CHAPTER 1

Getting Started

Introductory Concepts and Definitions


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Medical professionals rely on measurements of *pressure* and *temperature*, introduced in Secs. 1.6 and 1.7.

Engineering Context

Although aspects of thermodynamics have been studied since ancient times, the formal study of thermodynamics began in the early nineteenth century through consideration of the capacity of hot objects to produce work. Today the scope is much larger. Thermodynamics now provides essential concepts and methods for addressing critical twenty-first-century issues, such as using fossil fuels more effectively, fostering renewable energy technologies, and developing more fuel-efficient means of transportation. Also critical are the related issues of greenhouse gas emissions and air and water pollution.

Thermodynamics is both a branch of science and an engineering specialty. The scientist is normally interested in gaining a fundamental understanding of the physical and chemical behavior of fixed quantities of matter at rest and uses the principles of thermodynamics to relate the properties of matter. Engineers are generally interested in studying *systems* and how they interact with their *surroundings*. To facilitate this, thermodynamics has been extended to the study of systems through which matter flows, including bioengineering and biomedical systems.

The **objective** of this chapter is to introduce you to some of the fundamental concepts and definitions that are used in our study of engineering thermodynamics. In most instances this introduction is brief, and further elaboration is provided in subsequent chapters.

LEARNING OUTCOMES

When you complete your study of this chapter, you will be able to...

- Explain several fundamental concepts used throughout the book, including closed system, control volume, boundary and surroundings, property, state, process, the distinction between extensive and intensive properties, and equilibrium.
- Identify SI and English Engineering units, including units for specific volume, pressure, and temperature.
- Describe the relationship among the Kelvin, Rankine, Celsius, and Fahrenheit temperature scales.
- Apply appropriate unit conversion factors during calculations.
- Apply the problem-solving methodology used in this book.

1.1 Using Thermodynamics

Engineers use principles drawn from thermodynamics and other engineering sciences, including fluid mechanics and heat and mass transfer, to analyze and design devices intended to meet human needs. Throughout the twentieth century, engineering applications of thermodynamics helped pave the way for significant improvements in our quality of life with advances in major areas such as surface transportation, air travel, space flight, electricity generation and transmission, building heating and cooling, and improved medical practices. The wide realm of these applications is suggested by **Table 1.1**.

In the twenty-first century, engineers will create the technology needed to achieve a sustainable future. Thermodynamics will continue to advance human well-being by addressing looming societal challenges owing to declining supplies of energy resources: oil, natural gas, coal, and fissionable material; effects of global climate change; and burgeoning population. Life in the United States is expected to change in several important respects by mid-century. In the area of power use, for example, electricity will play an even greater role than today. **Table 1.2** provides predictions of other changes experts say will be observed.

If this vision of mid-century life is correct, it will be necessary to evolve quickly from our present energy posture. As was the case in the twentieth century, thermodynamics will contribute significantly to meeting the challenges of the twenty-first century, including using fossil fuels more effectively, advancing renewable energy technologies, and developing more energy-efficient transportation systems, buildings, and industrial practices. Thermodynamics also will play a role in mitigating global climate change, air pollution, and water pollution. Applications will be observed in bioengineering, biomedical systems, and the deployment of nanotechnology. This book provides the tools needed by specialists working in all such fields. For nonspecialists, the book provides background for making decisions about technology related to thermodynamics—on the job, as informed citizens, and as government leaders and policy makers.

1.2 Defining Systems

The key initial step in any engineering analysis is to describe precisely what is being studied. In mechanics, if the motion of a body is to be determined, normally the first step is to define a *free body* and identify all the forces exerted on it by other bodies. Newton's second law of motion is then applied. In thermodynamics the term *system* is used to identify the subject of the analysis. Once the system is defined and the relevant interactions with other systems are identified, one or more physical laws or relations are applied.

system

The **system** is whatever we want to study. It may be as simple as a free body or as complex as an entire chemical refinery. We may want to study a quantity of matter contained within a closed, rigid-walled tank, or we may want to consider something such as a pipeline through which natural gas flows. The composition of the matter inside the system may be fixed or may be changing through chemical or nuclear reactions. The shape or volume of the system being analyzed is not necessarily constant, as when a gas in a cylinder is compressed by a piston or a balloon is inflated.

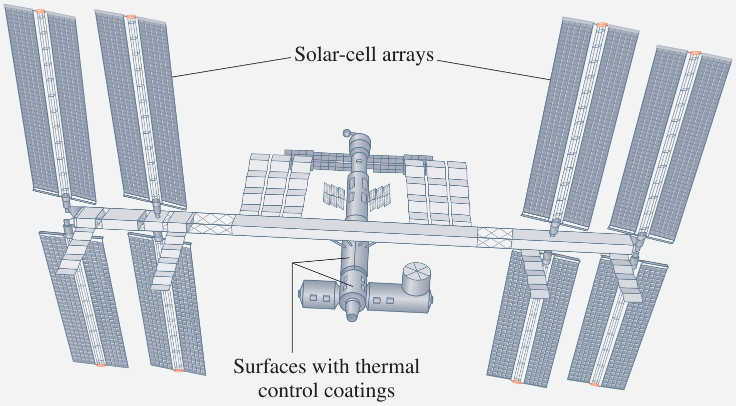
surroundings
boundary

Everything external to the system is considered to be part of the system's **surroundings**. The system is distinguished from its surroundings by a specified **boundary**, which may be at rest or in motion. You will see that the interactions between a system and its surroundings, which take place across the boundary, play an important part in engineering thermodynamics.

Two basic kinds of systems are distinguished in this book. These are referred to, respectively, as *closed systems* and *control volumes*. A closed system refers to a fixed quantity of matter, whereas a control volume is a region of space through which mass may flow. The term *control mass* is sometimes used in place of closed system, and the term *open system* is used interchangeably with control volume. When the terms *control mass* and *control volume* are used, the system boundary is often referred to as a *control surface*.

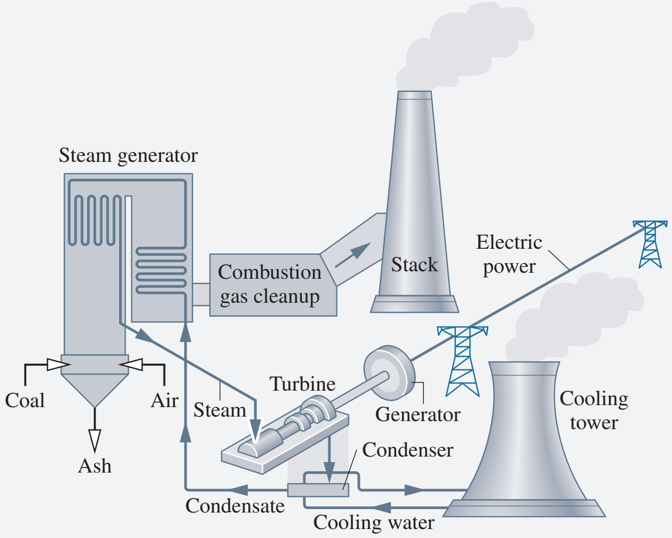
TABLE 1.1 **Selected Areas of Application of Engineering Thermodynamics**

- Aircraft and rocket propulsion
- Alternative energy systems
  - Fuel cells
  - Geothermal systems
  - Magnetohydrodynamic (MHD) converters
  - Ocean thermal, wave, and tidal power generation
  - Solar-activated heating, cooling, and power generation
  - Thermoelectric and thermionic devices
  - Wind turbines
- Automobile engines
- Bioengineering applications
- Biomedical applications
- Combustion systems
- Compressors, pumps
- Cooling of electronic equipment
- Cryogenic systems, gas separation, and liquefaction
- Fossil and nuclear-fueled power stations
- Heating, ventilating, and air-conditioning systems
  - Absorption refrigeration and heat pumps
  - Vapor-compression refrigeration and heat pumps
- Steam and gas turbines
  - Power production
  - Propulsion

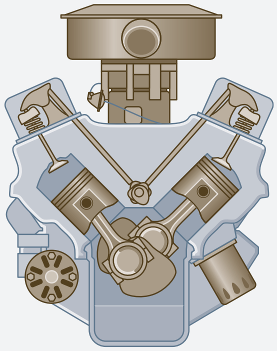


International Space Station

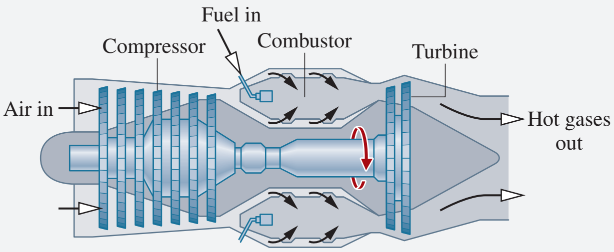
Refrigerator



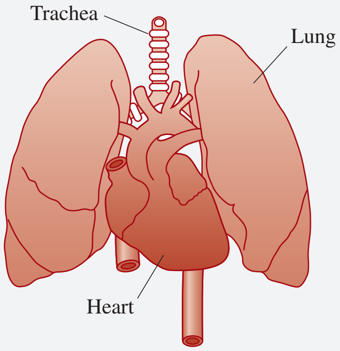
Electrical power plant



Vehicle engine



Turbojet engine



Biomedical applications

TABLE 1.2 **Predictions of Life in the United States in 2050**

At home

- Homes are constructed better to reduce heating and cooling needs.
- Homes have systems for electronically monitoring and regulating energy use.
- Appliances and heating and air-conditioning systems are more energy-efficient.
- Use of solar energy for space and water heating is common.
- More food is produced locally.

Transportation

- Plug-in hybrid vehicles and all-electric vehicles dominate.
- One-quarter of transport fuel is biofuels.
- Use of public transportation within and between cities is common.
- An expanded passenger railway system is widely used.

Lifestyle

- Efficient energy-use practices are utilized throughout society.
- Recycling is widely practiced, including recycling of water.
- Distance learning is common at most educational levels.
- Telecommuting and teleconferencing are the norm.
- The Internet is predominately used for consumer and business commerce.

Power generation

- Electricity plays a greater role throughout society.
- Wind, solar, and other renewable technologies contribute a significant share of the nation's electricity needs.
- A mix of conventional fossil-fueled and nuclear power plants provides a smaller, but still significant, share of the nation's electricity needs.
- A smart and secure national power transmission grid is in place.

1.2.1 Closed Systems

closed system

isolated system

A **closed system** is defined when a particular quantity of matter is under study. A closed system always contains the same matter. There can be no transfer of mass across its boundary. A special type of closed system that does not interact in any way with its surroundings is called an **isolated system**.

Figure 1.1 shows a gas in a piston–cylinder assembly. When the valves are closed, we can consider the gas to be a closed system. The boundary lies just inside the piston and cylinder walls, as shown by the dashed lines on the figure. Since the portion of the boundary between the gas and the piston moves with the piston, the system volume varies. No mass would cross this or any other part of the boundary. If combustion occurs, the composition of the system changes as the initial combustible mixture becomes products of combustion.

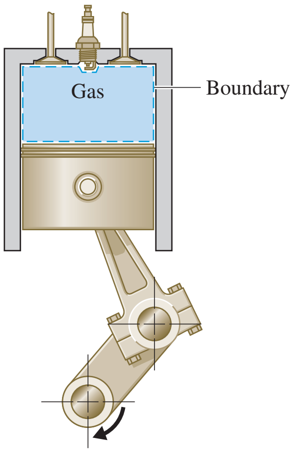


FIG. 1.1 Closed system: A gas in a piston–cylinder assembly.

1.2.2 Control Volumes

control volume

In subsequent sections of this book, we perform thermodynamic analyses of devices such as turbines and pumps through which mass flows. These analyses can be conducted in principle by studying a particular quantity of matter, a closed system, as it passes through the device. In most cases it is simpler to think instead in terms of a given region of space through which mass flows. With this approach, a *region* within a prescribed boundary is studied. The region is called a **control volume**. Mass crosses the boundary of a control volume.

A diagram of an engine is shown in **Fig. 1.2*a***. The dashed line defines a control volume that surrounds the engine. Observe that air, fuel, and exhaust gases cross the boundary. A schematic such as in **Fig. 1.2*b*** often suffices for engineering analysis. Control volume applications in biology and botany are illustrated is **Figs. 1.3** and **1.4** respectively.

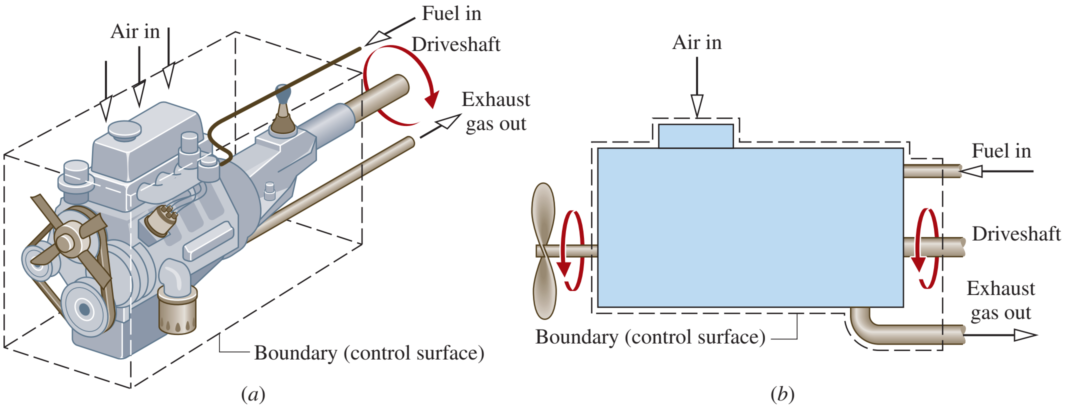


FIG. 1.2 Example of a control volume (open system). An automobile engine.

1.2.3 Selecting the System Boundary

The system boundary should be delineated carefully before proceeding with any thermodynamic analysis. However, the same physical phenomena often can be analyzed in terms of alternative choices of the system, boundary, and surroundings. The choice of a particular boundary defining a particular system depends heavily on the convenience it allows in the subsequent analysis.

In general, the choice of system boundary is governed by two considerations: (1) what is known about a possible system, particularly at its boundaries, and (2) the objective of the analysis.

> **FOR EXAMPLE**
>
> **Figure 1.5 shows a sketch of an air compressor connected to a storage tank. The system boundary shown on the figure encloses the compressor, tank, and all of the piping. This boundary might be selected if the electrical power input is known, and the objective of the analysis is to determine how long the compressor must operate for the pressure in the tank to rise to a specified value. Since mass crosses the boundary, the system would be a control volume. A control volume enclosing only the compressor might be chosen if the condition of the air entering and exiting the compressor is known, and the objective is to determine the electric power input.**

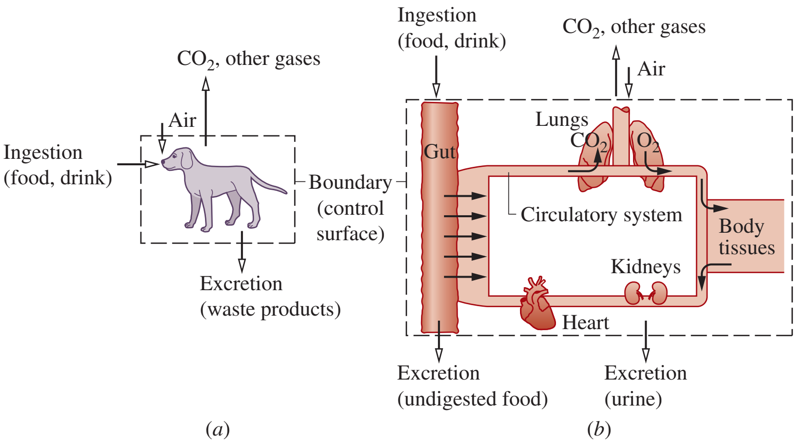


FIG. 1.3 Example of a control volume (open system) in biology.

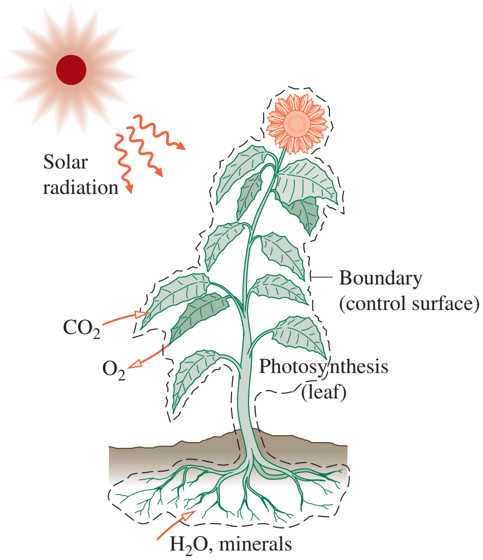


FIG. 1.4 Example of a control volume (open system) in botany.

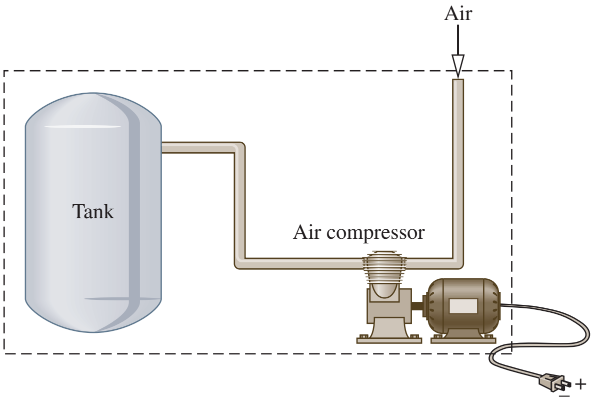


FIG. 1.5 Air compressor and storage tank.

Animation

System Types Tabs a, b, and c

TAKE NOTE...

Animations reinforce many of the text presentations. You can view these animations by going to the e-book, WileyPLUS course, or student companion site for this book.

Animations are keyed to specific content by an adjacent icon.

The first of these icons appears here. In this example, the animation name "System Types" refers to the animation content while "Tabs a, b, and c" refers to the tabs of the animation recommended for viewing now to enhance your understanding.

1.3 Describing Systems and Their Behavior

Engineers are interested in studying systems and how they interact with their surroundings. In this section, we introduce several terms and concepts used to describe systems and how they behave.

1.3.1 Macroscopic and Microscopic Views of Thermodynamics

Systems can be studied from a macroscopic or a microscopic point of view. The macroscopic approach to thermodynamics is concerned with the gross or overall behavior. This is sometimes called *classical* thermodynamics. No model of the structure of matter at the molecular, atomic, and subatomic levels is directly used in classical thermodynamics. Although the behavior of systems is affected by molecular structure, classical thermodynamics allows important aspects of system behavior to be evaluated from observations of the overall system.

The microscopic approach to thermodynamics, known as *statistical* thermodynamics, is concerned directly with the structure of matter. The objective of statistical thermodynamics is to characterize by statistical means the average behavior of the particles making up a system of interest and relate this information to the observed macroscopic behavior of the system. For applications involving lasers, plasmas, high-speed gas flows, chemical kinetics, very low temperatures (cryogenics), and others, the methods of statistical thermodynamics are essential. The microscopic approach is used in this text to interpret *internal energy* in Chap. 2 and *entropy* in Chap 6. Moreover, as noted in Chap. 3, the microscopic approach is instrumental in developing certain data, for example *ideal gas specific heats*.

For a wide range of engineering applications, classical thermodynamics not only provides a considerably more direct approach for analysis and design but also requires far fewer mathematical complications. For these reasons the macroscopic viewpoint is the one adopted in this book. Finally, relativity effects are not significant for the systems under consideration in this book.

1.3.2 Property, State, and Process

To describe a system and predict its behavior requires knowledge of its properties and how those properties are related. A **property** is a macroscopic characteristic of a system such as mass, volume, energy, pressure, and temperature to which a numerical value can be assigned at a given time without knowledge of the previous behavior (*history*) of the system.

property

The word **state** refers to the condition of a system as described by its properties. Since there are normally relations among the properties of a system, the state often can be specified by providing the values of a subset of the properties. All other properties can be determined in terms of these few.

state

When any of the properties of a system changes, the state changes and the system is said to undergo a **process**. A process is a transformation from one state to another. If a system exhibits the same values of its properties at two different times, it is in the same state at these times. A system is said to be at **steady state** if none of its properties changes with time.

process

steady state

Many properties are considered during the course of our study of engineering thermodynamics. Thermodynamics also deals with quantities that are not properties, such as mass flow rates and energy transfers by work and heat. Additional examples of quantities that are not properties are provided in subsequent chapters. For a way to distinguish properties from *non*properties, see the following box.

➔ **Animation**

Property, State and Process Tab a

Distinguishing Properties from Nonproperties

At a given state, each property has a definite value that can be assigned without knowledge of how the system arrived at that state. The change in value of a property as the system is altered from one state to another is determined, therefore, solely by the two end states and is independent of the particular way the change of state occurred. The change is independent of the details of the process. Conversely, if the value of a quantity is independent of the process between two states, then that quantity is the change in a property. This provides a test for determining whether a quantity is a property: ***A quantity is a property if, and only if, its change in value between two states is independent of the process.*** It follows that if the value of a particular quantity depends on the details of the process, and not solely on the end states, that quantity cannot be a property.

1.3.3 Extensive and Intensive Properties

Thermodynamic properties can be placed in two general classes: extensive and intensive. A property is called **extensive** if its value for an overall system is the sum of its values for the parts into which the system is divided. Mass, volume, energy, and several other properties introduced later are extensive. Extensive properties depend on the size or extent of a system. The extensive properties of a system can change with time, and many thermodynamic analyses consist mainly of carefully accounting for changes in extensive properties such as mass and energy as a system interacts with its surroundings.

extensive property

Intensive properties are not additive in the sense previously considered. Their values are independent of the size or extent of a system and may vary from place to place within the system at any moment. Intensive properties may be functions of both position and time, whereas extensive properties can vary only with time. Specific volume (Sec. 1.5), pressure, and temperature are important intensive properties; several other intensive properties are introduced in subsequent chapters.

intensive property

FOR EXAMPLE

To illustrate the difference between extensive and intensive properties, consider an amount of matter that is uniform in temperature, and imagine that it is composed of several parts, as illustrated in Fig. 1.6. The mass of the whole is the sum of the masses of the parts, and the overall volume is the sum of the volumes of the parts. However, the temperature of the whole is not the sum of the temperatures of the parts; it is the same for each part. Mass and volume are extensive, but temperature is intensive.

➔ **Animation**

Extensive and Intensive Properties Tab a

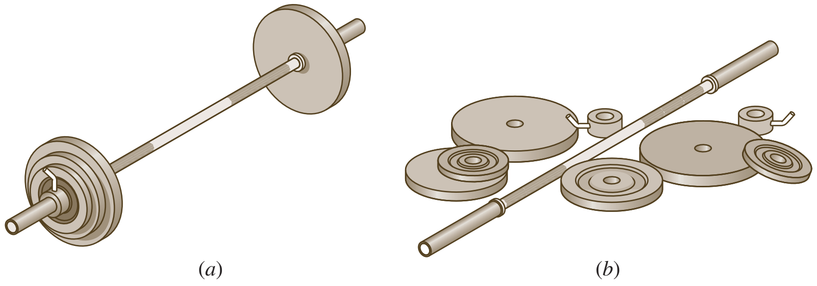

(a) (b)

FIG. 1.6 Figure used to discuss the extensive and intensive property concepts.

1.3.4 Equilibrium

equilibrium

Classical thermodynamics places primary emphasis on equilibrium states and changes from one equilibrium state to another. Thus, the concept of **equilibrium** is fundamental. In mechanics, equilibrium means a condition of balance maintained by an equality of opposing forces. In thermodynamics, the concept is more far-reaching, including not only a balance of forces but also a balance of other influences. Each kind of influence refers to a particular aspect of thermodynamic, or complete, equilibrium. Accordingly, several types of equilibrium must exist individually to fulfill the condition of complete equilibrium; among these are mechanical, thermal, phase, and chemical equilibrium.

equilibrium state

Criteria for these four types of equilibrium are considered in subsequent discussions. For the present, we may think of testing to see if a system is in thermodynamic equilibrium by the following procedure: Isolate the system from its surroundings and watch for changes in its observable properties. If there are no changes, we conclude that the system was in equilibrium at the moment it was isolated. The system can be said to be at an **equilibrium state**.

When a system is isolated, it does not interact with its surroundings; however, its state can change as a consequence of spontaneous events occurring internally as its intensive properties, such as temperature and pressure, tend toward uniform values. When all such changes cease, the system is in equilibrium. At equilibrium, temperature is uniform throughout the system. Also, pressure can be regarded as uniform throughout as long as the effect of gravity is not significant; otherwise, a pressure variation can exist, as in a vertical column of liquid.

It is not necessary that a system undergoing a process be in equilibrium *during* the process. Some or all of the intervening states may be nonequilibrium states. For many such processes, we are limited to knowing the state before the process occurs and the state after the process is completed.

1.4 Measuring Mass, Length, Time, and Force

When engineering calculations are performed, it is necessary to be concerned with the *units* of the physical quantities involved. A unit is any specified amount of a quantity by comparison with which any other quantity of the same kind is measured. For example, meters, centimeters, kilometers, feet, inches, and miles are all *units of length.* Seconds, minutes, and hours are alternative *time units.*

Because physical quantities are related by definitions and laws, a relatively small number of physical quantities suffice to conceive of and measure all others. These are called *primary dimensions.* The others are measured in terms of the primary dimensions and are called *secondary*. For example, if length and time were regarded as primary, velocity and area would be secondary.

A set of primary dimensions that suffice for applications in *mechanics* is mass, length, and time. Additional primary dimensions are required when additional physical phenomena come under consideration. Temperature is included for thermodynamics, and electric current is introduced for applications involving electricity.

base unit

Once a set of primary dimensions is adopted, a **base unit** for each primary dimension is specified. Units for all other quantities are then derived in terms of the base units. Let us illustrate these ideas by considering briefly two systems of units: SI units and English Engineering units.

TABLE 1.3 Units for Mass, Length, Time, and Force

	SI		English	
Quantity	Unit	Symbol	Unit	Symbol
mass	kilogram	kg	pound mass	lb
length	meter	m	foot	ft
time	second	s	second	s
force	newton	N	pound force	lbf
	(= 1 kg · m/s^2)		(= 32.1740 lb · ft/s^2)	

1.4.1 SI Units

In the present discussion we consider the SI system of units that takes mass, length, and time as primary dimensions and regards force as secondary. SI is the abbreviation for Système International d'Unités (International System of Units), which is the legally accepted system in most countries. The conventions of the SI are published and controlled by an international treaty organization. The **SI base units** for mass, length, and time are listed in Table 1.3 and discussed in the following paragraphs. The SI base unit for temperature is the kelvin, K.

SI base units

The SI base unit of mass is the kilogram, kg. It is equal to the mass of a particular cylinder of platinum–iridium alloy kept by the International Bureau of Weights and Measures near Paris. The mass standard for the United States is maintained by the National Institute of Standards and Technology (NIST). The kilogram is the only base unit still defined relative to a fabricated object.

The SI base unit of length is the meter (metre), m, defined as the length of the path traveled by light in a vacuum during a specified time interval. The base unit of time is the second, s. The second is defined as the duration of 9,192,631,770 cycles of the radiation associated with a specified transition of the cesium atom.

The SI unit of force, called the newton, is a secondary unit, defined in terms of the base units for mass, length, and time. Newton's second law of motion states that the net force acting on a body is proportional to the product of the mass and the acceleration, written $F \propto ma$. The newton is defined so that the proportionality constant in the expression is equal to unity. That is, Newton's second law is expressed as the equality

$$F = ma \tag{1.1}$$

The newton, N, is the force required to accelerate a mass of 1 kilogram at the rate of 1 meter per second per second. With Eq. 1.1

$$1 \text{ N} = (1 \text{ kg})(1 \text{ m/s}^2) = 1 \text{ kg} \cdot \text{m/s}^2 \tag{1.2}$$

FOR EXAMPLE

To illustrate the use of the SI units introduced thus far, let us determine the weight in newtons of an object whose mass is 1000 kg, at a place on Earth's surface where the acceleration due to gravity equals a *standard* value defined as 9.80665 m/s^2. Recalling that the weight of an object refers to the force of gravity and is calculated using the mass of the object, m, and the local acceleration of gravity, g, with Eq. 1.1 we get

$$\begin{aligned} F &= mg \\ &= (1000 \text{ kg})(9.80665 \text{ m/s}^2) = 9806.65 \text{ kg} \cdot \text{m/s}^2 \end{aligned}$$

This force can be expressed in terms of the newton by using Eq. 1.2 as a *unit conversion factor*. That is,

$$F = \left(9806.65 \frac{\text{kg} \cdot \text{m}}{\text{s}^2}\right) \left| \frac{1 \text{ N}}{1 \text{ kg} \cdot \text{m/s}^2} \right| = 9806.65 \text{ N}$$

TAKE NOTE...

Observe that in the calculation of force in newtons, the unit conversion factor is set off by a pair of vertical lines. This device is used throughout the text to identify unit conversions.

TABLE 1.4 **SI Unit Prefixes**

Factor	Prefix	Symbol
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p

Since weight is calculated in terms of the mass and the local acceleration due to gravity, the weight of an object can vary because of the variation of the acceleration of gravity with location, but its mass remains constant.

FOR EXAMPLE

If the object considered previously were on the surface of a planet at a point where the acceleration of gravity is one-tenth of the value used in the above calculation, the mass would remain the same but the weight would be one-tenth of the calculated value.

SI units for other physical quantities are also derived in terms of the SI base units. Some of the derived units occur so frequently that they are given special names and symbols, such as the newton. SI units for quantities pertinent to thermodynamics are given as they are introduced in the text. Since it is frequently necessary to work with extremely large or small values when using the SI unit system, a set of standard prefixes is provided in **Table 1.4** to simplify matters. For example, km denotes kilometer, that is, 10^3 m.

1.4.2 English Engineering Units

Although SI units are the worldwide standard, at the present time many segments of the engineering community in the United States regularly use other units. A large portion of America's stock of tools and industrial machines and much valuable engineering data utilize units other than SI units. For many years to come, engineers in the United States will have to be conversant with a variety of units.

English base units

In this section we consider a system of units that is commonly used in the United States, called the English Engineering system. The **English base units** for mass, length, and time are listed in Table 1.3 and discussed in the following paragraphs. English units for other quantities pertinent to thermodynamics are given as they are introduced in the text.

The base unit for length is the foot, ft, defined in terms of the meter as

$$1 \text{ ft} = 0.3048 \text{ m} \tag{1.3}$$

The inch, in., is defined in terms of the foot:

$$12 \text{ in.} = 1 \text{ ft}$$

One inch equals 2.54 cm. Although units such as the minute and the hour are often used in engineering, it is convenient to select the second as the English Engineering base unit for time.

The English Engineering base unit of mass is the pound mass, lb, defined in terms of the kilogram as

$$1 \text{ lb} = 0.45359237 \text{ kg} \tag{1.4}$$

The symbol lbm also may be used to denote the pound mass.

Once base units have been specified for mass, length, and time in the English Engineering system of units, a force unit can be defined, as for the newton, using Newton's second law written as Eq. 1.1. From this viewpoint, the English unit of force, the pound force, lbf, is the force required to accelerate one pound mass at 32.1740 ft/s^2, which is the standard acceleration of gravity. Substituting values into Eq. 1.1,

$$1 \text{ lbf} = (1 \text{ lb})(32.1740 \text{ ft/s}^2) = 32.1740 \text{ lb} \cdot \text{ft/s}^2 \tag{1.5}$$

With this approach force is regarded as *secondary*.

The pound force, lbf, is not equal to the pound mass, lb, introduced previously. Force and mass are fundamentally different, as are their units. The double use of the word "pound" can be confusing, so care must be taken to avoid error.

FOR EXAMPLE

To show the use of these units in a single calculation, let us determine the weight of an object whose mass is 1000 lb at a location where the local acceleration of gravity is 32.0 ft/s^2. By inserting values into Eq. 1.1 and using Eq. 1.5 as a unit conversion factor, we get

$$F = mg = (1000\ \text{lb})\left(32.0\ \frac{\text{ft}}{\text{s}^2}\right)\left|\frac{1\ \text{lbf}}{32.1740\ \text{lb}\cdot\text{ft/s}^2}\right| = 994.59\ \text{lbf}$$

This calculation illustrates that the pound force is a unit of force distinct from the pound mass, a unit of mass.

1.5 Specific Volume

Three measurable intensive properties that are particularly important in engineering thermodynamics are specific volume, pressure, and temperature. Specific volume is considered in this section. Pressure and temperature are considered in Secs. 1.6 and 1.7, respectively.

From the macroscopic perspective, the description of matter is simplified by considering it to be distributed continuously throughout a region. The correctness of this idealization, known as the *continuum* hypothesis, is inferred from the fact that for an extremely large class of phenomena of engineering interest the resulting description of the behavior of matter is in agreement with measured data.

When substances can be treated as continua, it is possible to speak of their intensive thermodynamic properties "at a point." Thus, at any instant the density ρ at a point is defined as

$$\rho = \lim_{V \to V'} \left(\frac{m}{V}\right) \tag{1.6}$$

where V' is the smallest volume for which a definite value of the ratio exists. The volume V' contains enough particles for statistical averages to be significant. It is the smallest volume for which the matter can be considered a continuum and is normally small enough that it can be considered a "point." With density defined by Eq. 1.6, density can be described mathematically as a continuous function of position and time.

Animation

Extensive and Intensive Properties Tabs b and c

The density, or local mass per unit volume, is an intensive property that may vary from point to point within a system. Thus, the mass associated with a particular volume V is determined in principle by integration

$$m = \int_V \rho\, dV \tag{1.7}$$

and *not* simply as the product of density and volume.

The **specific volume** v is defined as the reciprocal of the density, $v = 1/\rho$. It is the volume per unit mass. Like density, specific volume is an intensive property and may vary from point to point. SI units for density and specific volume are kg/m^3 and m^3/kg, respectively. They are also often expressed, respectively, as g/cm^3 and cm^3/g. English units used for density and specific volume in this text are lb/ft^3 and ft^3/lb, respectively.

specific volume

In certain applications it is convenient to express properties such as specific volume on a molar basis rather than on a mass basis. A mole is an amount of a given substance numerically equal to its molecular weight. In this book we express the amount of substance on a **molar basis** in terms of the kilomole (kmol) or the pound mole (lbmol), as appropriate. In each case we use

molar basis

$$\boxed{n = \frac{m}{M}} \tag{1.8}$$

The number of kilomoles of a substance, n, is obtained by dividing the mass, m, in kilograms by the molecular weight, M, in kg/kmol. Similarly, the number of pound moles, n, is obtained by dividing the mass, m, in pound mass by the molecular weight, M, in lb/lbmol. When m is in grams, Eq. 1.8 gives n in gram moles, or *mol* for short. Recall from chemistry that the number of molecules in a gram mole, called Avogadro's number, is 6.022×10^{23}. Appendix Tables A-1 and A-1E provide molecular weights for several substances.

To signal that a property is on a molar basis, a bar is used over its symbol. Thus, $\bar{v}$ signifies the volume per kmol or lbmol, as appropriate. In this text, the units used for $\bar{v}$ are m^3/kmol and ft^3/lbmol. With Eq. 1.8, the relationship between $\bar{v}$ and v is

$$\boxed{\bar{v} = Mv} \tag{1.9}$$

where M is the molecular weight in kg/kmol or lb/lbmol, as appropriate.

1.6 Pressure

Next, we introduce the concept of pressure from the continuum viewpoint. Let us begin by considering a small area, A, passing through a point in a fluid at rest. The fluid on one side of the area exerts a compressive force on it that is normal to the area, F_{normal}. An equal but oppositely directed force is exerted on the area by the fluid on the other side. For a fluid at rest, no other forces than these act on the area. The **pressure**, p, at the specified point is defined as the limit

pressure

Animation

Extensive and Intensive Properties Tab d

$$p = \lim_{A \to A'} \left(\frac{F_{\text{normal}}}{A} \right) \tag{1.10}$$

where A′ is the area at the "point" in the same limiting sense as used in the definition of density.

If the area A′ was given new orientations by rotating it around the given point, and the pressure determined for each new orientation, it would be found that the pressure at the point is the same in all directions *as long as the fluid is at rest*. This is a consequence of the equilibrium of forces acting on an element of volume surrounding the point. However, the pressure can vary from point to point within a fluid at rest; examples are the variation of atmospheric pressure with elevation and the pressure variation with depth in oceans, lakes, and other bodies of water.

Consider next a fluid in motion. In this case the force exerted on an area passing through a point in the fluid may be resolved into three mutually perpendicular components: one normal to the area and two in the plane of the area. When expressed on a unit area basis, the component normal to the area is called the *normal stress,* and the two components in the plane of the area are termed *shear stresses*. The magnitudes of the stresses generally vary with the orientation of the area. The state of stress in a fluid in motion is a topic that is normally treated thoroughly in *fluid mechanics*. The deviation of a normal stress from the pressure, the normal stress that would exist were the fluid at rest, is typically very small. In this book we assume that the normal stress at a point is equal to the pressure at that point. This assumption yields results of acceptable accuracy for the applications considered. Also, the term *pressure*, unless stated otherwise, refers to **absolute pressure**: pressure with respect to the zero pressure of a complete vacuum. The lowest possible value of absolute pressure is zero.

absolute pressure

1.6.1 Pressure Measurement

Manometers and barometers measure pressure in terms of the length of a column of liquid such as mercury, water, or oil. The manometer shown in **Fig. 1.7** has one end open to the atmosphere and the other attached to a tank containing a gas at a uniform pressure. Since pressures at equal elevations in a *continuous* mass of a liquid or gas *at rest* are equal, the pressures at points a and b of Fig. 1.7 are equal. Applying an elementary force balance, the gas pressure is

$$p = p_{\text{atm}} + \rho g L \tag{1.11}$$

where p_{atm} is the local atmospheric pressure, ρ is the density of the manometer liquid, g is the acceleration of gravity, and L is the difference in the liquid levels.

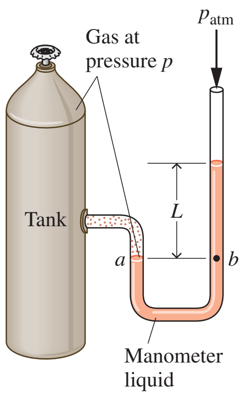


FIG. 1.7 Manometer.

The barometer shown in **Fig. 1.8** is formed by a closed tube filled with liquid mercury and a small amount of mercury vapor inverted in an open container of liquid mercury. Since the pressures at points a and b are equal, a force balance gives the atmospheric pressure as

$$p_{\text{atm}} = p_{\text{vapor}} + \rho_{\text{m}} g L \tag{1.12}$$

where ρ_{m} is the density of liquid mercury. Because the pressure of the mercury vapor is much less than that of the atmosphere, Eq. 1.12 can be approximated closely as $p_{\text{atm}} = \rho_{\text{m}} g L$. For short columns of liquid, ρ and g in Eqs. 1.11 and 1.12 may be taken as constant.

Pressures measured with manometers and barometers are frequently expressed in terms of the length L in millimeters of mercury (mmHg), inches of mercury (inHg), inches of water (inH_2O), and so on.

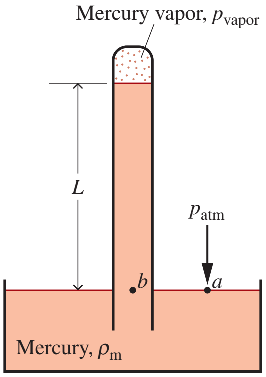


FIG. 1.8 Barometer.

FOR EXAMPLE

A barometer reads 750 mmHg. If $\rho_{\text{m}} = 13.59\ \text{g/cm}^3$ and $g = 9.81\ \text{m/s}^2$, the atmospheric pressure, in N/m^2, is calculated as follows:

$$\begin{aligned} p_{\text{atm}} &= \rho_m g L \\ &= \left[\left(13.59\,\frac{\text{g}}{\text{cm}^3}\right)\left|\frac{1\ \text{kg}}{10^3\ \text{g}}\right|\left|\frac{10^2\ \text{cm}}{1\ \text{m}}\right|^3\right]\left[9.81\,\frac{\text{m}}{\text{s}^2}\right]\left[(750\ \text{mmHg})\left|\frac{1\ \text{m}}{10^3\ \text{mm}}\right|\right]\left|\frac{1\ \text{N}}{1\ \text{kg}\cdot\text{m/s}^2}\right| \\ &= 10^5\ \text{N/m}^2 \end{aligned}$$

A Bourdon tube gage is shown in **Fig. 1.9**. The figure shows a curved tube having an elliptical cross section with one end attached to the pressure to be measured and the other end connected to a pointer by a mechanism. When fluid under pressure fills the tube, the elliptical section tends to become circular, and the tube straightens. This motion is transmitted by the mechanism to the pointer. By calibrating the deflection of the pointer for known pressures, a graduated scale can be determined from which any applied pressure can be read in suitable units. Because of its construction, the Bourdon tube measures the pressure relative to the pressure of the surroundings existing at the instrument. Accordingly, the dial reads zero when the inside and outside of the tube are at the same pressure.

Pressure can be measured by other means as well. An important class of sensors utilizes the *piezoelectric* effect: A charge is generated within certain solid materials when they are deformed. This mechanical input/electrical output provides the basis for pressure measurement as well as displacement and force measurements. Another important type of sensor employs a diaphragm that deflects when a force is applied, altering an inductance, resistance, or capacitance. **Figure 1.10** shows a piezoelectric pressure sensor together with an automatic data acquisition system.

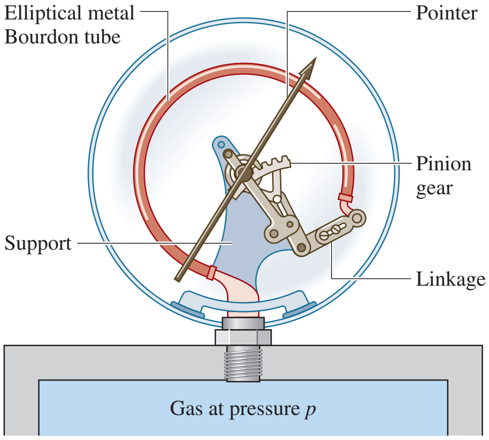


FIG. 1.9 Pressure measurement by a Bourdon tube gage.

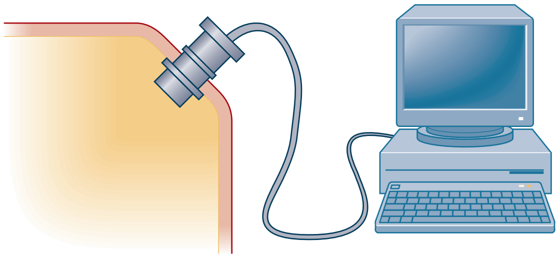


FIG. 1.10 Pressure sensor with automatic data acquisition.

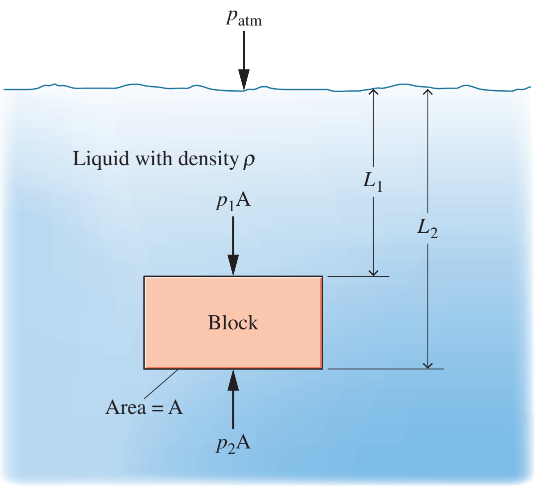


FIG. 1.11 Evaluation of buoyant force for a submerged body.

1.6.2 Buoyancy

buoyant force

When a body is completely or partially submerged in a liquid, the resultant pressure force acting on the body is called the **buoyant force**. Since pressure increases with depth from the liquid surface, pressure forces acting from below are greater than pressure forces acting from above; thus, the buoyant force acts vertically upward. The buoyant force has a magnitude equal to the weight of the displaced liquid (*Archimedes' principle*).

FOR EXAMPLE

Applying Eq. 1.11 to the submerged rectangular block shown in Fig. 1.11, the magnitude of the net force of pressure acting upward, the buoyant force, is

$$\begin{aligned} F &= A(p_2 - p_1) = A(p_{atm} + \rho g L_2) - A(p_{atm} + \rho g L_1) \\ &= \rho g A(L_2 - L_1) \\ &= \rho g V \end{aligned}$$

where V is the volume of the block and ρ is the density of the surrounding liquid. Thus, the magnitude of the buoyant force acting on the block is equal to the weight of the displaced liquid.

1.6.3 Pressure Units

The SI unit of pressure and stress is the pascal:

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

Multiples of the pascal, the kPa, the bar, and the MPa, are frequently used.

$$\begin{aligned} 1 \text{ kPa} &= 10^3 \text{ N/m}^2 \\ 1 \text{ bar} &= 10^5 \text{ N/m}^2 \\ 1 \text{ MPa} &= 10^6 \text{ N/m}^2 \end{aligned}$$

Commonly used English units for pressure and stress are pounds force per square foot, lbf/ft^2, and pounds force per square inch, lbf/in.^{2}

Although atmospheric pressure varies with location on the earth, a standard reference value can be defined and used to express other pressures.

$$1 \text{ standard atmosphere (atm)} = \begin{cases} 1.01325 \times 10^5 \text{ N/m}^2 \\ 14.696 \text{ lbf/in.}^2 \\ 760 \text{ mmHg} = 29.92 \text{ inHg} \end{cases} \tag{1.13}$$

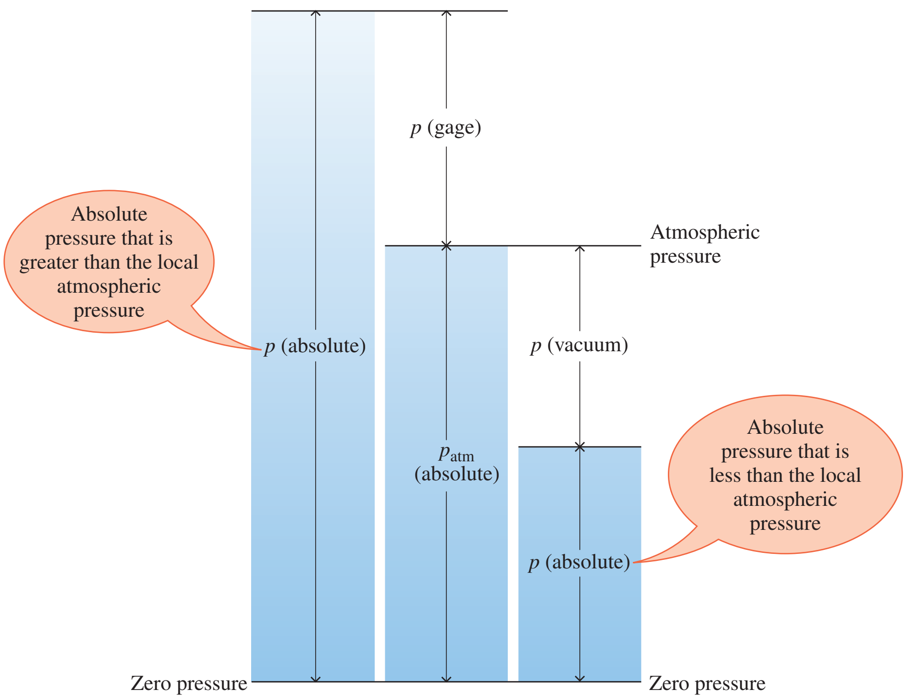


FIG. 1.12 Relationships among the absolute, atmospheric, gage, and vacuum pressures.

Since 1 bar (10^5 N/m^2) closely equals one standard atmosphere, it is a convenient pressure unit despite not being a standard SI unit. When working in SI, the bar, MPa, and kPa are all used in this text.

Although absolute pressures must be used in thermodynamic relations, pressure-measuring devices often indicate the *difference* between the absolute pressure of a system and the absolute pressure of the atmosphere existing outside the measuring device. The magnitude of the difference is called a **gage pressure** or a **vacuum pressure**. The term *gage pressure* is applied when the pressure of the system is greater than the local atmospheric pressure, p_{atm}.

gage pressure

vacuum pressure

$$p(\text{gage}) = p(\text{absolute}) - p_{\text{atm}}(\text{absolute}) \tag{1.14}$$

When the local atmospheric pressure is greater than the pressure of the system, the term *vacuum pressure* is used.

$$p(\text{vacuum}) = p_{\text{atm}}(\text{absolute}) - p(\text{absolute}) \tag{1.15}$$

> **TAKE NOTE...**
> **In this book, the term *pressure* refers to absolute pressure unless indicated otherwise.**

Engineers in the United States frequently use the letters a and g to distinguish between absolute and gage pressures. For example, the absolute and gage pressures in pounds force per square inch are written as psia and psig, respectively. The relationship among the various ways of expressing pressure measurements is shown in **Fig. 1.12**.

1.7 Temperature

In this section the intensive property temperature is considered along with means for measuring it. A concept of temperature, like our concept of force, originates with our sense perceptions. Temperature is rooted in the notion of the “hotness” or “coldness” of objects. We use our sense of touch to distinguish hot objects from cold objects and to arrange objects in their order of “hotness,” deciding that 1 is hotter than 2, 2 hotter than 3, and so on. But however sensitive human touch may be, we are unable to gauge this quality precisely.

Animation

Extensive and Intensive Properties Tab e

A definition of temperature in terms of concepts that are independently defined or accepted as primitive is difficult to give. However, it is possible to arrive at an objective understanding of *equality* of temperature by using the fact that when the temperature of an object changes, other properties also change.

thermal (heat) interaction

thermal equilibrium

temperature

To illustrate this, consider two copper blocks, and suppose that our senses tell us that one is warmer than the other. If the blocks were brought into contact and isolated from their surroundings, they would interact in a way that can be described as a **thermal (heat) interaction**. During this interaction, it would be observed that the volume of the warmer block decreases somewhat with time, while the volume of the colder block increases with time. Eventually, no further changes in volume would be observed, and the blocks would feel equally warm. Similarly, we would be able to observe that the electrical resistance of the warmer block decreases with time and that of the colder block increases with time; eventually the electrical resistances would become constant also. When all changes in such observable properties cease, the interaction is at an end. The two blocks are then in **thermal equilibrium**. Considerations such as these lead us to infer that the blocks have a physical property that determines whether they will be in thermal equilibrium. This property is called **temperature**, and we postulate that when the two blocks are in thermal equilibrium, their temperatures are equal.

zeroth law of thermodynamics

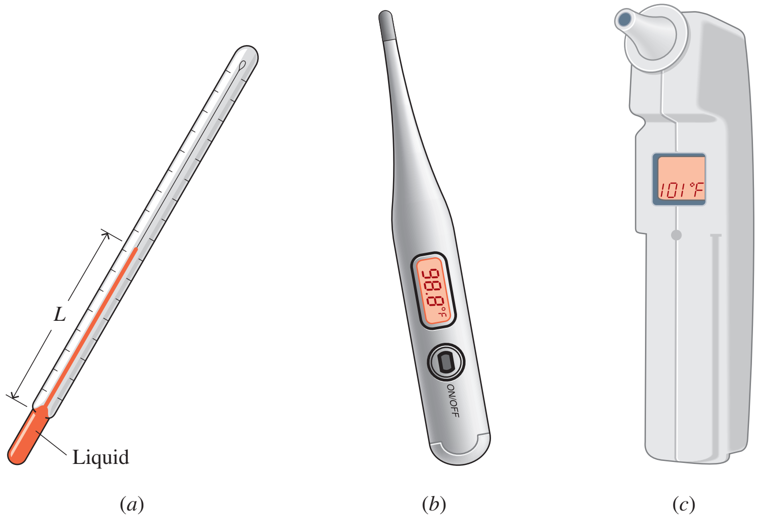
It is a matter of experience that when two objects are in thermal equilibrium with a third object, they are in thermal equilibrium with one another. This statement, which is sometimes called the **zeroth law of thermodynamics**, is tacitly assumed in every measurement of temperature. If we want to know if two objects are at the same temperature, it is not necessary to bring them into contact and see whether their observable properties change with time, as described previously. It is necessary only to see if they are individually in thermal equilibrium with a third object. The third object is usually a *thermometer*.

1.7.1 Thermometers

thermometric property

Any object with at least one measurable property that changes as its temperature changes can be used as a thermometer. Such a property is called a **thermometric property**. The particular substance that exhibits changes in the thermometric property is known as a *thermometric substance*.

A familiar device for temperature measurement is the liquid-in-glass thermometer pictured in **Fig. 1.13*a***, which consists of a glass capillary tube connected to a bulb filled with a liquid such as alcohol and sealed at the other end. The space above the liquid is occupied by the vapor of the liquid or an inert gas. As temperature increases, the liquid expands in volume and rises in the capillary. The length L of the liquid in the capillary depends on the temperature. Accordingly, the liquid is the thermometric substance and L is the thermometric property. Although this type of thermometer is commonly used for ordinary temperature measurements, it is not well suited for applications where extreme accuracy is required.



(*a*) (*b*) (*c*)

FIG. 1.13 Thermometers. (***a***) Liquid-in-glass. (***b***) Electrical-resistance. (***c***) Infrared-sensing ear thermometer.

More accurate sensors known as *thermocouples* are based on the principle that when two dissimilar metals are joined, an electromotive force (emf) that is primarily a function of temperature will exist in a circuit. In certain thermocouples, one thermocouple wire is platinum of a specified purity and the other is an alloy of platinum and rhodium. Thermocouples also utilize copper and constantan (an alloy of copper and nickel), iron and constantan, as well as several other pairs of materials. Electrical-resistance sensors are another important class of temperature measurement devices. These sensors are based on the fact that the electrical resistance of various materials changes in a predictable manner with temperature. The materials used for this purpose are normally conductors (such as platinum, nickel, or copper) or semiconductors. Devices using conductors are known as *resistance temperature detectors*. Semiconductor types are called *thermistors*. A battery-powered electrical-resistance thermometer commonly used today is shown in **Fig. 1.13b**.

A variety of instruments measure temperature by sensing radiation, such as the ear thermometer shown in **Fig. 1.13*c***. They are known by terms such as *radiation thermometers* and *optical pyrometers*. This type of thermometer differs from those previously considered because it is not required to come in contact with an object to determine its temperature, an advantage when dealing with moving objects or objects at extremely high temperatures.

1.7.2 Kelvin and Rankine Temperature Scales

Empirical means of measuring temperature such as considered in Sec. 1.7.1 have inherent limitations.

FOR EXAMPLE

The tendency of the liquid in a liquid-in-glass thermometer to freeze at low temperatures imposes a lower limit on the range of temperatures that can be measured. At high temperatures liquids vaporize and, therefore, these temperatures also cannot be determined by a liquid-in-glass thermometer. Accordingly, several *different* thermometers might be required to cover a wide temperature interval.

In view of the limitations of empirical means for measuring temperature, it is desirable to have a procedure for assigning temperature values that do not depend on the properties of any particular substance or class of substances. Such a scale is called a *thermodynamic* temperature scale. The **Kelvin scale** is an absolute thermodynamic temperature scale that provides a continuous definition of temperature, valid over all ranges of temperature. The unit of temperature on the Kelvin scale is the kelvin (K). The kelvin is the SI base unit for temperature. The lowest possible value of temperature on an absolute thermodynamic temperature scale is zero.

Kelvin scale

To develop the Kelvin scale, it is necessary to use the conservation of energy principle and the second law of thermodynamics; therefore, further discussion is deferred to Sec. 5.8 after these principles have been introduced. We note here, however, that the Kelvin scale has a zero of 0 K, and lower temperatures than this are not defined.

By definition, the **Rankine scale**, the unit of which is the degree rankine (°R), is proportional to the Kelvin temperature according to

Rankine scale

$$\boxed{T(^\circ\mathrm{R}) = 1.8T(\mathrm{K})} \tag{1.16}$$

As evidenced by Eq. 1.16, the Rankine scale is also an absolute thermodynamic scale with an absolute zero that coincides with the absolute zero of the Kelvin scale. In thermodynamic relationships, temperature is always in terms of the Kelvin or Rankine scale unless specifically stated otherwise. Still, the Celsius and Fahrenheit scales considered next are commonly encountered.

1.7.3 Celsius and Fahrenheit Scales

The relationship of the Kelvin, Rankine, Celsius, and Fahrenheit scales is shown in **Fig. 1.14** together with values for temperature at three fixed points: the triple point, ice point, and steam point.

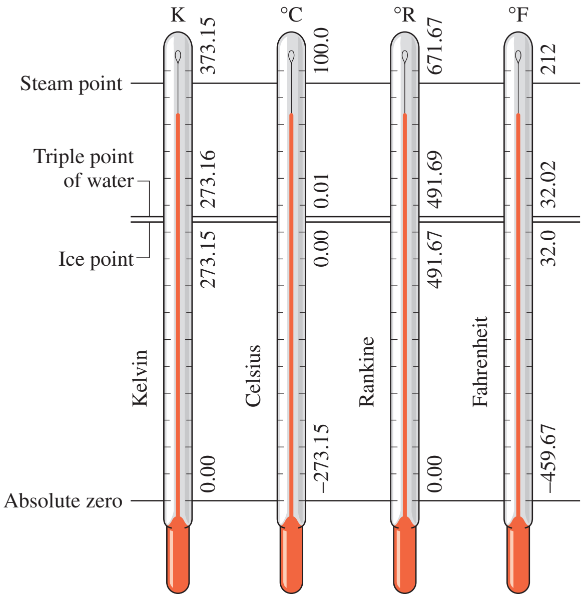


FIG. 1.14 Comparison of temperature scales.

triple point

By international agreement, temperature scales are defined by the numerical value assigned to the easily reproducible **triple point** of water: the state of equilibrium among steam, ice, and liquid water (Sec. 3.2). As a matter of convenience, the temperature at this standard fixed point is defined as 273.16 kelvins, abbreviated as 273.16 K. This makes the temperature interval from the *ice point*[1] (273.15 K) to the *steam point*[2] equal to 100 K and thus in agreement with the Celsius scale, which assigns 100 degrees to the same interval.

Celsius scale

The **Celsius temperature scale** uses the unit degree Celsius (°C), which has the same magnitude as the kelvin. Thus, temperature *differences* are identical on both scales. However, the zero point on the Celsius scale is shifted to 273.15 K, as shown by the following relationship between the Celsius temperature and the Kelvin temperature:

$$\boxed{T(°\mathrm{C}) = T(\mathrm{K}) - 273.15} \tag{1.17}$$

From this it can be concluded that on the Celsius scale the triple point of water is 0.01°C and that 0 K corresponds to −273.15°C. These values are shown on Fig. 1.14.

Fahrenheit scale

A degree of the same size as that on the Rankine scale is used in the **Fahrenheit scale**, but the zero point is shifted according to the relation

$$\boxed{T(°\mathrm{F}) = T(°\mathrm{R}) - 459.67} \tag{1.18}$$

Substituting Eqs. 1.17 and 1.18 into Eq. 1.16, we get

$$\boxed{T(°\mathrm{F}) = 1.8T(°\mathrm{C}) + 32} \tag{1.19}$$

This equation shows that the Fahrenheit temperature of the ice point (0°C) is 32°F and of the steam point (100°C) is 212°F. The 100 Celsius or Kelvin degrees between the ice point and steam point correspond to 180 Fahrenheit or Rankine degrees, as shown in Fig. 1.14.

TAKE NOTE...

When making engineering calculations, it's usually okay to round off the last numbers in Eqs. 1.17 and 1.18 to 273 and 460, respectively. This is frequently done in this book.

---

[1] The state of equilibrium between ice and air-saturated water at a pressure of 1 atm.

[2] The state of equilibrium between steam and liquid water at a pressure of 1 atm.

1.8 Engineering Design and Analysis

The word *engineer* traces its roots to the Latin *ingeniare*, relating to *invention*. Today invention remains a key engineering function having many aspects ranging from developing new devices to addressing complex social issues using technology. In pursuit of many such activities, engineers are called upon to design and analyze devices intended to meet human needs. Design and analysis are considered in this section.

1.8.1 Design

Engineering design is a decision-making process in which principles drawn from engineering and other fields such as economics and statistics are applied, usually iteratively, to devise a system, system component, or process. Fundamental elements of design include the establishment of objectives, synthesis, analysis, construction, testing, evaluation, and redesign (as necessary). Designs typically are subject to a variety of **constraints** related to economics, safety, environmental impact, and so on.

design constraints

Design projects usually originate from the recognition of a need or an opportunity that is only partially understood initially. Thus, before seeking solutions it is important to define the design objectives. Early steps in engineering design include developing quantitative performance specifications and identifying alternative *workable* designs that meet the specifications. Among the workable designs are generally one or more that are "best" according to some criteria: lowest cost, highest efficiency, smallest size, lightest weight, and so on. Other important factors in the selection of a final design include reliability, manufacturability, maintainability, and marketplace considerations. Accordingly, a compromise must be sought among competing criteria, and there may be alternative design solutions that are feasible.[3]

1.8.2 Analysis

Design requires synthesis: selecting and putting together components to form a coordinated whole. However, as each individual component can vary in size, performance, cost, and so on, it is generally necessary to subject each to considerable study or analysis before a final selection can be made.

> **FOR EXAMPLE**
>
> **A proposed design for a fire-protection system might entail an overhead piping network together with numerous sprinkler heads. Once an overall configuration has been determined, detailed engineering analysis is necessary to specify the number and type of the spray heads, the piping material, and the pipe diameters of the various branches of the network. The analysis also must aim to ensure all components form a smoothly working whole while meeting relevant cost constraints and applicable codes and standards.**

Engineers frequently do analysis, whether explicitly as part of a design process or for some other purpose. Analyses involving systems of the kind considered in this book use, directly or indirectly, one or more of three basic laws. These laws, which are independent of the particular substance or substances under consideration, are

1. the conservation of mass principle
2. the conservation of energy principle
3. the second law of thermodynamics

In addition, relationships among the properties of the particular substance or substances considered are usually necessary (Chaps. 3, 6, 11–14). Newton's second law of motion (Chaps. 1, 2, 9), relations such as Fourier's conduction model (Chap. 2), and principles of engineering economics (Chap. 7) also may play a part.

---

[3] For further discussion, see A. Bejan, G. Tsatsaronis, and M. J. Moran, *Thermal Design and Optimization*, John Wiley & Sons, New York, 1996, Chap. 1.

The first steps in a thermodynamic analysis are defining the system and identifying relevant interactions with the surroundings. Attention then turns to the pertinent physical laws and relationships that allow the behavior of the system to be described in terms of an **engineering model**. The objective in modeling is to obtain a simplified representation of system behavior that is sufficiently faithful for the purpose of the analysis, even if many aspects exhibited by the actual system are ignored. For example, idealizations often used in mechanics to simplify an analysis and arrive at a manageable model include the assumptions of point masses, frictionless pulleys, and rigid beams. Satisfactory modeling takes experience and is a part of the *art* of engineering.

engineering model

Engineering analysis is most effective when it is done systematically. This is considered next.

1.9 Methodology for Solving Thermodynamics Problems

A major goal of this textbook is to help you learn how to solve engineering problems that involve thermodynamic principles. To this end, numerous solved examples and end-of-chapter problems are provided. It is extremely important for you to study the examples *and* solve problems, for mastery of the fundamentals comes only through practice.

To maximize the results of your efforts, it is necessary to develop a systematic approach. You must think carefully about your solutions and avoid the temptation of starting problems *in the middle* by selecting some seemingly appropriate equation, substituting in numbers, and quickly "punching up" a result on your calculator. Such a haphazard problem-solving approach can lead to difficulties as problems become more complicated. Accordingly, it is strongly recommended that problem solutions be organized using the following *five steps*, which are employed in the solved examples of this text.

① **Known** State briefly in your own words what is known. This requires that you read the problem carefully *and* think about it.

② **Find** State concisely in your own words what is to be determined.

③ **Schematic and Given Data** Draw a sketch of the system to be considered. Decide whether a closed system or control volume is appropriate for the analysis, and then carefully identify the boundary. Label the diagram with relevant information from the problem statement.

Record all property values you are given or anticipate may be required for subsequent calculations. Sketch appropriate property diagrams (see Sec. 3.2), locating key state points and indicating, if possible, the processes executed by the system.

The importance of good sketches of the system and property diagrams cannot be overemphasized. They are often instrumental in enabling you to think clearly about the problem.

④ **Engineering Model** To form a record of how you *model* the problem, list all *simplifying assumptions* and *idealizations* made to reduce it to one that is manageable. Sometimes this information also can be noted on the sketches of the previous step. The development of an appropriate model is a key aspect of successful problem solving.

⑤ **Analysis** Using your assumptions and idealizations, reduce the appropriate governing equations and relationships to forms that will produce the desired results.

It is advisable to work with equations as long as possible before substituting numerical data. When the equations are reduced to final forms, consider them to determine what additional data may be required. Identify the tables, charts, or property equations that provide the required values. Additional property diagram sketches may be helpful at this point to clarify states and processes.

When all equations and data are in hand, substitute numerical values into the equations. Carefully check that a consistent and appropriate set of units is being employed. Then perform the needed calculations.

Finally, consider whether the magnitudes of the numerical values are reasonable and the algebraic signs associated with the numerical values are correct.

The problem solution format used in this text is intended to *guide* your thinking, not substitute for it. Accordingly, you are cautioned to avoid the rote application of these five steps, for this alone would provide few benefits. Indeed, as a particular solution evolves you may have to return to an earlier step and revise it in light of a better understanding of the problem. For example, it might be necessary to add or delete an assumption, revise a sketch, determine additional property data, and so on.

The solved examples provided in the book are frequently annotated with various comments intended to assist learning, including commenting on what was learned, identifying key aspects of the solution, and discussing how better results might be obtained by relaxing certain assumptions.

In some of the earlier examples and end-of-chapter problems, the solution format may seem unnecessary or unwieldy. However, as the problems become more complicated you will see that it reduces errors, saves time, and provides a deeper understanding of the problem at hand.

The example to follow illustrates the use of this solution methodology together with important system concepts introduced previously, including identification of interactions occurring at the boundary.

EXAMPLE 1.1 | Using the Solution Methodology and System Concepts

A wind turbine–electric generator is mounted atop a tower. As wind blows steadily across the turbine blades, electricity is generated. The electrical output of the generator is fed to a storage battery.

a. Considering only the wind turbine–electric generator as the system, identify locations on the system boundary where the system interacts with the surroundings. Describe changes occurring within the system with time.

b. Repeat for a system that includes only the storage battery.

Solution

Known A wind turbine–electric generator provides electricity to a storage battery.

Find For a system consisting of (a) the wind turbine–electric generator, (b) the storage battery, identify locations where the system interacts with its surroundings, and describe changes occurring within the system with time.

Schematic and Given Data:

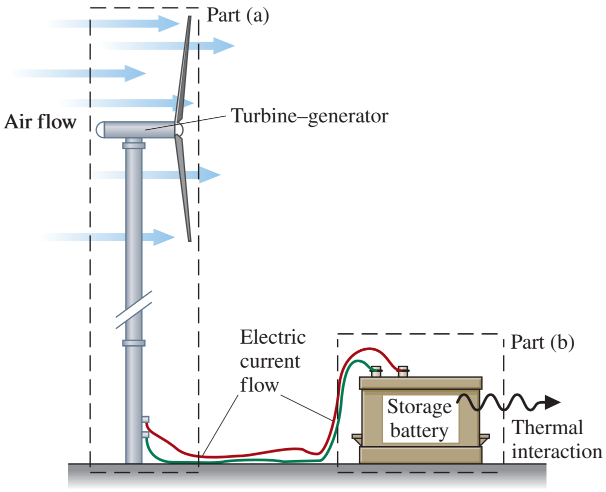


FIG. E1.1

Engineering Model

1. In part (a), the system is the control volume shown by the dashed line on the figure.
2. In part (b), the system is the closed system shown by the dashed line on the figure.
3. The wind is steady.

Analysis

a. In this case, the wind turbine is studied as a control volume with air flowing across the boundary. Another principal interaction between the system and surroundings is the electric current passing through the wires. From the macroscopic perspective, such an interaction is not considered a mass transfer, however. With a steady wind, the turbine–generator is likely to reach steady-state operation, where the rotational speed of the blades is constant and a steady electric current is generated.

❶ **b.** In this case, the battery is studied as a closed system. The principal interaction between the system and its surroundings is the electric current passing into the battery through the wires. As noted in part (a), this interaction is not considered a mass transfer. As the battery is charged and chemical reactions occur within it, the temperature of the battery surface may become somewhat elevated and a thermal interaction might occur between the battery and its surroundings. This interaction is likely to be of secondary importance. Also, as the battery is charged, the state within changes with time. The battery is not at steady state.

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❶ Using terms familiar from a previous physics course, the system of part (a) involves the *conversion* of kinetic energy to electricity, whereas the system of part (b) involves energy *storage* within the battery.

SKILLS DEVELOPED

Ability to…

- apply the problem-solving methodology used in this book.
- define a control volume and identify interactions on its boundary.
- define a closed system and identify interactions on its boundary.
- distinguish steady-state operation from nonsteady operation.

Quick Quiz

May an overall system consisting of the turbine–generator and battery be considered as operating at steady state? Explain. Ans. No. A system is at steady state only if *none* of its properties changes with time.

Chapter Summary and Study Guide

In this chapter, we have introduced some of the fundamental concepts and definitions used in the study of thermodynamics. The principles of thermodynamics are applied by engineers to analyze and design a wide variety of devices intended to meet human needs.

An important aspect of thermodynamic analysis is to identify systems and to describe system behavior in terms of properties and processes. Three important properties discussed in this chapter are specific volume, pressure, and temperature.

In thermodynamics, we consider systems at equilibrium states and systems undergoing processes (changes of state). We study processes during which the intervening states are not equilibrium states and processes during which the departure from equilibrium is negligible.

In this chapter, we have introduced SI and English Engineering units for mass, length, time, force, and temperature. You will need to be familiar with both sets of units as you use this book. For *Conversion Factors*, see inside the front cover of the book, the book companion site, or WileyPLUS course.

Chapter 1 concludes with discussions of how thermodynamics is used in engineering design and how to solve thermodynamics problems systematically.

This book has several features that facilitate study and contribute to understanding. For an overview, see *How to Use This Book Effectively* on the book companion site or in the WileyPLUS course.

The following checklist provides a study guide for this chapter. When your study of the text and the end-of-chapter exercises has been completed you should be able to

- write out the meanings of the terms listed in the margin throughout the chapter and explain each of the related concepts. The subset of key concepts listed is particularly important in subsequent chapters.
- identify an appropriate system boundary and describe the interactions between the system and its surroundings.
- work on a molar basis using Eq. 1.8.
- use SI and English units for mass, length, time, force, and temperature and apply appropriately Newton's second law and Eqs. 1.16–1.19.
- apply the methodology for problem solving discussed in Sec. 1.9.

Key Engineering Concepts

system
surroundings
boundary
closed system
control volume
property
state
process
extensive property
intensive property
equilibrium
specific volume
pressure
temperature
Kelvin scale
Rankine scale

Key Equations

$n = m/M$	(1.8)	Relation between amounts of matter on a mass basis, m, and on a molar basis, n.
$T(°\text{R}) = 1.8T(\text{K})$	(1.16)	Relation between the Rankine and Kelvin temperatures.
$T(°\text{C}) = T(\text{K}) - 273.15$	(1.17)	Relation between the Celsius and Kelvin temperatures.
$T(°\text{F}) = T(°\text{R}) - 459.67$	(1.18)	Relation between the Fahrenheit and Rankine temperatures.
$T(°\text{F}) = 1.8T(°\text{C}) + 32$	(1.19)	Relation between the Fahrenheit and Celsius temperatures.