and (V, m) intensive and extensive.
- Apply a force balance to a given system and relate it to pressure P.
- Know the difference between relative (gauge) and absolute pressure P.
- Understand the working of a manometer or a barometer and derive ΔP or P from height H.
- Know the difference between a relative and an absolute temperature T.
- Be familiar with magnitudes (v, ρ, P, T).

Most of these concepts will be repeated and reinforced in the following chapters, such as properties in Chapter 3, energy transfer as heat and work in Chapter 4, and internal energy in Chapter 5, together with their applications.

KEY CONCEPTS AND FORMULAS

Control volume	everything inside a control surface
Pressure definition	$P = \frac{F}{A}$ (mathematical limit for small A)
Specific volume	$v = \frac{V}{m}$
Density	$\rho = \frac{m}{V}$ (Tables A.3, A.4, A.5, F.2, F.3, and F.4)
Static pressure variation	$\Delta P = \rho g H$ (depth H in fluid of density ρ)
Absolute temperature	$T[\mathrm{K}] = T[^\circ\mathrm{C}] + 273.15$ $T[\mathrm{R}] = T[\mathrm{F}] + 459.67$
Units	Table A.1
Concepts from Physics	
Newton's law of motion	$F = ma$
Acceleration	$a = \frac{d^2x}{dt^2} = \frac{d\mathbf{V}}{dt}$
Velocity	$\mathbf{V} = \frac{dx}{dt}$

CONCEPT-STUDY GUIDE PROBLEMS

2.1 Make a control volume around the whole power plant in Fig. 1.2 and, with the help of Fig. 1.1, list the flows of mass and energy in or out and any storage of energy. Make sure you know what is inside and what is outside your chosen control volume.

2.2 Make a control volume around the rocket engine in Fig. 1.12. Identify the mass flows and show where you have significant kinetic energy and where storage changes.

2.3 Make a control volume that includes the steam flow in the main turbine loop in the nuclear propulsion system in Fig. 1.3. Identify mass flows (hot or cold) and energy transfers that enter or leave the control volume.

2.4 Separate the list P, F, V, v, ρ, T, a, m, L, t, and $\mathbf{V}$ into intensive properties, extensive properties, and non-properties.

2.5 An electric dip heater is put into a cup of water and heats it from 20°C to 80°C. Show the energy flow(s) and storage and explain what changes.

2.6 Water in nature exists in three different phases: solid, liquid, and vapor (gas). Indicate the relative magnitude of density and the specific volume for the three phases.

2.7 Is density a unique measure of mass distribution in a volume? Does it vary? If so, on what kind of scale (distance)?

2.8 The overall density of fibers, rock wool insulation, foams, and cotton is fairly low. Why?

2.9 What is the approximate mass of 1 L of engine oil? Atmospheric air?

2.10 Can you carry 1 m^3 of liquid water?

2.11 A heavy cabinet has four adjustable feet. What feature of the feet will ensure that they do not make dents in the floor?

2.12 The pressure at the bottom of a swimming pool is evenly distributed. Consider a stiff steel plate lying on the ground. Is the pressure below it just as evenly distributed?

2.13 Two divers swim at a depth of 20 m. One of them swims directly under a supertanker; the other avoids the tanker. Who feels greater pressure?

2.14 A manometer with water shows a ΔP of $P_0/10$; what is the column height difference?