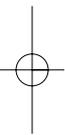
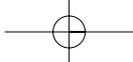


# Fundamentals of Engineering Thermodynamics

Michael J. Moran  
Howard N. Shapiro

**FIFTH EDITION**

SI Units





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# **Fundamentals of Engineering Thermodynamics**

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***Michael J. Moran***

The Ohio State University

***Howard N. Shapiro***

Iowa State University of Science and Technology



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# Preface

In this fifth edition we have retained the objectives of the first four editions:

- ▶ to present a thorough treatment of engineering thermodynamics from the classical viewpoint,
- ▶ to provide a sound basis for subsequent courses in fluid mechanics and heat transfer, and
- ▶ to prepare students to use thermodynamics in engineering practice.

While the fifth edition retains the basic organization and level of the previous editions, we have introduced several enhancements proven to be effective for student learning. Included are new text elements and interior design features that help students understand and apply the subject matter. With this fifth edition, we aim to continue our leadership in effective pedagogy, clear and concise presentations, sound developments of the fundamentals, and state-of-the-art engineering applications.

## New in the Fifth Edition

- ▶ An engaging new feature called **“Thermodynamics in the News”** is introduced in every chapter. *News* boxes tie stories of current interest to concepts discussed in the chapter. The news items provide students with a broader context for their learning and form the basis for new *Design and Open Ended* problems in each chapter.
- ▶ Other class-tested content changes have been introduced:
  - A new discussion of the state-of-the-art of fuel cell technology (Sec. 13.4).
  - Streamlined developments of the energy concept and the *first law of thermodynamics* (Secs. 2.3 and 2.5, respectively).
  - Streamlined developments of the mass and energy balances for a control volume (Secs. 4.1 and 4.2, respectively).
  - Enhanced presentation of second law material (Chap. 5) clearly identifies key concepts.
  - Restructuring of topics in *psychrometrics* (Chap. 12) and *enthalpy of combustion* and *heating values* (Chap. 13) further promotes student understanding.
  - Functional use of color facilitates data retrieval from the appendix tables.
- ▶ End-of-chapter problems have been substantially refreshed. As in previous editions, a generous collection of problems is provided. The problems are classified under headings to assist instructors in problem selection. Problems range from confidence-building exercises illustrating basic skills to more challenging ones that may involve several components and require higher-order thinking.
- ▶ The end-of-chapter problems are organized to provide students with the opportunity to develop engineering skills in three modes:
  - Conceptual.** See *Exercises: Things Engineers Think About*.
  - Skill Building.** See *Problems: Developing Engineering Skills*.
  - Design.** See *Design and Open ended Problems: Exploring Engineering Practice*.
- ▶ The *comfortable* interior design from previous editions has been enhanced with an even more learner-centered layout aimed at enhancing student understanding.

## Core Text Features

This edition continues to provide the core features that have made the text the global leader in engineering thermodynamics education.

- ▶ **Exceptional class-tested pedagogy.** Our pedagogy is the model that others emulate. For an overview, see *How to Use this Book Effectively* inside the front cover of the book.

- ▶ **Systematic problem solving methodology.** Our methodology has set the standard for thermodynamics texts in the way it encourages students to think systematically and helps them reduce errors.
- ▶ **Effective development of the second law of thermodynamics.** The text features the *entropy balance* (Chap. 6) recognized as the most effective way for students to learn how to apply the second law. Also, the presentation of *exergy analysis* (Chaps. 7 and 13) has become the state-of-the-art model for learning that subject matter.
- ▶ **Software to enhance problem solving for deeper learning.** We pioneered the use of software as an effective adjunct to learning engineering thermodynamics and solving engineering problems.
- ▶ **Sound developments of the application areas.** Included in Chaps. 8–14 are comprehensive developments of power and refrigeration cycles, psychrometrics, and combustion applications from which instructors can choose various levels of coverage ranging from short introductions to in-depth studies.
- ▶ **Emphasis on engineering design and analysis.** Specific text material on the design process is included in Sec. 1.7: *Engineering Design and Analysis* and Sec. 7.7: *Thermoeconomics*. Each chapter also provides carefully crafted *Design and Open Ended Problems* that allow students to develop an appreciation of engineering practice and to enhance a variety of skills such as creativity, formulating problems, making engineering judgments, and communicating their ideas.
- ▶ **Flexibility in units.** The text allows an SI or mixed SI/English presentation. Careful use of units and systematic application of unit conversion factors is emphasized throughout the text.

## Ways to Meet Different Course Needs

In recognition of the evolving nature of engineering curricula, and in particular of the diverse ways engineering thermodynamics is presented, the text is structured to meet a variety of course needs. The following table illustrates several possible uses of the text assuming a semester basis (3 credits). Coverage would be adjusted somewhat for courses on a quarter basis depending on credit value. Detailed syllabi for both semester and quarter bases are provided on the Instructor's Web Site. Courses could be taught in the second or third year to engineering students with appropriate background.

Type of course	Intended audience	Chapter coverage
Surveys	Non-majors	<ul style="list-style-type: none"> <li>▶ <u>Principles</u>. Chaps. 1–6.</li> <li>▶ <u>Applications</u>. Selected topics from Chaps. 8–10 (omit compressible flow in Chap. 9).</li> </ul>
	Majors	<ul style="list-style-type: none"> <li>▶ <u>Principles</u>. Chaps. 1–6.</li> <li>▶ <u>Applications</u>. Same as above plus selected topics from Chaps. 12 and 13.</li> </ul>
Two-course sequences	Majors	<ul style="list-style-type: none"> <li>▶ <u>First course</u>. Chaps. 1–8. (Chap. 7 may be deferred to second course or omitted.)</li> <li>▶ <u>Second course</u>. Selected topics from Chaps. 9–14 to meet particular course needs.</li> </ul>



---

## How to Use This Book Effectively

This book has several features that facilitate study and contribute further to understanding:

### ► Examples

- ▶ Numerous annotated solved examples are provided that feature the *solution methodology* presented in Sec. 1.7.3 and illustrated in Example 1.1. We encourage you to study these examples, including the accompanying comments.
- ▶ Less formal examples are given throughout the text. They open with  
▶ **for example...** and close with ◀. These examples also should be studied.

### ► Exercises

- ▶ Each chapter has a set of discussion questions under the heading *Exercises: Things Engineers Think About* that may be done on an individual or small-group basis. They are intended to allow you to gain a deeper understanding of the text material, think critically, and test yourself.
- ▶ A large number of end-of-chapter problems also are provided under the heading *Problems: Developing Engineering Skills*. The problems are sequenced to coordinate with the subject matter and are listed in increasing order of difficulty. The problems are also classified under headings to expedite the process of selecting review problems to solve.  
Answers to selected problems are provided in the appendix (pp. 865–868).
- ▶ Because one purpose of this book is to help you prepare to use thermodynamics in engineering practice, design considerations related to thermodynamics are included. Every chapter has a set of problems under the heading *Design and Open Ended Problems: Exploring Engineering Practice* that provide brief design experiences to help you develop creativity and engineering judgment. They also provide opportunities to practice communication skills.

### ► Further Study Aids

- ▶ Each chapter opens with an introduction giving the engineering context and stating the *chapter objective*.
- ▶ Each chapter concludes with a *chapter summary and study guide* that provides a point of departure for examination reviews.
- ▶ Key words are listed in the margins and coordinated with the text material at those locations.
- ▶ Key equations are set off by a double horizontal bar, as, for example, Eq. 1.10.
- ▶ *Methodology update* in the margin identifies where we refine our problem-solving methodology, as on p. 9, or introduce conventions such as rounding the temperature 273.15 K to 273 K, as on p. 20.
- ▶ For quick reference, conversion factors and important constants are provided on the next page.
- ▶ A list of symbols is provided on the inside back cover and facing page.



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## Constants

**Universal Gas Constant**

$$\bar{R} = 8.314 \text{ kJ/kmol} \cdot \text{K}$$

**Standard Atmospheric Pressure**

$$1 \text{ atm} = 1.01325 \text{ bar}$$

**Standard Acceleration of Gravity**

$$g = 9.80665 \text{ m/s}^2$$

**Temperature Relations**

$$T(^{\circ}\text{C}) = T(\text{K}) - 273.15$$



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## Acknowledgments

We thank the many users of our previous editions, located at more than 200 universities and colleges in the United States and Canada, and over the globe, who contributed to this revision through their comments and constructive criticism. Special thanks are owed to Prof. Ron Nelson, Iowa State University, for developing the *EES* solutions and for his assistance in updating the end-of-chapter problems and solutions. We also thank Prof. Daisie Boettner, United States Military Academy, West Point, for her contributions to the new discussion of fuel cell technology. Thanks are also due to many individuals in the John Wiley and Sons, Inc., organization who have contributed their talents and energy to this edition. We appreciate their professionalism and commitment.

We are extremely gratified by the reception this book has enjoyed, and we have aimed to make it even more effective in this fifth edition. As always, we welcome your comments, criticism, and suggestions.

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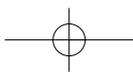
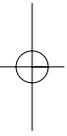
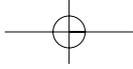
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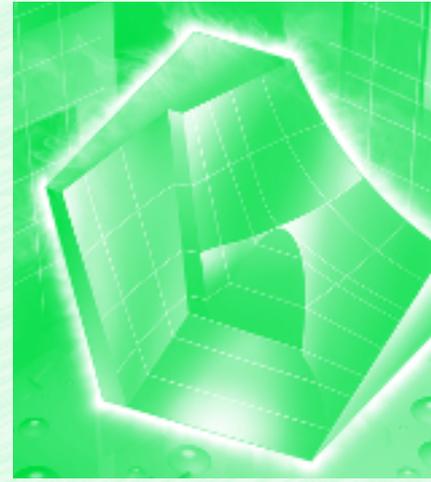
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# *Getting Started: Introductory Concepts and Definitions*

C  
H  
A  
P  
T  
E  
R



◀ chapter objective

## **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.

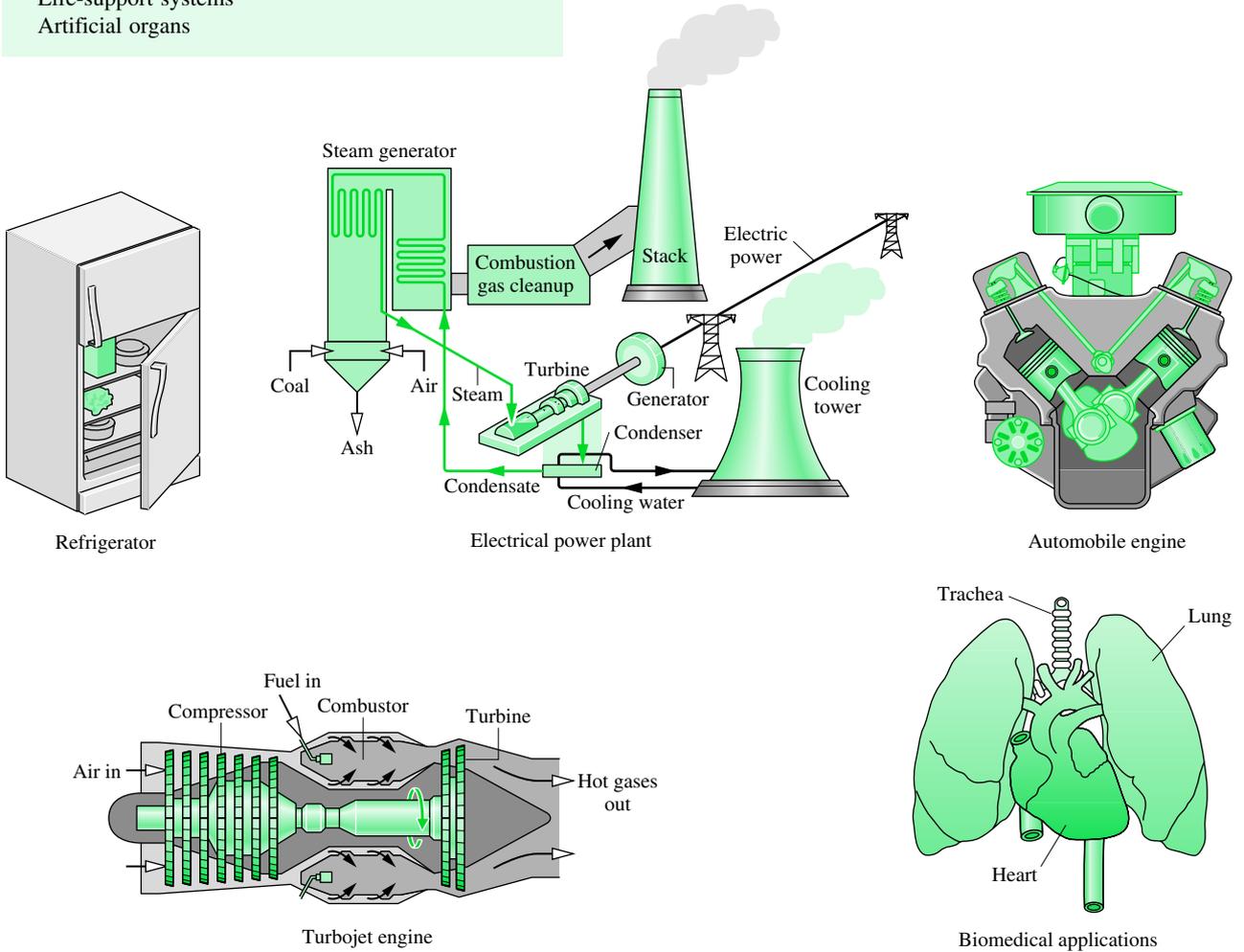
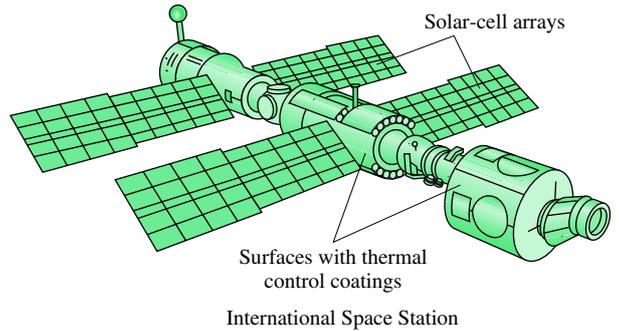
## **1.2 Defining Systems**

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

2 Chapter 1 Getting Started: Introductory Concepts and Definitions

TABLE 1.1 Selected Areas of Application of Engineering Thermodynamics

Automobile engines
Turbines
Compressors, pumps
Fossil- and nuclear-fueled power stations
Propulsion systems for aircraft and rockets
Combustion systems
Cryogenic systems, gas separation, and liquefaction
Heating, ventilating, and air-conditioning systems
Vapor compression and absorption refrigeration
Heat pumps
Cooling of electronic equipment
Alternative energy systems
Fuel cells
Thermoelectric and thermionic devices
Magnetohydrodynamic (MHD) converters
Solar-activated heating, cooling, and power generation
Geothermal systems
Ocean thermal, wave, and tidal power generation
Wind power
Biomedical applications
Life-support systems
Artificial organs



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.

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.

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. It is essential for the 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 is governed by the convenience it allows in the subsequent analysis.

### TYPES OF SYSTEMS

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.

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. The portion of the boundary between the gas and the piston moves with the piston. No mass would cross this or any other part of the boundary.

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.

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*.

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 1.3 shows a sketch of an air compressor connected to a storage tank. The system boundary shown on the figure encloses the compressor, tank, and all of the piping. This boundary might be selected if the electrical power input were

*system*

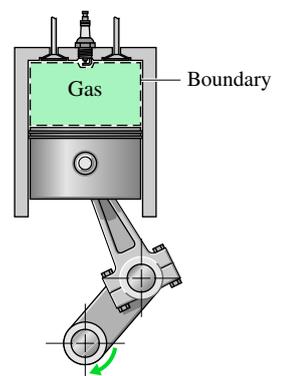
*surroundings*

*boundary*

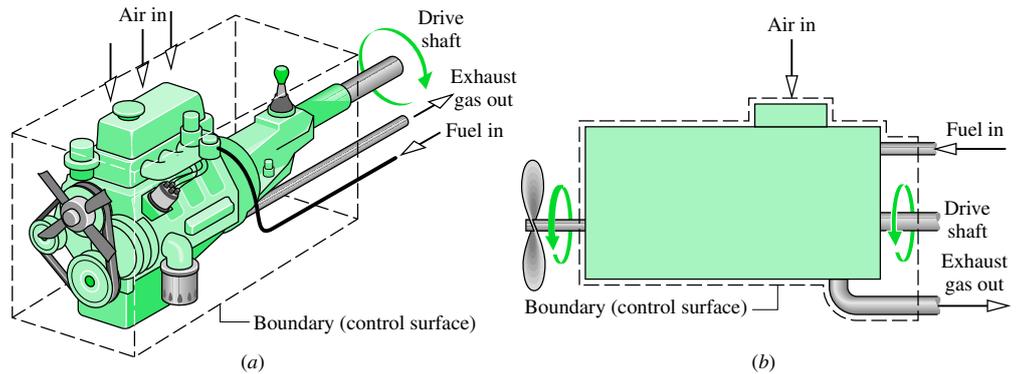
*closed system*

*isolated system*

*control volume*



▲ **Figure 1.1** Closed system: A gas in a piston–cylinder assembly.



▲ **Figure 1.2** Example of a control volume (open system). An automobile engine.

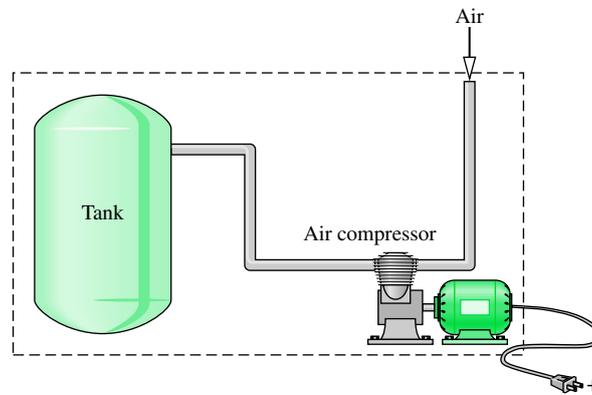
known, and the objective of the analysis were to determine how long the compressor must operate for the pressure in the tank to rise to a specified value. Since mass crosses the boundary, the system would be a control volume. A control volume enclosing only the compressor might be chosen if the condition of the air entering and exiting the compressor were known, and the objective were to determine the electric power input. ◀

### 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.

#### MACROSCOPIC AND MICROSCOPIC VIEWS OF THERMODYNAMICS

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



◀ **Figure 1.3** Air compressor and storage tank.

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. Moreover, the microscopic approach is instrumental in developing certain data, for example, ideal gas specific heats (Sec. 3.6).

For the great majority 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. When it serves to promote understanding, however, concepts are interpreted from the microscopic point of view. Finally, relativity effects are not significant for the systems under consideration in this book.

### PROPERTY, STATE, AND PROCESS

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

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.

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.

A *thermodynamic cycle* is a sequence of processes that begins and ends at the same state. At the conclusion of a cycle all properties have the same values they had at the beginning. Consequently, over the cycle the system experiences no *net* change of state. Cycles that are repeated periodically play prominent roles in many areas of application. For example, steam circulating through an electrical power plant executes a cycle.

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 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.

*property*

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*state*

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*process*

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*steady state*

*thermodynamic cycle*

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**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 of both position and time, whereas extensive properties vary at most with time. Specific volume (Sec. 1.5), pressure, and temperature are important intensive properties; several other intensive properties are introduced in subsequent chapters.

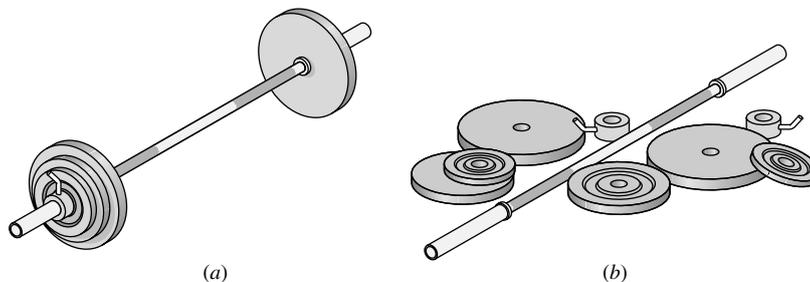
► *for example...* to illustrate the difference between extensive and intensive properties, consider an amount of matter that is uniform in temperature, and imagine that it is composed of several parts, as illustrated in Fig. 1.4. The mass of the whole is the sum of the masses of the parts, and the overall 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. ◀

**PHASE AND PURE SUBSTANCE**phase

The term *phase* refers to a quantity of matter that is homogeneous throughout in both chemical composition and physical structure. Homogeneity in physical structure means that the matter is all *solid*, or all *liquid*, or all *vapor* (or equivalently all *gas*). A system can contain one or more phases. For example, a system of liquid water and water vapor (steam) contains *two* phases. When more than one phase is present, the phases are separated by *phase boundaries*. Note that gases, say oxygen and nitrogen, can be mixed in any proportion to form a *single* gas phase. Certain liquids, such as alcohol and water, can be mixed to form a *single* liquid phase. But liquids such as oil and water, which are not miscible, form *two* liquid phases.

pure substance

A *pure substance* is one that is uniform and invariable in chemical composition. A pure substance can exist in more than one phase, but its chemical composition must be the same in each phase. For example, if liquid water and water vapor form a system with two phases, the system can be regarded as a pure substance because each phase has the same composition. A uniform mixture of gases can be regarded as a pure substance provided it remains a gas and does not react chemically. Changes in composition due to chemical reaction are



▲ **Figure 1.4** Figure used to discuss the extensive and intensive property concepts.

considered in Chap. 13. A system consisting of air can be regarded as a pure substance as long as it is a mixture of gases; but if a liquid phase should form on cooling, the liquid would have a different composition from the gas phase, and the system would no longer be considered a pure substance.

## 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.

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

When a system is isolated, it does not interact with its surroundings; however, its state can change as a consequence of spontaneous events occurring internally as its intensive properties, such as temperature and pressure, tend toward uniform values. When all such changes cease, the system is in equilibrium. Hence, for a system to be in equilibrium it must be a single phase or consist of a number of phases that have no tendency to change their conditions when the overall system is isolated from its surroundings. 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.

## ACTUAL AND QUASIEQUILIBRIUM PROCESSES

There is no requirement that a system undergoing an actual 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. However, even if the intervening states of the system are not known, it is often possible to evaluate certain *overall* effects that occur during the process. Examples are provided in the next chapter in the discussions of *work* and *heat*. Typically, nonequilibrium states exhibit spatial variations in intensive properties at a given time. Also, at a specified position intensive properties may vary with time, sometimes chaotically. Spatial and temporal variations in properties such as temperature, pressure, and velocity can be measured in certain cases. It may also be possible to obtain this information by solving appropriate governing equations, expressed in the form of differential equations, either analytically or by computer.

Processes are sometimes modeled as an idealized type of process called a *quasiequilibrium (or quasistatic) process*. A quasiequilibrium process is one in which the departure from thermodynamic equilibrium is at most infinitesimal. All states through which the system passes in a quasiequilibrium process may be considered equilibrium states. Because nonequilibrium effects are inevitably present during actual processes, systems of engineering interest can at best approach, but never realize, a quasiequilibrium process.

*equilibrium*

*equilibrium state*

*quasiequilibrium process*

Our interest in the quasiequilibrium process concept stems mainly from two considerations:

- ▶ Simple thermodynamic models giving at least *qualitative* information about the behavior of actual systems of interest often can be developed using the quasiequilibrium process concept. This is akin to the use of idealizations such as the point mass or the frictionless pulley in mechanics for the purpose of simplifying an analysis.
- ▶ The quasiequilibrium process concept is instrumental in deducing relationships that exist among the properties of systems at equilibrium (Chaps. 3, 6, and 11).

## 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 may be called *primary dimensions*. The others may be 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.

Two commonly used sets of primary dimensions that suffice for applications in *mechanics* are (1) mass, length, and time and (2) force, 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 the SI system of units.

### ▶ 1.4.1 SI Units

The system of units called SI, 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.

*SI base units*

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

**TABLE 1.2** Units and dimensions for Mass, Length, Time

Quantity	SI		
	Unit	Dimension	Symbol
mass	kilogram	M	kg
length	meter	L	m
time	second	t	s

$F \propto ma$ . 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

$$F = ma \quad (1.1)$$

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

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

► **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  $9.80665 \text{ m/s}^2$ . 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

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

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, say, 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 in Table 1.3.

**TABLE 1.3**

Quantity	Dimensions	Units	Symbol	Name
Velocity	$Lt^{-1}$	m/s		
Acceleration	$Lt^{-2}$	$\text{m/s}^2$		
Force	$MLt^{-2}$	$\text{kg m/s}^2$	N	newtons
Pressure	$ML^{-1}t^{-2}$	$\text{kg m/s}^2 (\text{N/m}^2)$	Pa	pascal
Energy	$ML^2 t^{-2}$	$\text{kg m}^2/\text{s}^2 (\text{N m})$	J	joule
Power	$ML^2 t^{-3}$	$\text{kg m}^2/\text{s}^3 (\text{J/s})$	W	watt

**METHODOLOGY UPDATE**

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

**TABLE 1.4** SI Unit Prefixes

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

Since it is frequently necessary to work with extremely large or small values when using the SI unit system, a set of standard prefixes is provided in Table 1.4 to simplify matters. For example, km denotes kilometer, that is,  $10^3$  m.

### ► 1.4.2 English Engineering Units

Although SI units are the worldwide standard, at the present time many segments of the engineering community in the United States regularly use 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.

## 1.5 Two Measurable Properties: Specific Volume and Pressure

Three intensive properties that are particularly important in engineering thermodynamics are specific volume, pressure, and temperature. In this section specific volume and pressure are considered. Temperature is the subject of Sec. 1.6.

### ► 1.5.1 Specific Volume

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  $\rho$  at a point is defined as

$$\rho = \lim_{V \rightarrow V'} \left( \frac{m}{V} \right) \quad (1.3)$$

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. 1.8, 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

$$m = \int_V \rho dV \quad (1.4)$$

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  $\text{kg}/\text{m}^3$  and  $\text{m}^3/\text{kg}$ , respectively. However, they are also often expressed, respectively, as  $\text{g}/\text{cm}^3$  and  $\text{cm}^3/\text{g}$ .

In certain applications it is convenient to express properties such as a specific volume on a molar basis rather than on a mass basis. The amount of a substance can be given on a

*molar basis* in terms of the kilomole (kmol) or the pound mole (lbmol), as appropriate. In either case we use *molar basis*

$$n = \frac{m}{M} \quad (1.5)$$

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. Appendix Table A-1 provides 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. In this text, the units used for  $\bar{v}$  are m<sup>3</sup>/kmol. With Eq. 1.10, the relationship between  $\bar{v}$  and  $v$  is

$$\bar{v} = Mv \quad (1.6)$$

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

### ► 1.5.2 Pressure

Next, we introduce the concept of pressure from the continuum viewpoint. Let us begin by considering a small area  $A$  passing through a point in a fluid at rest. The fluid on one side of the area exerts a compressive force on it that is normal to the area,  $F_{\text{normal}}$ . 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*

$$p = \lim_{A \rightarrow A'} \left( \frac{F_{\text{normal}}}{A} \right) \quad (1.7)$$

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.

### PRESSURE UNITS

The SI unit of pressure and stress is the pascal.

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

However, in this text it is convenient to work with multiples of the pascal: the kPa, the bar, and the MPa.

$$1 \text{ kPa} = 10^3 \text{ N/m}^2$$

$$1 \text{ bar} = 10^5 \text{ N/m}^2$$

$$1 \text{ MPa} = 10^6 \text{ N/m}^2$$

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

$$1 \text{ standard atmosphere (atm)} = 1.01325 \times 10^5 \text{ N/m}^2$$

*absolute pressure*

Pressure as discussed above is called *absolute pressure*. Throughout this book the term pressure refers to absolute pressure unless explicitly stated otherwise. Although absolute pressures must be used in thermodynamic relations, pressure-measuring devices often indicate the *difference* between the absolute pressure in 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 in the system is greater than the local atmospheric pressure,  $p_{\text{atm}}$ .

*gage pressure*

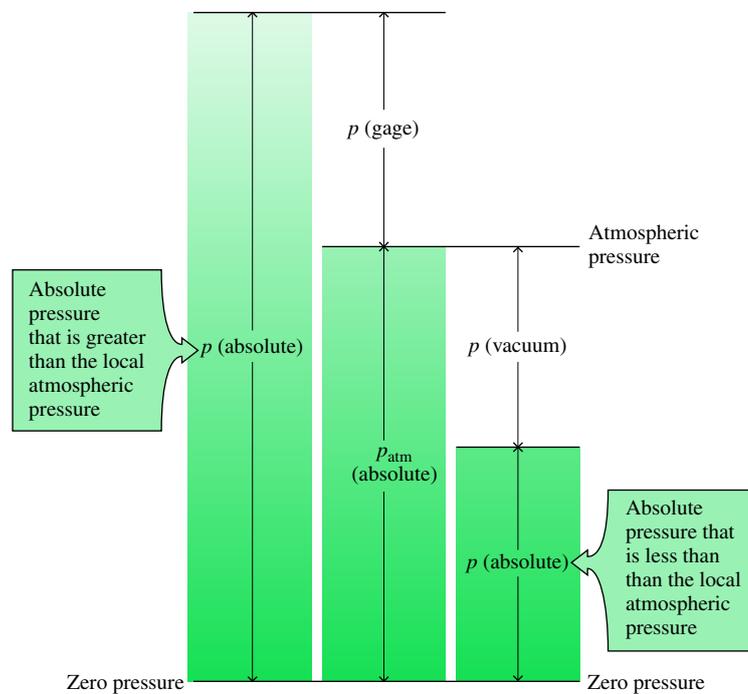
*vacuum pressure*

$$p(\text{gage}) = p(\text{absolute}) - p_{\text{atm}}(\text{absolute}) \quad (1.8)$$

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

$$p(\text{vacuum}) = p_{\text{atm}}(\text{absolute}) - p(\text{absolute}) \quad (1.9)$$

The relationship among the various ways of expressing pressure measurements is shown in Fig. 1.5.



▲ **Figure 1.5** Relationships among the absolute, atmospheric, gage, and vacuum pressures.

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