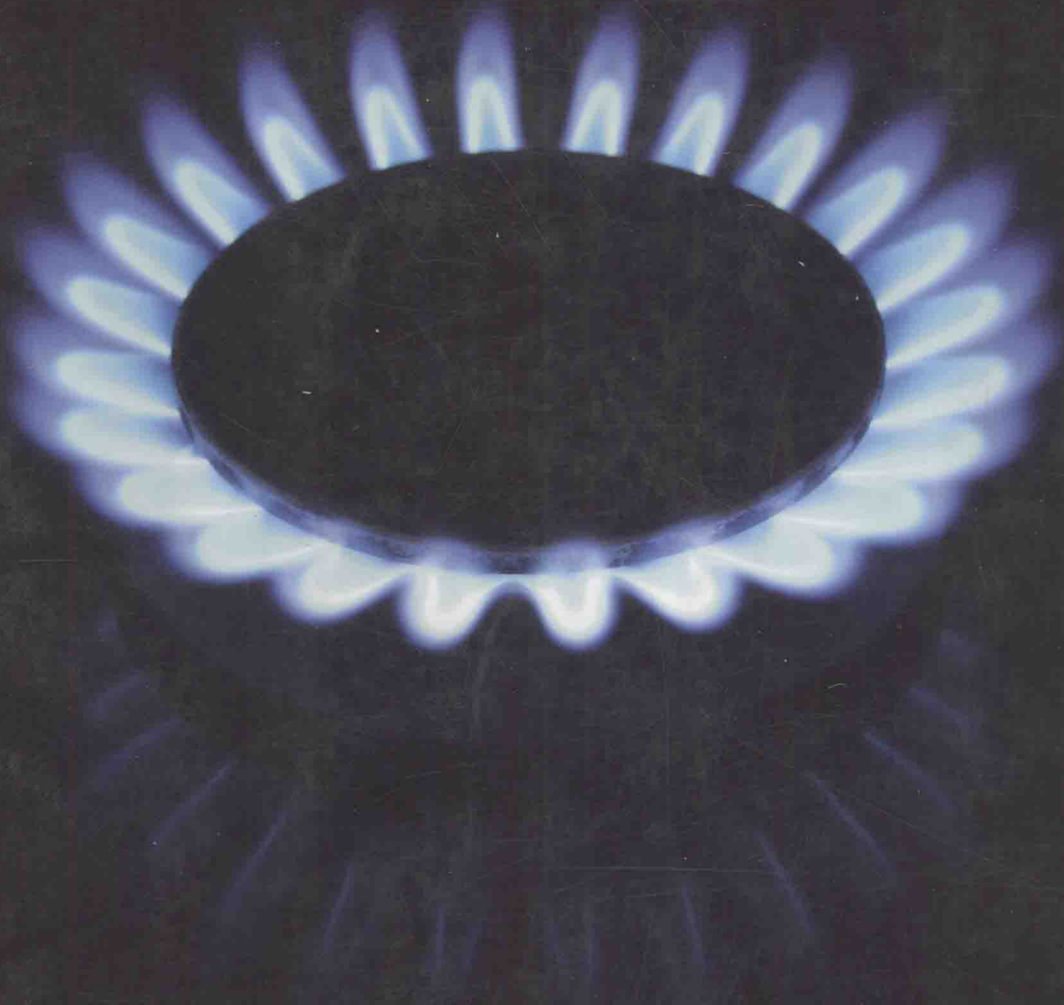
Fundamentals of Engineering Thermodynamics

Michael J. Moran | Howard N. Shapiro

Sixth Edition



SI Version

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Preface

Thermodynamics became a formal area of study in the nineteenth century through consideration of the capacity of hot bodies to produce work. Throughout the twentieth century engineering applications of thermodynamics helped pave the way for increased human well being with advances in major areas such as transportation, power generation, and heating/cooling of buildings. In the twenty-first century, thermodynamics will continue to provide concepts and methods essential for addressing critical societal issues.

Twenty-first century issues where thermodynamics will contribute significantly include using fossil fuels more effectively, fostering renewable energy technologies, and developing more fuel-efficient transportation systems. Other critical areas where thermodynamics will play a role are in mitigating global warming, air pollution, and water pollution. Applications in bioengineering, biomedical systems, and nanotechnology are also emerging. This book provides the tools needed by specialists working in all such fields. For non-specialists, the book provides background for making decisions about technology related to thermodynamics—on the job and as informed citizens.

The sixth edition considers many of these new applications while retaining the basic organization and level of the previous editions. Several enhancements to improve student learning have been introduced. Included are new text elements and interior design features that help students to better understand and apply the subject matter. With this edition we continue our effective pedagogy, clear and concise presentations at a level appropriate for college sophomores and juniors, sound developments of the fundamentals, and state-of-the-art engineering applications.

New in the Sixth Edition

- An engaging 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.
- 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.*

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* on page vii.

- **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.

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	► Principles. Chaps. 1–6. ► Applications. Selected topics from Chaps. 8–10 (omit compressible flow in Chap. 9).
	Majors	► Principles. Chaps. 1–6. ► Applications. Same as above plus selected topics from Chaps. 12 and 13.
Two-course sequences	Majors	► First course. Chaps. 1–8. (Chap. 7 may deferred to second course or omitted.) ► Second course. Selected topics from Chaps. 9–14 to meet particular course needs.

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 on the book companion site: www.wiley.com/go/global/moran.
- ▶ 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 in the back matter.

Conversion Factors

Mass and Density
1 kg = 2.2046 lb

Length
1 cm = 0.3937 in.

Velocity
1 km/h = 0.62137 mile/h

Volume
1 cm^3 = 0.061024 $in.^3$

Force
1 N = 1 kg · m/s^2

Pressure
1 Pa = 1 N/m^2

Energy and Specific Energy
1 J = 1 N · m = 0.73756 ft · lbf

Energy Transfer Rate
1 W = 1 J/s = 3.413 Btu/h

Specific Heat
1 kJ/kg · K = 0.238846 Btu/lb · °R

Constants

Universal Gas Constant
$\overline{R} = 8.314$ kJ/kmol · K

Standard Acceleration of Gravity
$g = 9.80665$ m/s^2

Standard Atmospheric Pressure
1 atm = 1.01325 bar

Temperature Relations
$T(°C) = T(K) - 273.15$

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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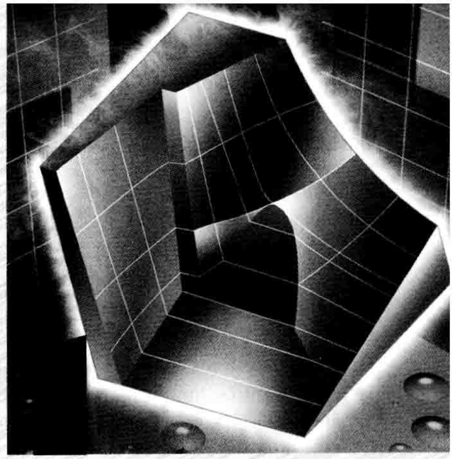
*All available on the book companion site: www.wiley.com/go/global/moran

CHAPTER



Getting Started: Introductory Concepts and Definitions

ENGINEERING CONTEXT The word thermodynamics stems from the Greek words *therme* (heat) and *dynamis* (force). Although various aspects of what is now known as thermodynamics have been of interest since antiquity, the formal study of thermodynamics began in the early nineteenth century through consideration of the motive power of *heat:* the capacity of hot bodies to produce *work*. Today the scope is larger, dealing generally with *energy* and with relationships among the *properties* of matter.

Thermodynamics is both a branch of physics and an engineering science. 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, engineers extend the subject of thermodynamics to the study of systems through which matter flows.

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.

◀ **chapter objective**

1.1 Using Thermodynamics

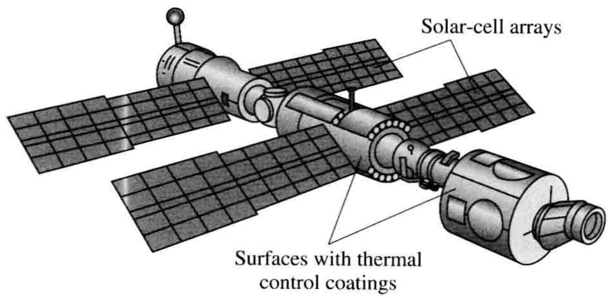
Engineers use principles drawn from thermodynamics and other engineering sciences, such as fluid mechanics and heat and mass transfer, to analyze and design things intended to meet human needs. The wide realm of application of these principles is suggested by Table 1.1, which lists a few of the areas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

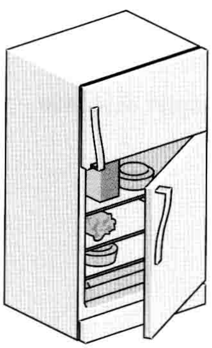
An important step in any engineering analysis is to describe precisely what is being studied. In mechanics, if the motion of a body is to be determined, normally the first step is to define a *free body* and identify all the forces exerted on it by other bodies. Newton's second

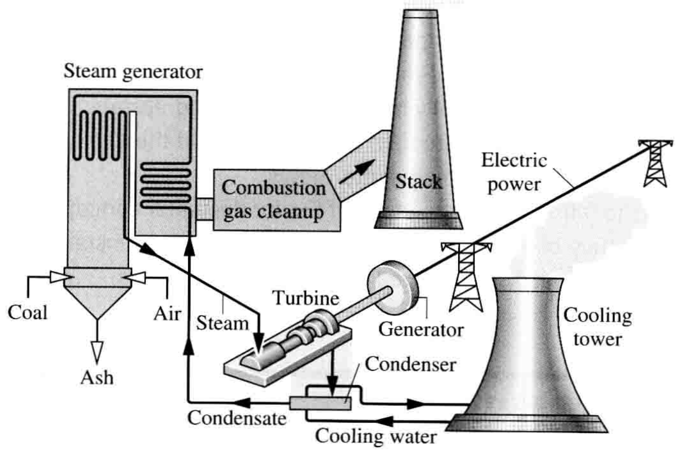
TABLE 1.1 Selected Areas of Application of Engineering Thermodynamics

- 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

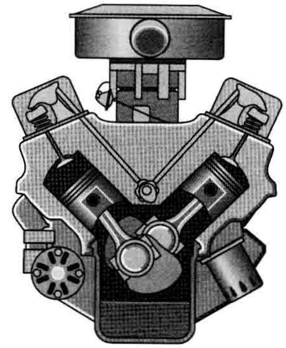


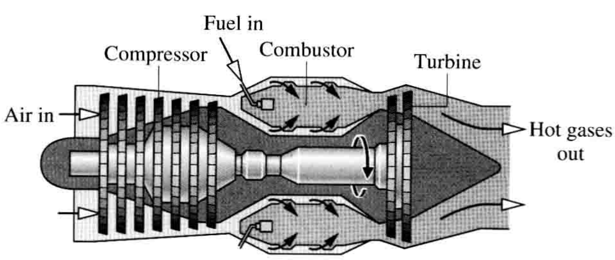
International Space Station


Refrigerator

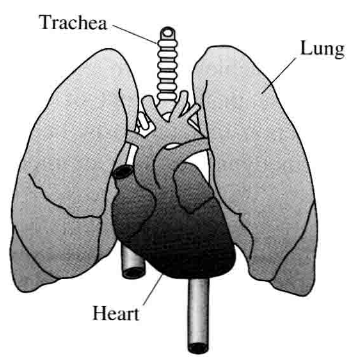


Electrical power plant


Automobile engine



Turbojet engine



Biomedical applications

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. 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.

closed system

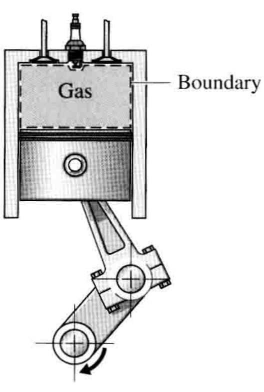
isolated system

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. 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.

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.

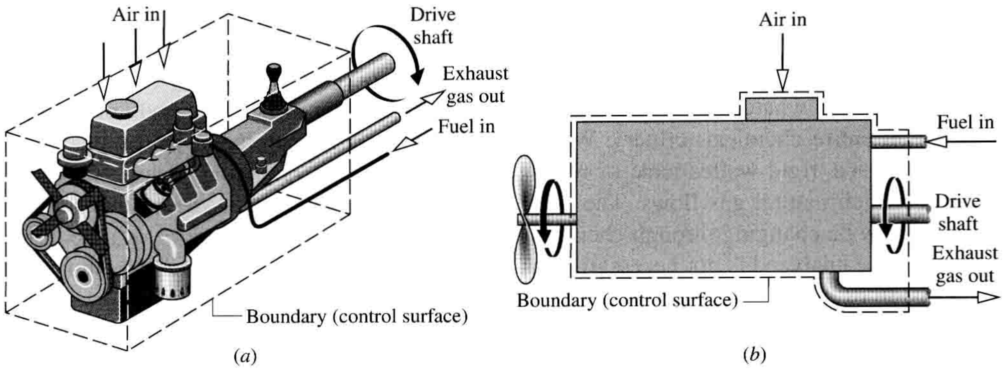


▲ **Figure 1.1** Closed system: A gas in a piston–cylinder assembly.

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



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

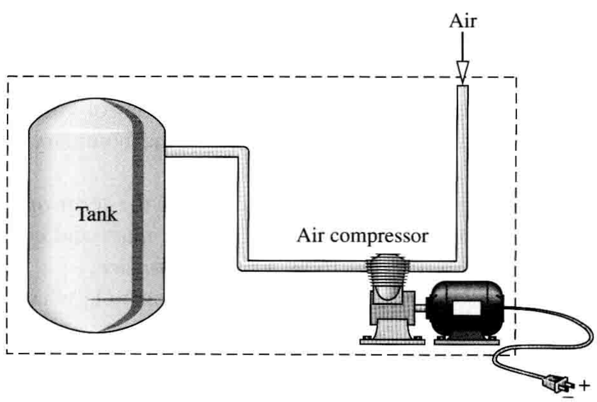
known, and the objective of the analysis were to determine how long the compressor must operate for the pressure in the tank to rise to a specified value. Since mass crosses the boundary, the system would be a control volume. A control volume enclosing only the compressor might be chosen if the condition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

property

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

state

When any of the properties of a system 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.

process

steady state

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.

thermodynamic 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.

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. ◄

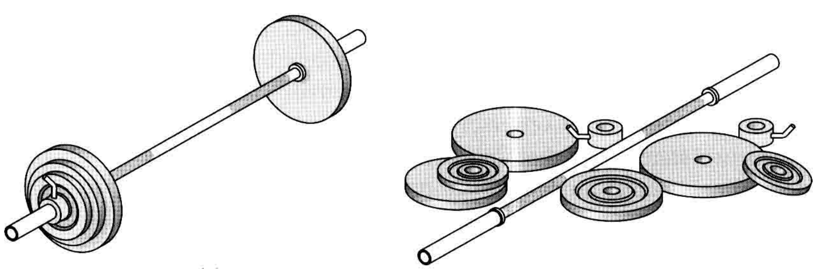
PHASE AND PURE SUBSTANCE

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



(*a*) (*b*)

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