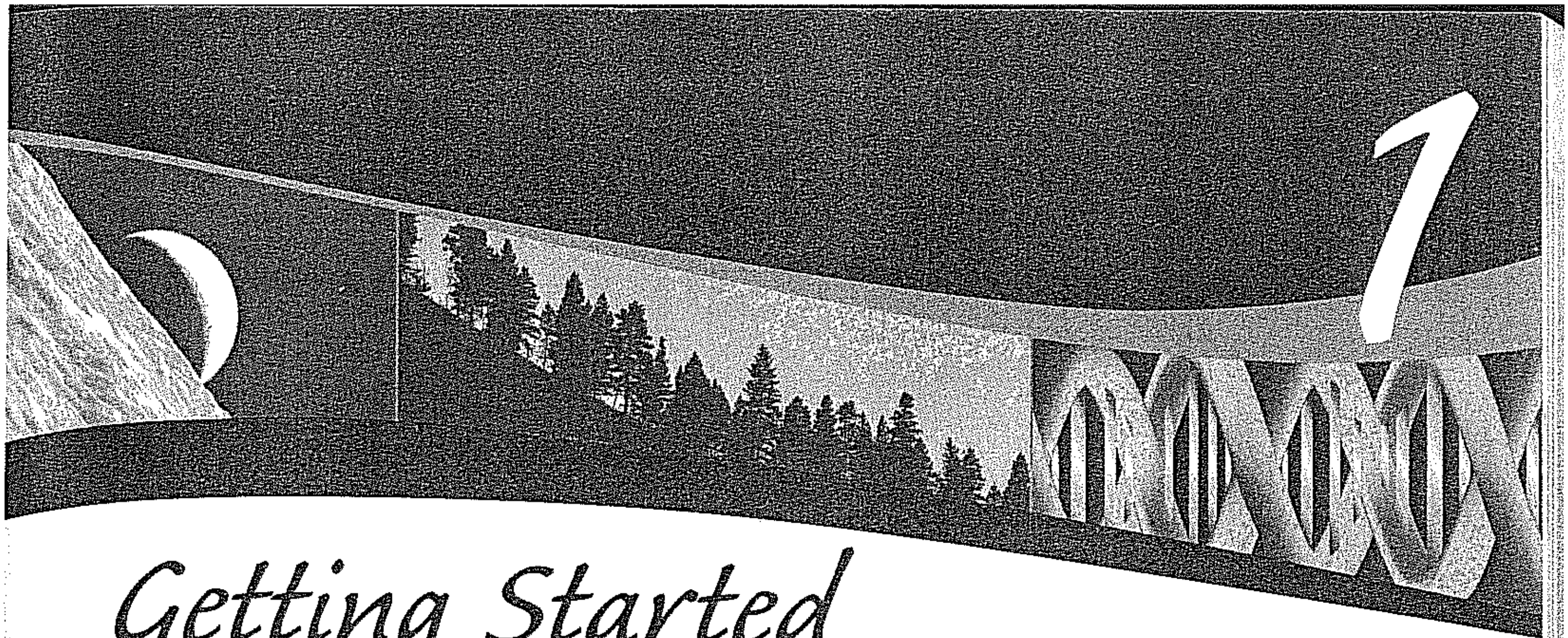


1

Getting Started

Introductory Concepts and Definitions

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 the introduction is brief, and further elaboration is provided in subsequent chapters.

Learning Objectives

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

✓ demonstrate understanding of 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.

✓ apply SI and English Engineering units, including units for specific volume, pressure, and temperature.

✓ work with the Kelvin, Rankine, Celsius, and Fahrenheit temperature scales.

✓ apply the problem-solving methodology used in this book.

1.1 Using Thermodynamics

Engineers use principles drawn from thermodynamics and other engineering sciences, such as fluid mechanics and heat and mass transfer, to analyze and design things intended to meet human needs. The wide realm of application of these principles is suggested by Table 1.1, which lists a few of the areas where engineering thermodynamics is important.

Engineers seek to achieve improved designs and better performance, as measured by factors such as an increase in the output of some desired product, a reduced input of a scarce resource, a reduction in total costs, or a lesser environmental impact. The principles of engineering thermodynamics play an important part in achieving these goals.

1.2 Defining Systems

An important 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*.

1.2.1 Closed Systems

closed system

isolated system

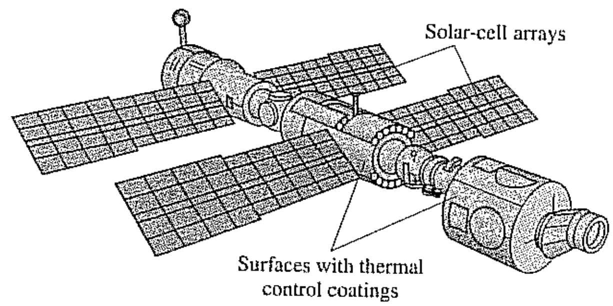
A ***closed system*** is defined when a particular quantity of matter is under study. A closed system always contains the same matter. There can be no transfer of mass across its boundary. A special type of closed system that does not interact in any way with its surroundings is called an ***isolated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

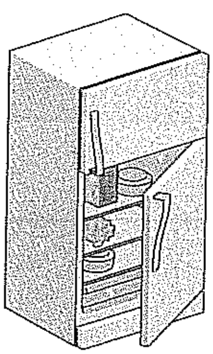
Table 1.1

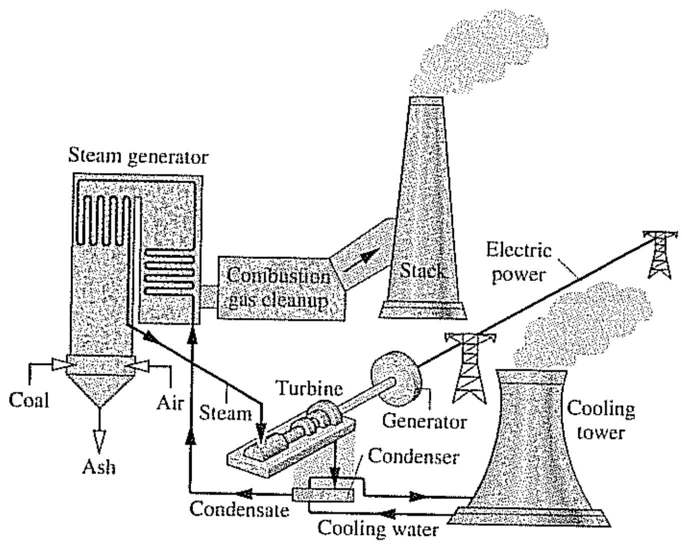
Selected Areas of Application of Engineering Thermodynamics

- 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

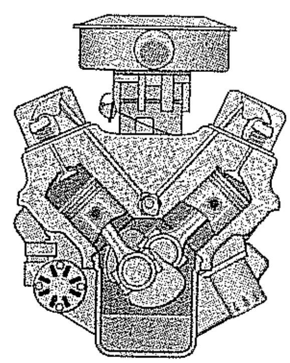


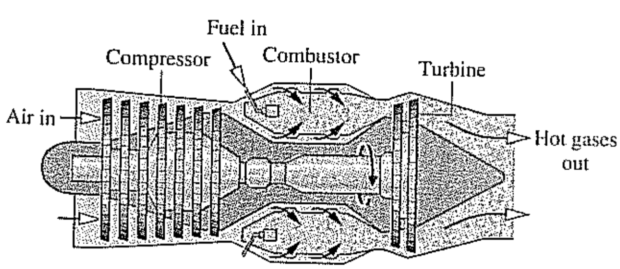
International Space Station


Refrigerator

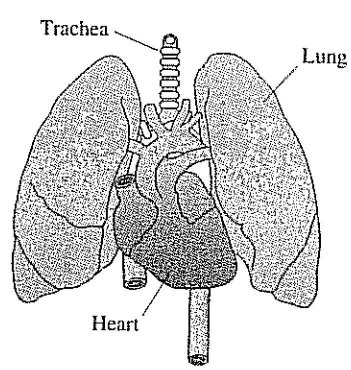


Electrical power plant


Automobile engine



Turbojet engine



Biomedical applications

occurs, the composition of the system changes as the initial combustible mixture becomes products of combustion.

1.2.2 Control Volumes

control volume

In subsequent sections of this book, thermodynamic analyses are made 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 may cross 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.

Bio... connections

Living things and their organs can be studied as control volumes. For the pet shown in Fig. 1.3*a*, air, food, and drink essential to sustain life and for activity enter across the boundary, and waste products exit. A schematic such as Fig. 1.3*b* can suffice for biological analysis. Particular organs, such as the heart, also can be studied as control volumes. As shown in Fig. 1.4, plants can be studied from a control volume viewpoint. Intercepted solar radiation is used in the production of essential chemical substances within plants by *photosynthesis*. During photosynthesis, plants take in carbon dioxide from the atmosphere and discharge oxygen to the atmosphere. Plants also draw in water and nutrients through their roots.

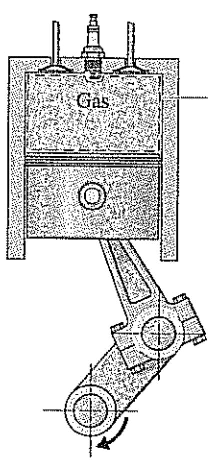


Fig. 1.1 Closed system: A gas in a piston–cylinder assembly.

1.2.3 Selecting the System Boundary

It is essential for the system boundary to 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

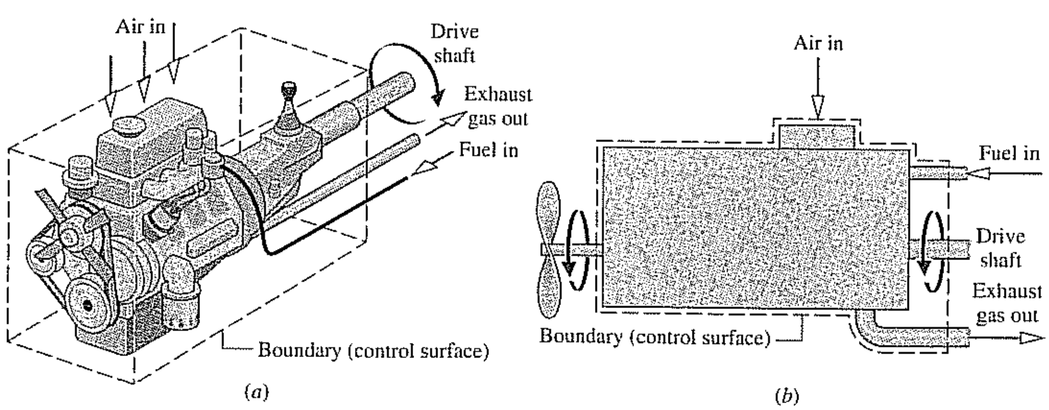


Fig. 1.2 Example of a control volume (open system). An automobile engine.

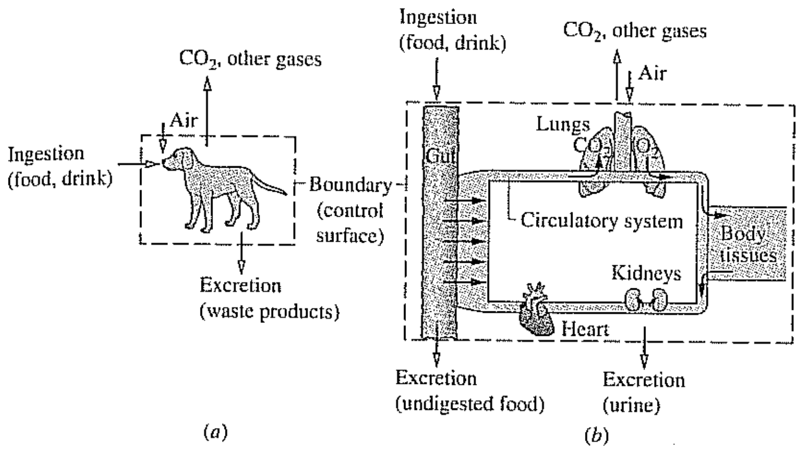


Fig. 1.3 Example of a control volume (open system) in biology.

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.

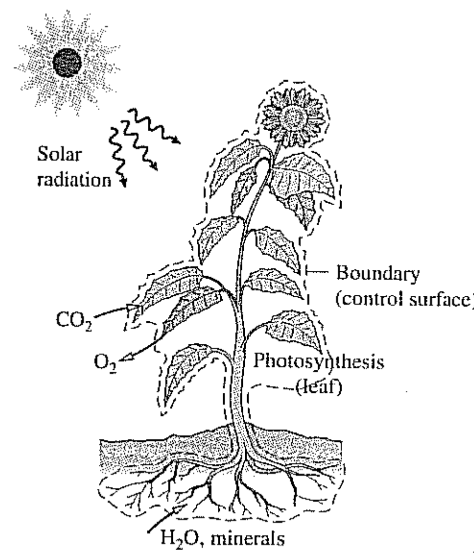


Fig. 1.4 Example of a control volume (open system) in botany.

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

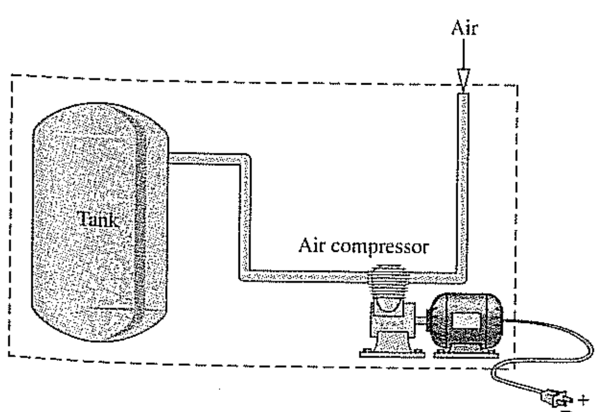


Fig. 1.5 Air compressor and storage tank.

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

property

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.

state

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.

process

steady state

When any of the properties of a system change, the state changes and the system is said to have undergone a ***process.*** A process is a transformation from one state to another. However, 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.

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 box.

1.3.3 Extensive and Intensive Properties

extensive property

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.

intensive 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. Thus, intensive properties may be functions

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. Therefore, the change in value of a property as the system is altered from one state to another is determined solely by the two end states and is independent of the particular way the change of state occurred. That is, 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.

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.

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.

1.3.4 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

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.***

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.

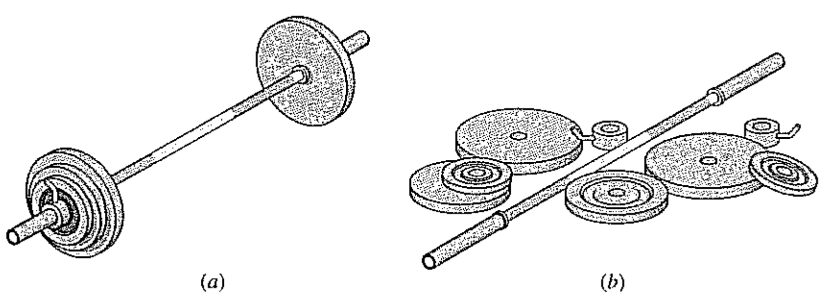


Fig. 1.6 Figure used to discuss the extensive and intensive property concepts.

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.

There is no requirement 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* are 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.

1.4.1 SI Units

SI base units

In the present discussion we consider the system of units called SI 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 1.2 and discussed in the following paragraphs. The SI base unit for temperature is the kelvin, K.

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

Table 1.2

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 (= 1 kg · m/s^2)	N	pound force (= 32.1740 lb · ft/s^2)	lbf

and Measures near Paris. The mass standard for the United States is maintained by the National Institute of Standards and Technology. 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 the 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.

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 1.3 to simplify matters. For example, km denotes kilometer, that is, 10^3 m.

Table 1.3

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

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 some 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 1.2 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, however, and 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.

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.

specific 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. However, 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.

molar basis

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

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

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

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

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

Horizons

Big Hopes For Nanotechnology

Nanoscience is the study of molecules and molecular structures, called nanostructures, having one or more dimensions less than about 100 nanometers. One nanometer is one billionth of a meter: 1 nm $= 10^{-9}$ m. To grasp this level of smallness, a stack of 10 hydrogen atoms would have a height of 1 nm, while a human hair has a diameter about 50,000 nm. *Nanotechnology* is the engineering of nanostructures into useful products. At the nanotechnology scale, behavior may differ from our macroscopic expectations. For example, the *averaging* used to assign property values *at a point* in the continuum model may no longer apply owing to the interactions among the atoms under consideration. Also at these scales, the nature of physical phenomena such as current flow may depend explicitly on the physical size of devices. After a decade of research, nanotechnology is now poised to provide new products with a broad range of uses, including implantable chemotherapy devices, biosensors for glucose detection in diabetics, novel electronic devices, new energy conversion technologies, and 'smart materials', as for example fabrics that allow water vapor to escape while keeping liquid water out.

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

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

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.

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

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

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.

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

$$p_{atm} = p_{vapor} + \rho_m g L \tag{1.12}$$

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 $p_{atm} = \rho_m g L$. For short columns of liquid, ρ and g in Eqs. 1.11 and 1.12 may be taken as constant.

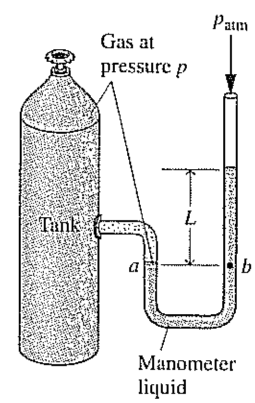


Fig. 1.7 Manometer.

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. **FOR EXAMPLE...** a barometer reads 750 mmHg. If $\rho_m = 13.59\ g/cm^3$ and $g = 9.81\ m/s^2$, the atmospheric pressure, in N/m^2, is calculated as follows:

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

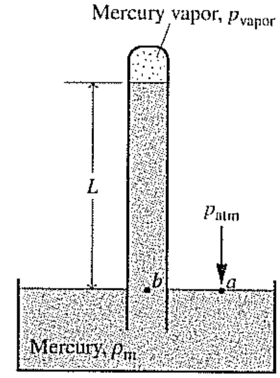


Fig. 1.8 Barometer.

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 utilize 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.

1.6.2 Pressure Units

The SI unit of pressure and stress is the pascal.

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

However, multiples of the pascal: the kPa, the bar, and the MPa are frequently used.

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

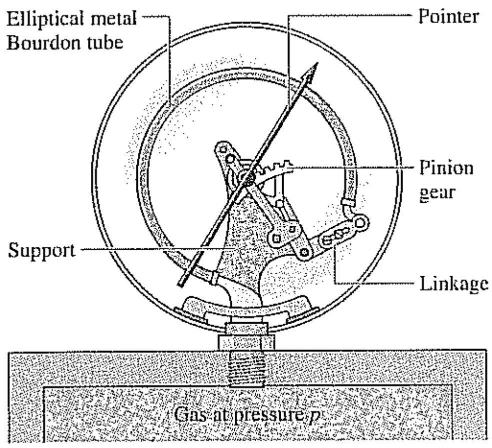


Fig. 1.9 Pressure measurement by a Bourdon tube gage.

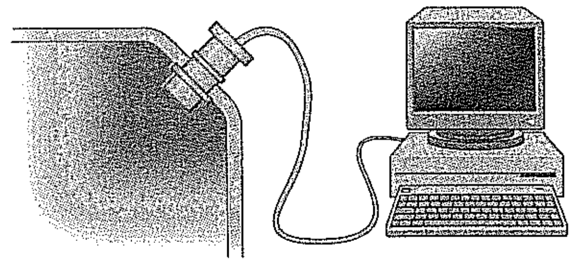


Fig. 1.10 Pressure sensor with automatic data acquisition.

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.

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

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.

gage pressure

vacuum pressure

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}.

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

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

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

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. 1.11.

Bio... connections

One in three Americans is said to have high blood pressure. Since this can lead to heart disease, strokes, and other serious medical complications, medical practitioners recommend regular blood pressure checks for everyone. Blood pressure measurement aims to determine the maximum pressure (systolic pressure) in an artery when the heart is pumping blood and the minimum pressure (diastolic pressure) when the heart is resting, each pressure expressed in millimeters of mercury, mmHg. The systolic and diastolic pressures of healthy persons should be less than about 120 mmHg and 80 mmHg, respectively.

The standard blood pressure measurement apparatus in use for decades involving an inflatable cuff, mercury manometer, and stethoscope is gradually being replaced because of concerns over mercury toxicity and in response to special requirements, including monitoring during clinical exercise and during anesthesia. Also, for home use and self-monitoring, many patients prefer easy-to-use automated devices that provide digital displays of blood pressure data. This has prompted biomedical engineers to rethink blood pressure measurement and develop new mercury-free and stethoscope-free approaches. One of these uses a highly-sensitive pressure transducer to detect pressure oscillations within an inflated cuff placed around the patient's arm. The monitor's software uses these data to calculate the systolic and diastolic pressures, which are displayed digitally.

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.

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.

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

thermal (heat) interaction

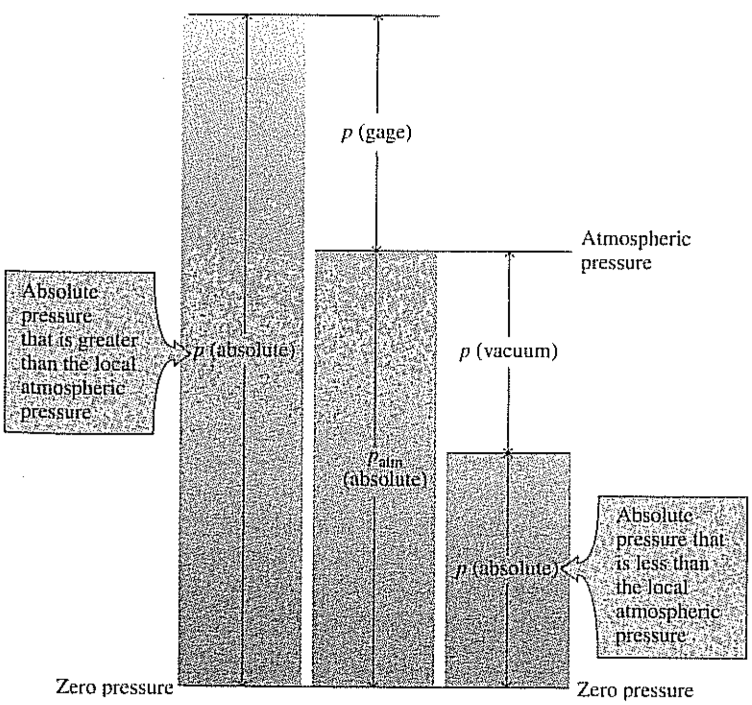


Fig. 1.11 Relationships among the absolute, atmospheric, gage, and vacuum pressures.

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.

thermal equilibrium

temperature

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. Thus, 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.*

zeroth law of thermodynamics

1.7.1 Thermometers

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.

thermometric property

A familiar device for temperature measurement is the liquid-in-glass thermometer pictured in Fig. 1.12*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.

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. 1.12(*b*).

A variety of instruments measure temperature by sensing radiation, such as the ear thermometer shown in Fig. 1.12(*c*). They are known by terms such as *radiation thermometers* and *optical pyrometers*. This type of thermometer differs from those previously considered in that it is not required to come in contact with the object whose temperature is to be determined, an advantage when dealing with moving objects or objects at extremely high temperatures.

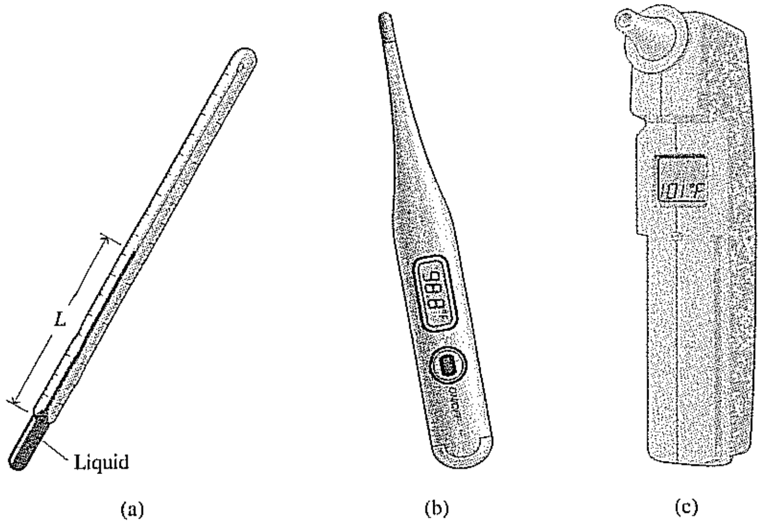


Fig. 1.12 Thermometers. (*a*) Liquid-in-glass. (*b*) Electrical-resistance (*c*) Infrared-sensing ear thermometer.

Energy & Environment

The mercury-in-glass fever thermometers, once found in nearly every medicine cabinet, are a thing of the past. The *American Academy of Pediatrics* has designated mercury as too toxic to be present in the home. Families are turning to safer alternatives and disposing of mercury thermometers. Proper disposal is an issue, experts say.

The safe disposal of millions of obsolete mercury-filled thermometers has emerged in its own right as an environmental issue. For proper disposal, thermometers must be taken to hazardous-waste collection stations rather than simply thrown in the trash where they can be easily broken, releasing mercury. Loose fragments of broken thermometers and anything that contacted mercury should be transported in closed containers to appropriate disposal sites.

The present generation of liquid-in-glass fever thermometers for home use contains patented liquid mixtures that are nontoxic, safe alternatives to mercury. Other types of thermometers also are used in the home, including battery-powered electrical-resistance thermometers.

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 does 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.

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. However, we note here that the Kelvin scale has a zero of 0 K, and lower temperatures than this are not defined.

Rankine scale

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

$$T(°\text{R}) = 1.8T(\text{K}) \tag{1.16}$$

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. 1.13 together with values for temperature at three fixed points: the triple point, ice point, and steam point.

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 between 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 over the interval with the Celsius scale, which assigns 100 Celsius degrees to it.

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

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

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. 1.13.

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

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

Substituting Eqs. 1.17 and 1.18 into Eq. 1.16, it follows that

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

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. 1.13.

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.

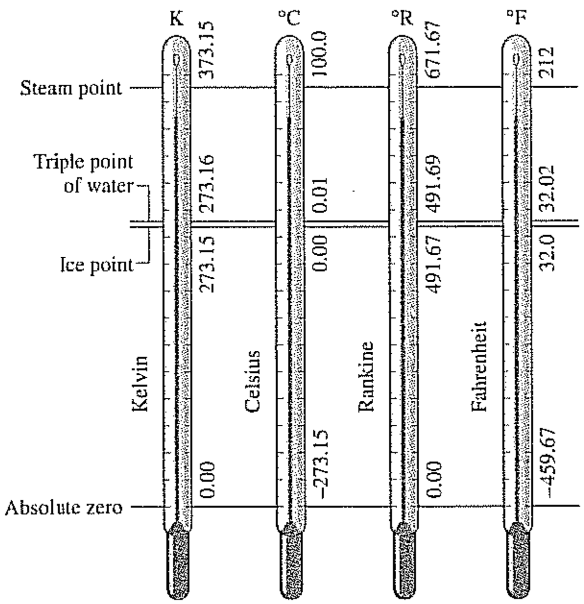


Fig. 1.13 Comparison of temperature scales.

Bio... connections

Cryobiology, the science of life at low temperatures, comprises the study of biological materials and systems (proteins, cells, tissues, and organs) at temperatures ranging from the cryogenic (below about 120 K) to the hypothermic (low body temperature). Applications include freeze-drying pharmaceuticals, cryosurgery for removing unhealthy tissue, study of cold-adaptation of animals and plants, and long-term storage of cells and tissues (called *cryopreservation*).

Cryobiology has challenging engineering aspects owing to the need for refrigerators capable of achieving the low temperatures required by researchers. Freezers to support research requiring cryogenic temperatures in the low-gravity environment of the International Space Station, shown in Table 1.1, are illustrative. Such freezers must be extremely compact and miserly in power use. Further, they must pose no hazards. On-board research requiring a freezer might include the growth of near-perfect protein crystals, important for understanding the structure and function of proteins and ultimately in the design of new drugs.

1.8 Engineering Design and Analysis

An important engineering function is to design and analyze things 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, and evaluation. 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 pinning down 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, etc. 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 would be 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 must also aim to ensure that 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) may also play a part.

engineering model

The first steps in a thermodynamic analysis are definition of the system and identification of the 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 analysis is most effective when it is done systematically. This is considered next.

[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.

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, we strongly recommend that problem solutions be organized using the *five steps* in the box below, which are employed in the solved examples of this text.

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

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

❸ **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.

❹ **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.

❺ **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. Such comments are optional in your solutions.

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:

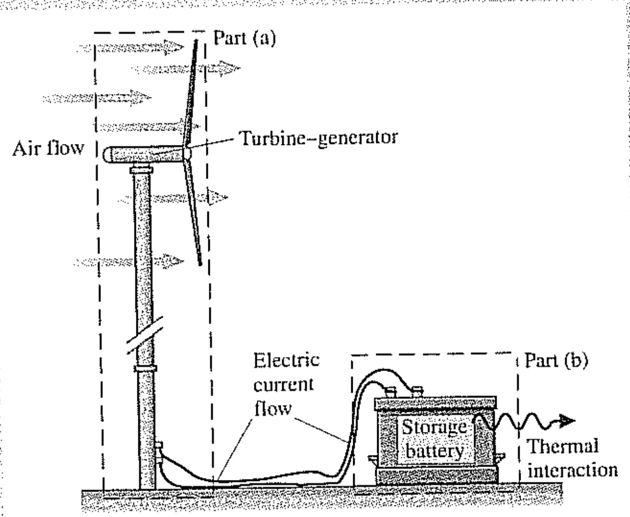


Fig. E1.1

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 change 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.

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* inside the front cover of the book.

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 understand each of the related concepts. The subset of key concepts listed below is particularly important in subsequent chapters.
- ✓ 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.
- ✓ work on a molar basis using Eq. 1.8.
- ✓ identify an appropriate system boundary and describe the interactions between the system and its surroundings.
- ✓ apply the methodology for problem solving discussed in Sec. 1.9.

Key Engineering Concepts

surroundings p. 2
boundary p. 2
closed system p. 2
control volume p. 4
property p. 6
state p. 6
process p. 6
extensive property p. 6
intensive property p. 6
equilibrium p. 7
specific volume p. 11
pressure p. 12
temperature p. 16
Kelvin scale p. 17
Rankine scale p. 18

Key Equations

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

Exercises: things engineers think about

1. Consider a leaf blower driven by a gasoline engine as the system. Would it be best analyzed as a closed system or a control volume? Are there any environmental impacts associated with such a leaf blower? Repeat if it were an *electrically-driven* leaf blower.

2. What components would be required for a high school laboratory project aimed at determining the electricity generated by a hamster running on its exercise wheel?

3. Based on the macroscopic view, a quantity of air at 100 kPa, 20°C is in equilibrium. Yet the atoms and molecules of the air are in constant motion. How do you reconcile this apparent contradiction?

4. Air at 1 atm, 70°F in a closed tank adheres to the continuum hypothesis. Yet when sufficient air has been drawn from the tank, the hypothesis no longer applies to the remaining air. Why?

5. What is a *nanotube*?

6. Can the value of an intensive property such as pressure or temperature be uniform with position throughout a system? Be constant with time? Both?

7. You may have used the mass unit *slug* in previous engineering or physics courses. What is the relation between the slug and pound mass? Is the slug a convenient mass unit?

8. Laura takes an elevator from the tenth floor of her office building to the lobby. Should she expect the air pressure on the two levels to differ much?

9. Are the *systolic* and *diastolic* pressures reported in blood pressure measurements absolute, gage, or vacuum pressures?

10. A data sheet indicates that the pressure at the inlet to a pump is −15 kPa. What does the negative sign denote?

11. When buildings have large exhaust fans, exterior doors can be difficult to open due to a pressure difference between the inside and outside. Do you think you could open a 4- by 7-ft door if the inside pressure were 0.04 lbf/in^2 (vacuum)?

12. How do dermatologists remove pre-cancerous skin blemishes *cryosurgically*?

13. When the instrument panel of a car provides the outside air temperature, where is the temperature sensor located?

Problems: developing engineering skills

Exploring System Concepts

1.1 Using the Internet, obtain information about the operation of an application listed or shown in Table 1.1. Obtain sufficient information to provide a full description of the application, together with relevant thermodynamic aspects. Present your findings in a memorandum.

1.2 As illustrated in Fig. P1.2, water circulates through a piping system, servicing various household needs. Considering the water heater as a system, identify locations on the system boundary where the system interacts with its surroundings and describe events within the system. Repeat for the dishwasher and for the shower. Present your findings in a memorandum.

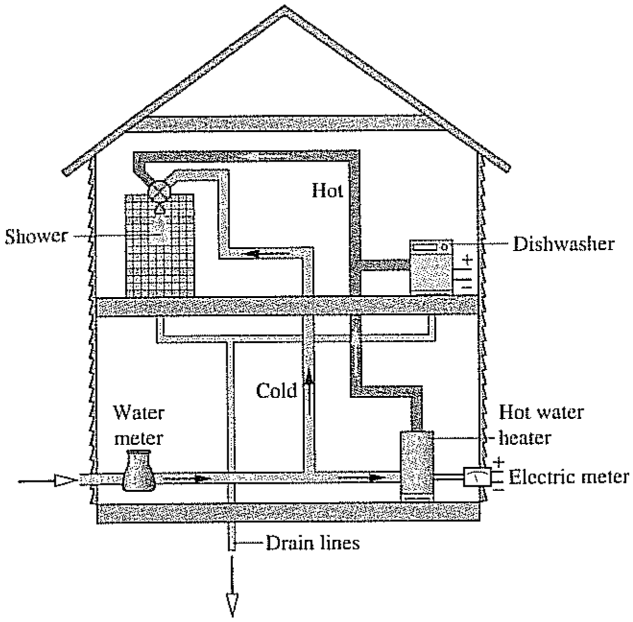

Fig. P1.2

1.3 Reef aquariums such as shown in Fig. P1.3 are popular attractions. Such facilities employ a variety of devices, including heaters, pumps, filters, and controllers, to create a healthy environment for the living things residing in the aquarium, which typically include species of fish, together with corals, clams, and anemone. Considering a reef aquarium as a system, identify locations on the system boundary where the system interacts with its surroundings. Using the Internet, describe events within the system, and comment on measures for the health and safety of the aquatic life. Present your findings in a memorandum.

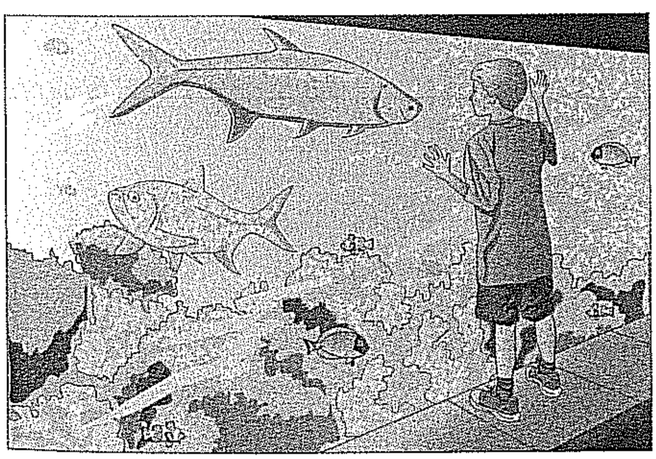

Fig. P1.3

Working with Force and Mass

1.4 An object has a mass of 10 lb. Determine its weight, in lbf, at a location where the acceleration of gravity is 31.0 ft/s^2.

1.5 An object weighs 25 kN at a location where the acceleration of gravity is 9.8 m/s^2. Determine its mass, in kg.

1.6 If Superman has a mass of 100 kg on his birth planet Krypton, where the acceleration of gravity is 25 m/s^2, determine (a) his weight on Krypton, in N, and (b) his mass, in kg, and weight, in N, on Earth where g = 9.81 m/s^2.

1.7 A person whose mass is 150 lb weighs 144.4 lbf. Determine (a) the *local* acceleration of gravity, in ft/s^2, and (b) the person's mass, in lb and weight, in lbf, if g = 32.174 ft/s^2.

1.8 A gas occupying a volume of 25 ft^3 weighs 3.5 lbf on the moon, where the acceleration of gravity is 5.47 ft/s^2. Determine its weight, in lbf, and density, in lb/ft^3, on Mars, where g = 12.86 ft/s^2.

1.9 In severe head-on automobile accidents, a deceleration of 60 g's or more (1 g = 32.2 ft/s^2) often results in a fatality. What force, in lbf, acts on a child whose mass is 50 lb, when subjected to a deceleration of 60 g's?

1.10 Atomic and molecular weights of some common substances are listed in Appendix Tables A-1 and A-1E. Using data from the appropriate table, determine

(a) the mass, in kg, of 10 kmol of each of the following: air, H_2O, Cu, SO_2.

(b) the number of lbmol in 20 lb of each of the following: Ar, H_2, N_2, C.

1.11 When an object of mass 5 kg is suspended from a spring, the spring is observed to stretch by 8 cm. The deflection of the spring is related linearly to the weight of the suspended mass. What is the proportionality constant, in newtons per cm, if g = 9.81 m/s^2?

1.12 A spring compresses in length by 0.12 in. for every 1 lbf of applied force. Determine the deflection, in inches, of the spring caused by the weight of an object whose mass is 15 lb. The local acceleration of gravity is g = 31.4 ft/s^2.

1.13 A simple instrument for measuring the acceleration of gravity employs a *linear* spring from which a mass is suspended. At a location on Earth where the acceleration of gravity is 32.174 ft/s^2, the spring extends 0.291 in. If the spring extends 0.116 in. when the instrument is on Mars, what is the Martian acceleration of gravity? How much would the spring extend on the moon, where g = 5.471 ft/s^2?

1.14 Estimate the magnitude of the force, in lbf, exerted by a seat belt on a 200-lb driver during a frontal collision that decelerates a car from 10 mi/h to rest in 0.1 s. Express the car's deceleration in multiples of the standard acceleration of gravity, or g's.

1.15 An object whose mass is 2 kg is subjected to an applied upward force. The only other force acting on the object is the force of gravity. The net acceleration of the object is upward with a magnitude of 5 m/s^2. The acceleration of gravity is 9.81 m/s^2. Determine the magnitude of the applied upward force, in N.

1.16 An object whose mass is 35 lb is subjected to an applied upward force of 15 lbf. The only other force acting on the object is the force of gravity. Determine the net acceleration of the object, in ft/s^2, assuming the acceleration of gravity is constant, g = 32.2 ft/s^2. Is the net acceleration upward or downward?

1.17 An astronaut weighs 700 N on Earth where g = 9.81 m/s^2. What is the astronaut's weight, in N, on an orbiting space station where the acceleration of gravity is 6 m/s^2? Express each weight in lbf.

1.18 If the variation of the acceleration of gravity, in m/s^2, with elevation z, in m, above sea level is $g = 9.81 - (3.3 \times 10^{-6})z$, determine the percent change in weight of an airliner landing from a cruising altitude of 10 km on a runway at sea level.

1.19 The storage tank of a water tower is nearly spherical in shape with a radius of 30 ft. If the density of the water is 62.4 lb/ft^3, what is the mass of water stored in the tower, in lb, when the tank is full? What is the weight, in lbf, of the water if the local acceleration of gravity is 32.1 ft/s^2?

1.20 As shown in Fig. P1.20, a cylinder of compacted scrap metal measuring 2 m in length and 0.5 m in diameter is suspended from a spring scale at a location where the acceleration of gravity is 9.78 m/s^2. If the scrap metal density, in kg/m^3, varies with position z, in m, according to $\rho = 7800 - 360(z/L)^2$, determine the reading of the scale, in N.

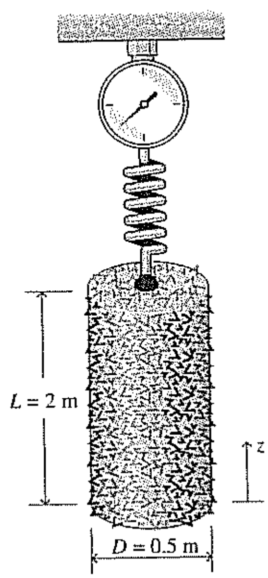

Fig. P1.20

Using Specific Volume and Pressure

1.21 A closed system consists of 0.5 kmol of ammonia occupying a volume of 6 m^3. Determine (a) the weight of the system, in N, and (b) the specific volume, in m^3/kmol and m^3/kg. Let $g = 9.81$ m/s^2.

1.22 A spherical balloon holding 35 lb of air has a diameter of 10 ft. For the air, determine (a) the specific volume, in ft^3/lb and ft^3/lbmol, and (b) the weight, in lbf. Let $g = 31.0$ ft/s^2.

1.23 A closed vessel having a volume of 1 liter holds 2.5×10^{22} molecules of ammonia vapor. For the ammonia, determine (a) the amount present, in kg and kmol, and (b) the specific volume, in m^3/kg and m^3/kmol.

1.24 The specific volume of water vapor at 0.3 MPa, 160°C is 0.651 m^3/kg. If the water vapor occupies a volume of 2 m^3, determine (a) the amount present, in kg and kmol, and (b) the number of molecules.

1.25 Fifteen kg of carbon dioxide (CO_2) gas is fed to a cylinder having a volume of 20 m^3 and initially containing 15 kg of CO_2 at a pressure of 10 bar. Later a pinhole develops and the gas slowly leaks from the cylinder.

(a) Determine the specific volume, in m^3/kg, of the CO_2 in the cylinder initially. Repeat for the CO_2 in the cylinder after the 15 kg has been added.

(b) Plot the amount of CO_2 that has leaked from the cylinder, in kg, versus the specific volume of the CO_2 remaining in the cylinder. Consider v ranging up to 1.0 m^3/kg.

1.26 Go to *http://www.weather.gov* for weather data at three locations of your choice. At each location express the local atmospheric pressure in bar and atmospheres.

1.27 A closed system consisting of 5 kg of a gas undergoes a process during which the relationship between pressure and specific volume is $pv^{1.3} = constant$. The process begins with $p_1 = 1$ bar, $v_1 = 0.2$ m^3/kg and ends with $p_2 = 0.25$ bar. Determine the final volume, in m^3, and plot the process on a graph of pressure versus specific volume.

1.28 A closed system consisting of 2 lb of a gas undergoes a process during which the relation between pressure and volume is $pV^n = constant$. The process begins with $p_1 =$ 20 lbf/in.^{2}, $V_1 = 10$ ft^3 and ends with $p_2 = 100$ lbf/in.^{2}, $V_2 =$ 2.9 ft^3. Determine (a) the value of n and (b) the specific volume at states 1 and 2, each in ft^3/lb. (c) Sketch the process on pressure-volume coordinates.

1.29 A system consists of nitrogen (N_2) in a piston–cylinder assembly, initially at $p_1 = 20$ lbf/in.^{2}, and occupying a volume of 2.5 ft^3. The nitrogen is compressed to $p_2 = 100$ lbf/in.^{2} and a final volume of 1.5 ft^3. During the process, the relation between pressure and volume is linear. Determine the pressure, in lbf/in.^{2}, at an intermediate state where the volume is 2.1 ft^3, and sketch the process on a graph of pressure versus volume.

1.30 A gas initially at $p_1 = 1$ bar and occupying a volume of 1 liter is compressed within a piston–cylinder assembly to a final pressure $p_2 = 4$ bar.

(a) If the relationship between pressure and volume during the compression is $pV = constant$, determine the volume, in liters, at a pressure of 3 bar. Also plot the overall process on a graph of pressure versus volume.

(b) Repeat for a linear pressure–volume relationship between the same end states.

1.31 A gas contained within a piston–cylinder assembly undergoes three processes in series:

Process 1–2: Compression with $pV = constant$ from $p_1 = 1$ bar, $V_1 = 1.0$ m^3 to $V_2 = 0.2$ m^3

Process 2–3: Constant-pressure expansion to $V_3 = 1.0$ m^3

Process 3–1: Constant volume

Sketch the processes in series on a p–V diagram labeled with pressure and volume values at each numbered state.

1.32 As shown in Fig. 1.7, a manometer is attached to a tank of gas in which the pressure is 104.0 kPa. The manometer liquid is mercury, with a density of 13.59 g/cm^3. If $g = 9.81$ m/s^2 and the atmospheric pressure is 101.33 kPa, calculate

(a) the difference in mercury levels in the manometer, in cm.

(b) the gage pressure of the gas, in kPa.

1.33 A vacuum gage at the intake duct to a fan gives a reading of 4.2 in. of manometer fluid. The surrounding atmospheric pressure is 14.5 lbf/in.^{2} Determine the absolute pressure inside the duct, in lbf/in.² The density of the manometer fluid is 49.94 lb/ft³, and the acceleration of gravity is 32.2 ft/s².

1.34 The absolute pressure inside a tank is 0.4 bar, and the surrounding atmospheric pressure is 98 kPa. What reading would a Bourdon gage mounted in the tank wall give, in kPa? Is this a *gage* or *vacuum* reading?

1.35 The barometer shown in Fig. P1.35 contains mercury (ρ = 13.59 g/cm³). If the local atmospheric pressure is 100 kPa and g = 9.81 m/s², determine the height of the mercury column, L, in mmHg and inHg.

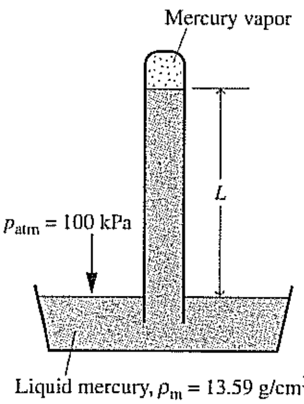

Fig. P1.35

1.36 Water flows through a *Venturi meter*, as shown in Fig. P1.36. The pressure of the water in the pipe supports columns of water that differ in height by 10 in. Determine the difference in pressure between points a and b, in lbf/in.² Does the pressure increase or decrease in the direction of flow? The atmospheric pressure is 14.7 lbf/in.², the specific volume of water is 0.01604 ft³/lb, and the acceleration of gravity is g = 32.0 ft/s².

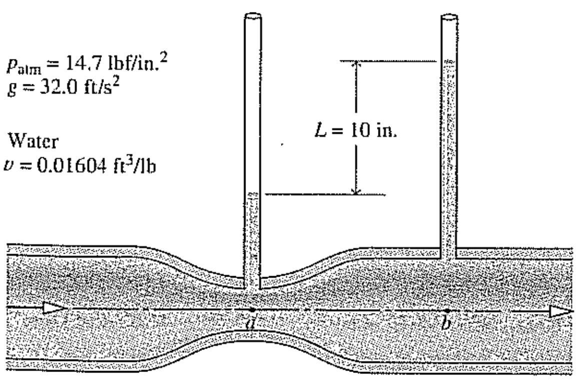

Fig. P1.36

1.37 Figure P1.37 shows a tank within a tank, each containing air. The absolute pressure in tank A is 267.7 kPa. Pressure gage A is located inside tank B and reads 140 kPa. The U-tube manometer connected to tank B contains mercury. Using data on the diagram, determine the absolute pressure inside tank B, in kPa, and the column length L, in cm. The atmospheric pressure surrounding tank B is 101 kPa. The acceleration of gravity is g = 9.81 m/s².

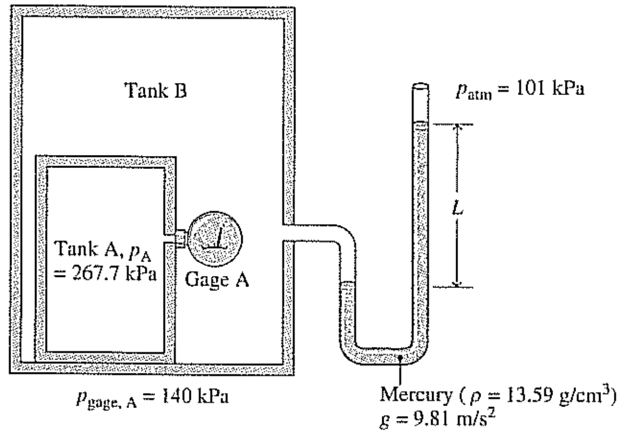

Fig. P1.37

1.38 As shown in Fig. P1.38, an underwater exploration vehicle submerges to a depth of 1000 ft. If the atmospheric pressure at the surface is 1 atm, the water density is 62.4 lb/ft³, and g = 32.2 ft/s², determine the pressure on the vehicle, in atm.

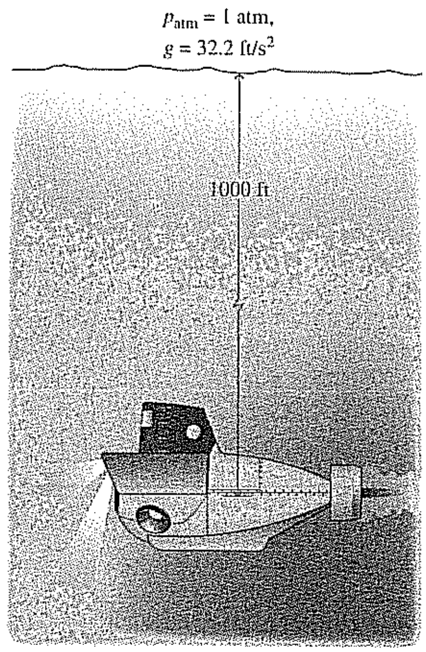

Fig. P1.38

1.39 A vacuum gage indicates that the pressure of carbon dioxide in a closed tank is −10 kPa. A mercury barometer gives the local atmospheric pressure as 750 mmHg. Determine the absolute pressure of the carbon dioxide, in kPa. The density of mercury is 13.59 g/cm³ and g = 9.81 m/s².

1.40 Refrigerant 22 vapor enters the compressor of a refrigeration system at an absolute pressure of 20 lbf/in.² A pressure gage at the compressor exit indicates a pressure of 280 lbf/in.² (gage). The atmospheric pressure is 14.6 lbf/in.² Determine the change in absolute pressure from inlet to exit, in lbf/in.², and the ratio of exit to inlet pressure.

1.41 As shown in Fig. P1.41, air is contained in a vertical piston-cylinder assembly fitted with an electrical resistor. The atmosphere exerts a pressure of 14.7 lbf/in² on the top of the piston, which has a mass of 100 lb and face area of 1 ft^2. As electric current passes through the resistor, the volume of the air increases while the piston moves smoothly in the cylinder. The local acceleration of gravity is $g = 32.0$ ft/s^2. Determine the pressure of the air in the piston-cylinder assembly, in lbf/in^2 and psig.

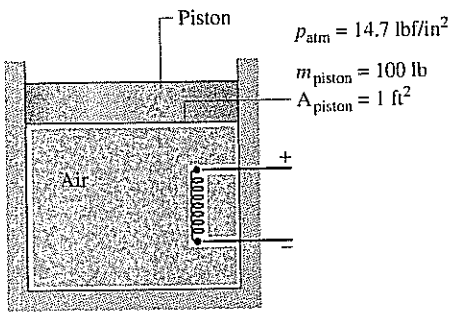

Fig. P1.41

1.42 Warm air is contained in a piston-cylinder assembly oriented horizontally as shown in Fig. P1.42. The air cools slowly from an initial volume of 0.003 m^3 to a final volume of 0.002 m^3. During the process, the spring exerts a force that varies linearly from an initial value of 900 N to a final value of zero. The atmospheric pressure is 100 kPa, and the area of the piston face is 0.018 m^2. Friction between the piston and the cylinder wall can be neglected. For the air in the piston-cylinder assembly, determine the initial and final pressures, each in kPa and atm.

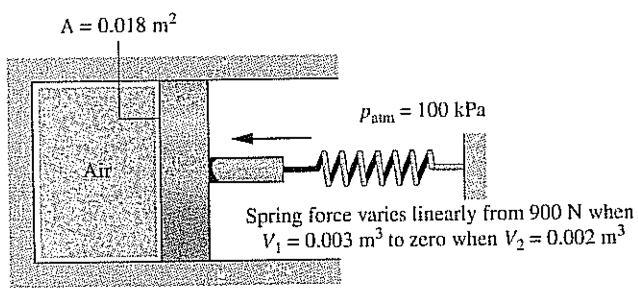

Fig. P1.42

1.43 Air contained within a vertical piston–cylinder assembly is shown in Fig. P1.43. On its top, the 10-kg piston is attached to a spring and exposed to an atmospheric pressure of 1 bar. Initially, the bottom of the piston is at $x = 0$, and the spring exerts a negligible force on the piston. The valve is opened and air enters the cylinder from the supply line, causing the volume of the air within the cylinder to increase by 3.9×10^{-4} m^3. The force exerted by the spring as the air expands within the cylinder varies linearly with x according to

$$F_{spring} = kx$$

where k = 10,000 N/m. The piston face area is 7.8×10^{-3}m^2. Ignoring friction between the piston and the cylinder wall, determine the pressure of the air within the cylinder, in bar, when the piston is in its initial position. Repeat when the piston is in its final position. The local acceleration of gravity is 9.81 m/s^2.

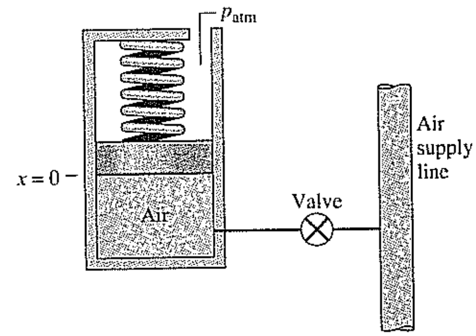

Fig. P1.43

1.44 Determine the total force, in kN, on the bottom of a 100 × 50 m swimming pool. The depth of the pool varies linearly along its length from 1 m to 4 m. Also, determine the pressure on the floor at the center of the pool, in kPa. The atmospheric pressure is 0.98 bar, the density of the water is 998.2 kg/m^3, and the local acceleration of gravity is 9.8 m/s^2.

1.45 The pressure from water mains located at street level may be insufficient for delivering water to the upper floors of tall buildings. In such a case, water may be pumped up to a tank that feeds water to the building by gravity. For an open storage tank atop a 300-ft-tall building, determine the pressure, in lbf/in^2, at the bottom of the tank when filled to a depth of 20 ft. The density of water is 62.2 lb/ft^3, g = 32.0 ft/s^2, and the local atmospheric pressure is 14.7 lbf/in^2.

1.46 As shown in Figure P1.46, an *inclined* manometer is used to measure the pressure of the gas within the reservoir. (a) Using data on the figure, determine the gas pressure, in lbf/in.^{2} (b) Express the pressure as a gage or a vacuum pressure, as appropriate, in lbf/in^2. (c) What advantage does an inclined manometer have over the U-tube manometer shown in Figure 1.7?

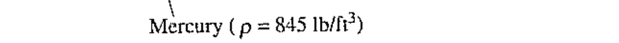

Fig. P1.46

1.47 The variation of pressure within the biosphere affects not only living things but also systems such as aircraft and undersea exploration vehicles.

(a) Plot the variation of atmospheric pressure, in atm, versus elevation z above sea level, in km, ranging from 0 to 10 km. Assume that the specific volume of the atmosphere, in m^3/kg, varies with the local pressure p, in kPa, according to $v = 72.435/p$.

(b) Plot the variation of pressure, in atm, versus depth z below sea level, in km, ranging from 0 to 2 km. Assume that the specific volume of seawater is constant, $v = 0.956 \times 10^{-3}\ \text{m}^3/\text{kg}$.

In each case, $g = 9.81\ \text{m/s}^2$ and the pressure at sea level is 1 atm.

1.48 One thousand kg of natural gas at 100 bar and 255 K is stored in a tank. If the pressure, p, specific volume, v, and temperature, T, of the gas are related by the following expression

$$p = [(5.18 \times 10^{-3})T/(v - 0.002668)] - (8.91 \times 10^{-3})/v^2$$

where v is in m^3/kg, T is in K, and p is in bar, determine the volume of the tank, in m^3. Also, plot pressure versus specific volume for the *isotherms* T = 250, 500, and 1000 K.

1.49 An 82.3-ft^3 tank contains water vapor at 1500 lbf/in.^2 and 1140°R. If the pressure, p, specific volume, v, and temperature, T, of water vapor are related by the expression

$$p = [(0.5954)T/(v - 0.2708)] - (63.36)/v^2$$

where v is in ft^3/lb, T is in °R, and p is in lbf/in.^2, determine the mass of water in the tank. Also, plot pressure versus specific volume for the *isotherms* T = 1200, 1400, and 1600°R.

Exploring Temperature

1.50 Convert the following temperatures from °C to °F: (a) 21°C, (b) −40°C, (c) 500°C, (d) 0°C, (e) 100°C, (f) −273.15°C. Convert each temperature to °R.

1.51 Convert the following temperatures from °F to °C: (a) 68°F, (b) −40°F, (c) 500°F, (d) 0°F, (e) 212°F, (f) −459.67°F. Convert each temperature to K.

1.52 Natural gas is burned with air to produce gaseous products at 1985°C. Express this temperature in K, °R and °F.

1.53 The temperature of a child ill with a fever is measured as 40°C. The child's normal temperature is 37°C. Express both temperatures in °F.

1.54 Does the Rankine degree represent a larger or smaller temperature unit than the Kelvin degree? Explain.

1.55 As shown in Fig. P1.55, a small-diameter water pipe passes through the 6-in.-thick exterior wall of a dwelling. Assuming that temperature varies linearly with position x through the wall from 68°F to 20°F, would the water in the pipe freeze? Explain.

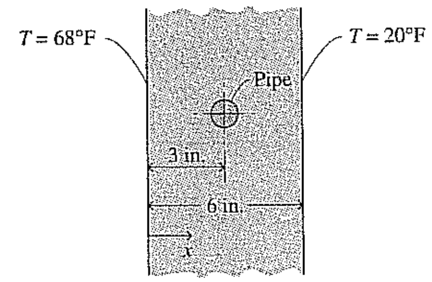

Fig. P1.55

1.56 What is (a) the lowest *naturally* occurring temperature recorded on Earth, (b) the lowest temperature recorded in a laboratory on Earth, (c) the lowest temperature recorded in the Earth's solar system, and (d) the temperature of deep space, each in K?

1.57 What is the maximum increase and maximum decrease in body temperature, each in °C, from a normal body temperature of 37°C that humans can experience before serious medical complications result?

1.58 For liquid-in-glass thermometers, the *thermometric* property is the change in length of the thermometer liquid with temperature. However, other effects are present that can affect the temperature reading of such thermometers. What are some of these?

Design & open ended problems: Exploring engineering practice

1.1D The issue of *global warming* is receiving considerable attention these days. Write a technical report including at least three references on the subject of global warming. Explain what is meant by the term global warming and discuss objectively the scientific evidence that is cited as the basis for the argument that global warming is occurring.

1.2D Barometers and liquid-in-glass thermometers have customarily used mercury, which is now recognized as a biohazard. Investigate medical complications of mercury exposure. Write a report including at least three references.

1.3D List several aspects of engineering economics relevant to design. What are the important contributors to *cost* that should be considered in engineering design? Discuss what is meant by *annualized costs*. Present your findings in a memorandum.

1.4D Determine the respective contributions to the electric power provided to customers by the electric utility serving your locale attributable to coal, natural gas, oil, biomass, nuclear power, hydropower, wind power, and solar power. Summarize your findings in a *pie chart*. For each contribution providing 1%, or more, of the total, identify associated air emissions, solid waste produced, including radioactive waste, and wildlife impacts. Write a report including at least three references.

1.5D Magnetic resonance imaging (MRI) employs a strong magnetic field to produce detailed pictures of internal organs and tissues. As shown in Fig. P1.5D, the patient reclines on a table that slides into the cylindrical opening where the field is created. Considering a MRI scanner as a system, identify locations on the system boundary where the system interacts with its surroundings. Also describe events occurring within the system and the measures taken for patient comfort and safety. Write a report including at least three references.

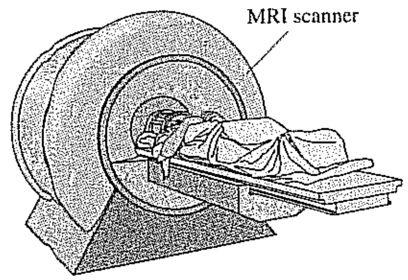

Fig. P1.5D

1.6D The *sphygmomanometer* commonly used to measure blood pressure is shown in Fig. P1.6D. During testing, the cuff is placed around the patient's arm and fully inflated by repeated squeezing of the inflation bulb. Then, as the cuff pressure is gradually reduced, arterial sounds known as *Korotkoff* sounds are monitored with a stethoscope. Using these sounds as cues, the *systolic* and *diastolic* pressures can be identified. These pressures are reported in terms of the mercury column length, in mmHg. Investigate the physical basis for the Korotkoff sounds, their role in identifying the systolic and diastolic pressures, and why these pressures are significant in medical practice. Write a report including at least three references.

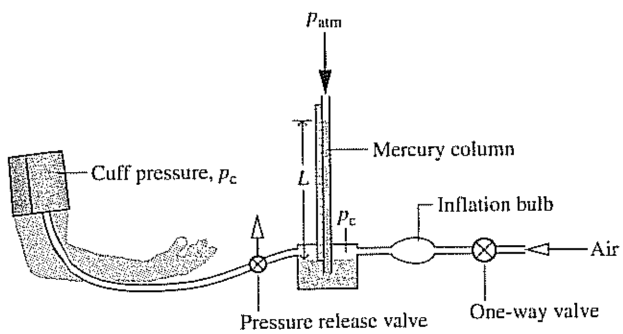

Fig. P1.6D

1.7D Design a low-cost, compact, light-weight, hand-held, human-powered air pump capable of directing a stream of air for cleaning computer keyboards, circuit boards, and hard-to-reach locations in electronic devices. The pump cannot use electricity, including batteries, nor employ any chemical propellants. All materials must be recyclable. Owing to existing patent protections, the pump must be a *distinct alternative* to the familiar tube and plunger bicycle pump and to existing products aimed at accomplishing the specified computer and electronic cleaning tasks.

1.8D In Bangladesh, unsafe levels of arsenic, which is a tasteless, odorless, and colorless poison, are present in underground wells providing drinking water to millions of people living in rural areas. The task is to identify affordable, easy-to-use treatment technologies for removing arsenic from their drinking water. Technologies considered should include, but not be limited to, applications of *smart materials* and other nanotechnology approaches. Write a report including at least three references.

1.9D Conduct a term-length design project in the realm of bioengineering done on either an independent or a small-group basis. The project might involve a device or technique for minimally invasive surgery, an implantable drug-delivery device, a biosensor, artificial blood, or something of special interest to you or your design group. Take several days to research your project idea and then prepare a brief written proposal, including several references, that provides a general statement of the core concept plus a list of objectives. During the project, observe good design practices such as discussed in Sec. 1.3 of *Thermal Design and Optimization*, John Wiley & Sons Inc., New York, 1996, by A. Bejan, G. Tsatsaronis, and M.J. Moran. Provide a well-documented final report, including several references.

1.10D Conduct a term-length design project involving the International Space Station pictured in Table 1.1 done on either an independent or a small-group basis. The project might involve an experiment that is best conducted in a low-gravity environment, a device for the comfort or use of the astronauts, or something of special interest to you or your design group. Take several days to research your project idea and then prepare a brief written proposal, including several references, that provides a general statement of the core concept plus a list of objectives. During the project, observe good design practices such as discussed in Sec. 1.3 of *Thermal Design and Optimization*, John Wiley & Sons Inc., New York, 1996, by A. Bejan, G. Tsatsaronis, and M. J. Moran. Provide a well-documented final report, including several references.