CENGAGE

Principles of ENGINEERING THERMODYNAMICS

2nd Edition

John R. Reisel

CONVERSION FACTORS

Area:	$1\ m^2 = 10^4\ cm^2 = 10^6\ mm^2$
	$1\ m^2 = 10.764\ ft^2$
	$1\ ft^2 = 144\ in^2$
	$1\ ft^2 = 0.092903\ m^2$
Density:	$1\ g/cm^3 = 1000\ kg/m^3$
	$1\ g/cm^3 = 62.428\ lbm/ft^3$
	$1\ lbm/ft^3 = 16.018\ kg/m^3$
Energy:	1 J = 0.73756 ft-lbf
	1 kJ = 737.56 ft-lbf
	1 kJ = 0.9478 Btu
	1 ft-lbf = 1.35582 J
	1 Btu = 778.17 ft-lbf
	1 Btu = 1.0551 kJ
	1 kcal = 4.1868 kJ
Energy Transfer Rate:	1 W = 3.413 Btu/h
	1 kW = 1.341 hp
	1 Btu/h = 0.293 W
	1 hp = 2545 Btu/h
	1 hp = 550 ft-lbf/s
	1 hp = 0.7457 kW
	1 ton of refrigeration = 200 Btu/min
	1 ton of refrigeration = 211 kJ/min
Force:	$1\ N = 1\ kg\text{-}m/s^2$
	1 N = 0.22481 lbf
	1 lbf = 4.4482 N
Length:	1 cm = 0.3937 in.
	1 in. = 2.54 cm
	1 m = 3.2808 ft
	1 ft = 0.3048 m
	1 mile = 1.6093 km
	1 km = 0.62137 mile
Mass:	1 kg = 2.2046 lbm
	1 lbm = 0.4536 kg
Pressure:	$1\ Pa = 1\ N/m^2$
	$1\ Pa = 1.4504 \times 10^{-4}\ lbf/in^2$
	1 atm = 101.325 kPa
	1 bar = 100 kPa
	$1\ lbf/in^2 = 6894.8\ Pa$

$1\ \text{lbf/in}^2 = 144\ \text{lbf/ft}^2$
$1\ \text{atm} = 14.696\ \text{lbf/in}^2$

Specific Energy:

$1\ \text{kJ/kg} = 0.42992\ \text{Btu/lbm}$
$1\ \text{Btu/lbm} = 2.326\ \text{kJ/kg}$

Specific Heat:

$1\ \text{kJ/kg·K} = 0.238846\ \text{Btu/lbm·R}$
$1\ \text{kcal/kg·K} = 1\ \text{Btu/lbm·R}$
$1\ \text{Btu/h·R} = 4.1868\ \text{kJ/kg·K}$

Volume:

$1\ \text{cm}^3 = 0.061024\ \text{in}^3$
$1\ \text{m}^3 = 35.315\ \text{ft}^3$
$1\ \text{L} = 0.001\ \text{m}^3$
$1\ \text{in}^3 = 16.387\ \text{cm}^3$
$1\ \text{ft}^3 = 0.028317\ \text{m}^3$
$1\ \text{gal} = 0.13368\ \text{ft}^3$
$1\ \text{gal} = 0.0037854\ \text{m}^3$

COMMON CONSTANTS

Universal Ideal Gas Constant:

$\bar{R} = 8.314\ \text{kJ/kmol·K}$
$= 1545\ \text{ft-lbf/lbmol·R}$
$= 1.986\ \text{Btu/lbmol·R}$

Standard acceleration due to gravity:

$g = 9.8067\ \text{m/s}^2$
$= 32.174\ \text{ft/s}^2$

Standard Atmospheric Pressure:

$1\ \text{atm} = 101.325\ \text{kPa}$
$= 14.696\ \text{lbf/in}^2$
$= 760\ \text{mm Hg} = 29.92\ \text{in. Hg}$

EE Unit Conversion Constant:

$g_c = 32.174\ \text{lbm-ft/(lbf-s}^2)$

Principles of Engineering Thermodynamics

Second Edition

John R. Reisel
University of Wisconsin – Milwaukee

CENGAGE

Australia • Brazil • Canada • Mexico • Singapore • United Kingdom • United States

CENGAGE

***Principles of Engineering Thermodynamics,* Second Edition**
John R. Reisel

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To my wife Jennifer, and my children Theresa and Thomas—may Thermodynamics continue to provide them with modern wonders.

Contents

Preface

Mission

Why should an engineering student want to study thermodynamics? The answers are all around you. Look at all of the devices that use energy—electric lights, automobiles, computers, smartphones, and so many more. Things that don't directly use energy likely were made by machines that do use energy. In today's world, energy is being used everywhere, and Thermodynamics is the study of energy. Engineers need to know how to use energy effectively. As such, the goal of this book is to prepare students to be practicing engineers with an intuitive understanding of how energy-related systems work and how the performance of such systems is affected by variations in its operational parameters.

While the basic principles and concepts of thermodynamics were developed well over 100 years ago, they are still being used today to analyze and explain how things work in the world. Thermodynamics makes all of today's technology possible, and will continue to power the development of new technology in the future. Therefore, engineers need to have a strong fundamental understanding of thermodynamics in order to continue to develop technology to improve the world.

This textbook is written with the philosophy that it is most important to prepare engineers to understand how to use thermodynamics in professional practice. Engineers must gain an intuitive understanding of how changes in a parameter of a system will impact the energy-related performance of a process. The approach taken in this book is to help students develop this understanding. Throughout the book, students will be asked to use modern computational tools of their choosing to quickly vary the parameters of a system so that they can recognize interactions between features in systems. A historical problem with learning thermodynamics is that it is often taught as a subject that involves only solving individual problems with tabulated property data. Students who learn thermodynamics in such a manner often end up as practicing engineers who do not recognize how various parameters may impact the energy consumption of a piece of equipment or a process. For example, an engineering student may learn in thermodynamics how to solve for the power required to operate an air compressor. However, as a working engineer they may not realize that the energy consumption can be reduced by compressing cold air rather than hot air. As a result, their company may continue to pull hot air from the interior of a factory into the compressor intake, rather than using cold exterior air in the winter, which would waste both energy and money. This book aims to correct this deficiency that has plagued thermodynamics education in the past by encouraging and directing the students to explore the relationships between system parameters.

Special Features of the Book

Emphasis on Computer-based Properties and Equation Solving Platforms

To aid in their understanding of energy relationships, students are strongly encouraged to develop computer-based models of devices, processes, and cycles, and to take advantage of the plethora of Internet-based programs and computer apps for rapidly finding thermodynamic data; these are things that practicing engineers do regularly. Students who are comfortable with a particular equation-solving platform are encouraged to use that platform for their equation development. Some platforms may directly connect into thermodynamic property data, making such platforms potentially easier to use for students already familiar with the platform. Alternatively, an external property-data program can be used to find values for the properties, and these values can be directly input into an equation-solving program. This approach allows students to spend more time focusing on thermodynamics and less time learning a new piece of software.

Parametric Analysis-Based Problems

In keeping with the goal of developing an intuitive understanding of how thermodynamic systems work, many examples and problems throughout the book guide students to perform parametric analyses. These problems are designed to isolate a particular quantity and allow the students to learn how variation of that quantity affects the rest of the system.

Streamlining of Thermodynamic Topics

Another philosophical difference behind this textbook is a streamlining of the material presented in this book in comparison to other thermodynamics books. The content of this book focuses on what is most important for most students to learn about thermodynamics as they strive to become practicing engineers. This is not to say that there are not many other important topics in the subject of thermodynamics. However, the author believes that these topics are more suited for a higher-level engineering thermodynamics course—primarily a course to be taken by students engaged in graduate studies in energy-related areas.

Course Organization

The content of this book is suitable for either a one-semester course or a two-semester course sequence for thermodynamics. For a one-semester course, it is suggested that the material covered be Chapters 1-6, and if time permits some coverage of basic cycles (such as the basic Rankine cycle or the Otto cycle in Chapter 7, or the vapor-compression refrigeration cycle in Chapter 8) may be included. A two-semester sequence would include the remainder of the material in Chapters 7-11 in the second semester of thermodynamics. This second course focuses on applying the basic principles covered in the first course in practical systems. Students who complete only the first course will have a strong understanding of the basic engineering principles of thermodynamics and have some knowledge of the interrelationship between parameters impacting thermodynamic systems. A student who completes two courses will have a much deeper understanding of the relationship between thermodynamics parameters and will be capable of applying thermodynamics in a wide variety of mechanical systems.

This book aims to make thermodynamics enjoyable for students and help them understand the importance of thermodynamics in today's world. Many of the problems facing the world today revolve around the use of energy. Through the use of this book, it is expected that many more engineers will be prepared and eager to help solve these energy-related problems by properly applying the classic concepts of thermodynamics.

New in the Second Edition

A key concept behind this book is to keep the amount of content in the textbook manageable for today's students. As such, many of the changes in the second edition involve editorial changes to the content, with the intent of these changes being to improve the pedagogy of the text.

A new feature found throughout the textbook is "Question for Thought/Discussion." The purpose of these questions is to act as a stimulus for students to think about topics related to Thermodynamics and engineering. The questions are often centered on non-technical concepts. By thinking about and discussing these questions, students will gain insights into how energy use impacts individuals and the world. This will help them understand how engineers may use this information as they design and build. Instructors can either ask students to think about these questions on their own, or they can have class discussions on the topics. An added benefit is that attention paid to these questions should help programs meet the ABET student outcomes.

To address their growing use in many internal combustion engines in hybrid vehicles, a section on the Atkinson and Miller cycles has been added to Chapter 7. While the analysis of these cycles is not tremendously different from more traditional engine cycles, this section will draw attention to the evolving nature of engine design.

Finally, over 100 new end-of-chapter problems have been added to the textbook, offering up a new array of exercises through which students can learn thermodynamics.

Supplements for the Instructor

Supplements to the text include a Solution and Answer Guide that provides complete solutions to the end-of-chapter problems, Lecture Note PowerPoint™ slides, and an image library of all figures in the book. These can be found on the password-protected Instructor's Resources website for the book at login.cengage.com.

Acknowledgments

I would like to acknowledge the helpful comments and suggestions of the many reviewers of this book as it underwent development, including

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- Francisco Ruiz, *Illinois Institute of Technology*
- David Sawyers, *Ohio Northern University*
- Keith Strevett, *University of Oklahoma*
- Victor Taveras, *West Kentucky Community and Technical College*

Their work has helped immensely in improving this book.

I also wish to thank those who taught me thermodynamics, including Charles Marston at Villanova University and Normand Laurendeau at Purdue University. Without their outstanding abilities to teachs thermodynamics, I may never have developed the passion I have for thermodynamics. I also would like to acknowledge my colleagues, both at the University of Wisconsin—Milwaukee and elsewhere, for their thoughtful discussions on thermodynamics education over the years, which helped to form my perspective on how thermodynamics should be taught. This perspective has reached fruition in this book. The students whom I have taught over the years also deserve recognition for their patience as I've experimented with different pedagogical approaches.

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John R. Reisel

About the Author

John R. Reisel is a Professor in the Mechanical Engineering Department at the University of Wisconsin—Milwaukee (UWM). He received his B.M.E., with a minor in Mathematics, from Villanova University, and his M.S. and Ph.D. in Mechanical Engineering from Purdue University. His areas of research interest include combustion, energy usage modeling, energy efficiency, fuel production, sustainable engineering, and engineering education. He has received numerous awards in engineering education, including the UWM Distinguished Undergraduate Teaching Award and the UWM College of Engineering and Applied Science Outstanding Teaching Award. He was also a recipient of the SAE Ralph R. Teetor Educational Award.

Dr. Reisel is a member of the American Society for Engineering Education (ASEE), the American Society of Mechanical Engineers (ASME), the Combustion Institute, the European Society for Engineering Education (SEFI), and the Society of Automotive Engineers (SAE). He has served as division chair of the Engineering and Public Policy Division of ASEE, and program chair of the Technological and Engineering Literacy/Philosophy of Engineering of ASEE. Dr. Reisel is a registered Professional Engineer in the state of Wisconsin.

Digital Resources

CENGAGE | WEBASSIGN

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In addition to common question types such as multiple choice, fill-in-the-blank, essay, and numerical, you can also incorporate robust answer entry palettes (mathPad, chemPad, calcPad, physPad, Graphing Tool) to input and grade symbolic expressions, equations, matrices, and chemical structures using powerful computer algebra systems.

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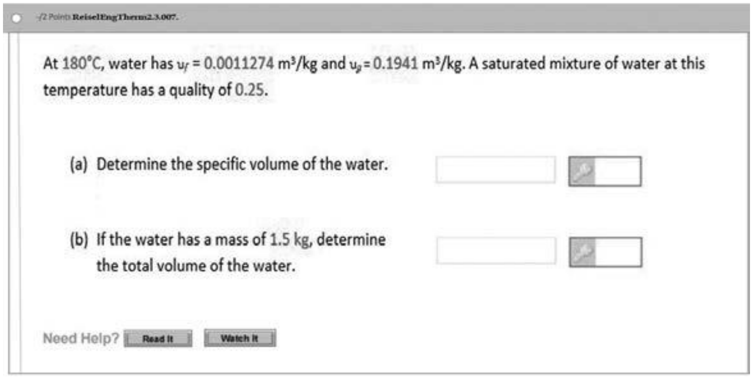

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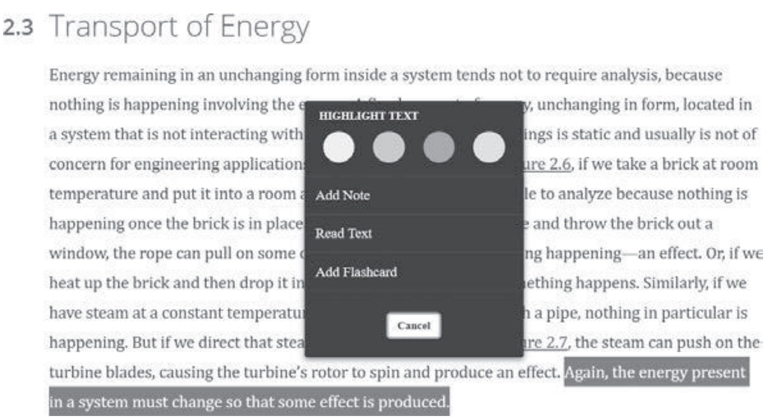

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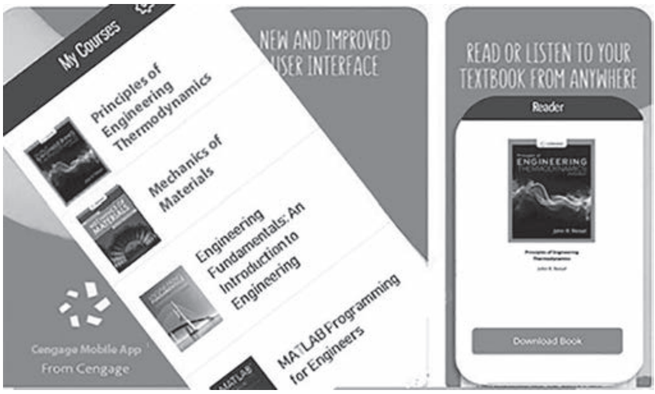

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CHAPTER 1

Introduction to Thermodynamics and Energy

Learning Objectives

Upon completion of Chapter 1, you will be able to:

1.1 Describe what the subject of thermodynamics studies, and identify the types of engineering applications that involve thermodynamics;

1.2 Discuss concepts such as thermodynamic systems, processes, thermodynamic equilibrium, and properties;

1.3 Manipulate different temperature scales;

1.4 Recognize the difference between mass and force;

1.5 Use the basic properties of volume and pressure;

1.6 Explain and apply the Zeroth Law of Thermodynamics; and

1.7 Identify the different phases of matter.

Look around you. What do you see? You probably see people and things in motion, electrical devices in operation, and comfortable buildings. What you are seeing is energy being used. The use of energy is so commonplace that most people don't even notice it until it is unavailable, such as during an electrical power outage in a storm, or when an automobile runs out of fuel, or when someone is weak due to a lack of food. Anything that moves needs some energy to do so. Anything that is powered by electricity needs energy. Even the earth as a whole needs energy from the sun to stay warm and for life to flourish. The world as we know it exists because of energy in action.

If you have been even casually following the news in recent years, you have probably seen stories involving energy in the world. Stories on the rising costs and stressed supplies of petroleum or electricity are common. There are serious concerns over the effects on the environment caused by the rising levels of carbon dioxide (CO_2) in the atmosphere produced through the burning of fossil fuels. As people seek new, cleaner sources of energy, we see wind turbines rising across the world and solar panels appearing in locations that have rarely seen the use of such technology. The price and availability of energy, as well as how its use impacts the environment, is increasingly important to society.

Yet the demand that humans have for energy is at its greatest level ever. Not only are there more people than ever before, but people worldwide want the goods and standard of living associated with the wealthiest nations. People want ready access to transportation, and transportation systems require energy. People want buildings heated and cooled to the desired comfort level, and this requires energy. Factories use prodigious amounts of energy to produce the products that people want. Growing and transporting food requires energy. The demand for energy has never been higher, and it is likely to keep growing.

It can even be said that the harnessing of energy sources has been a key element in the development of civilization. **Figure 1.1** shows a number of examples of how the use of energy by people has developed over time. People learned how to control fire for heating and cooking. People harnessed the power of wind to pump water. Engines were developed to allow the chemical energy in a fuel to do useful work for us. Humans even learned how to unleash the power locked inside atoms to generate electricity. In the future, we don't know how humans will use the energy present in nature all around us, but it is likely that new means of harnessing energy will be needed to keep the development of civilization moving forward.

Engineers play a key role in creating systems that convert energy from one form to another, usually taking energy in a form that is otherwise rather useless and transforming

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SpaceKris/Shutterstock.com

FIGURE 1.1 Various images showing the application of energy by humans throughout history: a fire, a windmill, an automobile engine, and a nuclear power plant.

it so that people can use it to do something productive. For example, the energy bound up in the molecules that make up the fluid called "gasoline" is of little use as is. But if the gasoline is ignited with air in a combustion process, large amounts of heat can be released, and this heat can be used to create a high-temperature, high-pressure gas that can push on a piston in an engine, as shown in **Figure 1.2**; the work produced can be used to propel a vehicle forward. Engineers also play a key role in designing systems that use energy efficiently. Engineers can create devices that use less energy to accomplish the same task, and by using less energy these devices save consumers money. Furthermore, more efficient devices reduce the overall demand for more energy. For example, even a technology as widespread as lighting, illustrated in **Figure 1.3**, has seen dramatic improvements in energy efficiency. Light-emitting diode (LED) lights can be six times more efficient than incandescent bulbs and 40% more efficient than compact fluorescent lights, and last much longer than either technology. If engineers are to develop means of using energy efficiently while benefiting humankind significantly, they must understand the basic science behind energy.

Thermodynamics is the science of energy. If you look at the original Greek roots of the word, *thermos* means "heat" and *dynamikos* means "power"—and power applied to an object produces movement. Thermodynamics is the power of heat, or the movement of heat. As our understanding of energy has evolved, we recognize that energy involves more than just heat, and, as such, thermodynamics is considered the science of all energy. In engineering, we use thermodynamics to understand how energy is transformed from one form to another to accomplish a given purpose. Thus, we will be exploring not only the basic laws that describe thermodynamics but also the technology that is employed to accomplish tasks using energy.

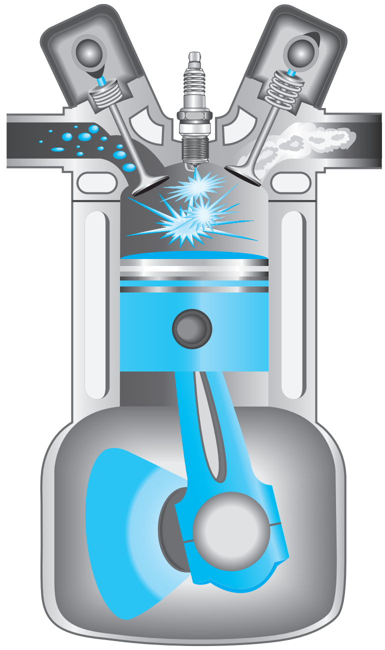

FIGURE 1.2 A cutaway image of an internal-combustion engine cylinder.

FIGURE 1.3 Examples of lighting technology: an incandescent light bulb, a compact fluorescent fixture, and an LED bulb.

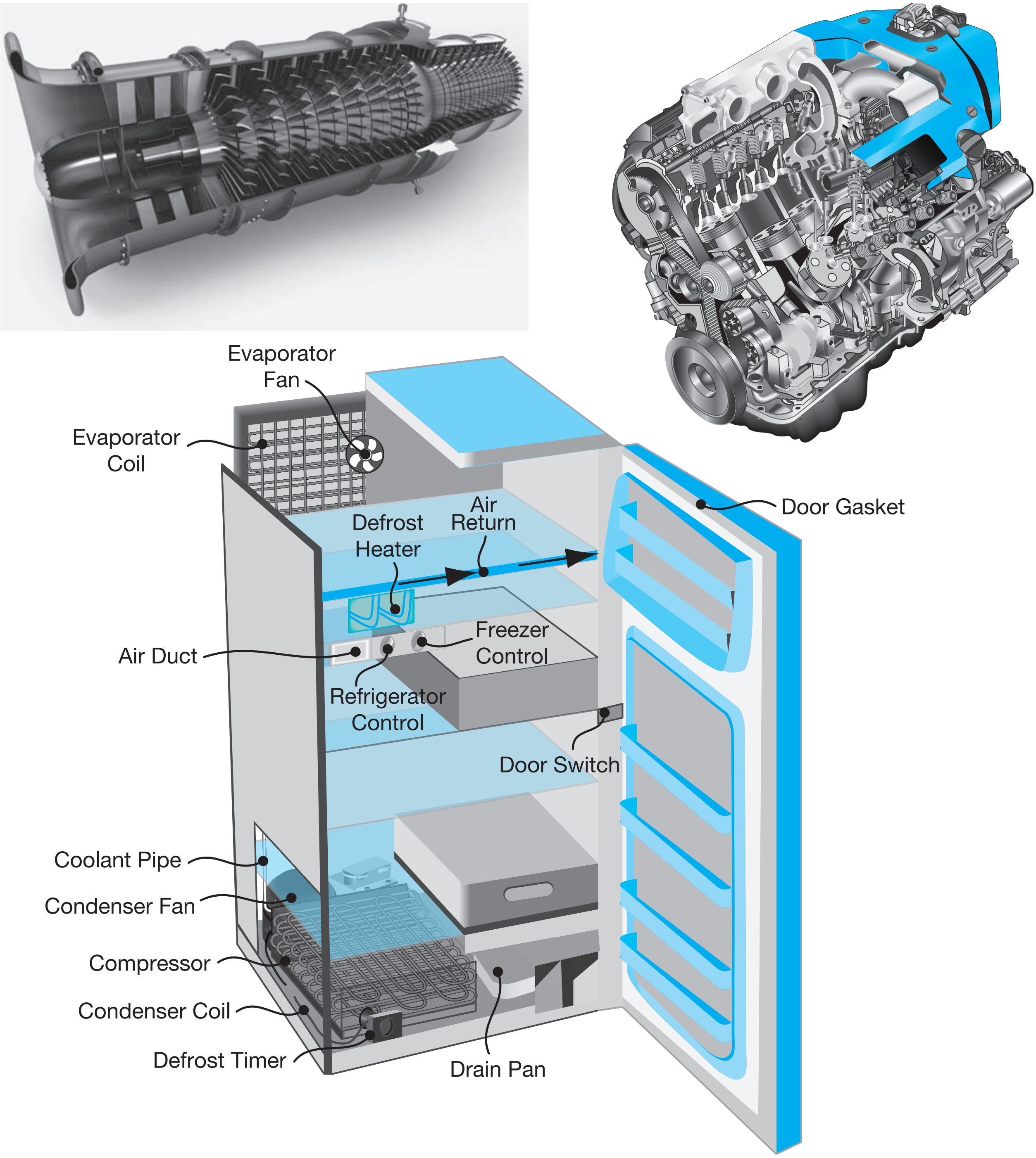

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FIGURE 1.4 Cutaway images of common energy-related technology: a gas turbine engine, a reciprocating engine, and a refrigerator.

Figure 1.4 shows many applications in the world today, developed by engineers, that use energy and for which thermodynamics is an integral design component. Turbines are used to transform the energy in a working fluid into a rotational motion of a shaft that in turn produces electricity in a generator. The turbines take in a high-energy gas or vapor (which generally has a high temperature and pressure) and extract energy from that fluid to produce the work needed to turn the shaft (also known as a rotor). A low-energy fluid is exhausted from the turbine. An automobile engine takes high-temperature, high-pressure gases (formed from the combustion of fuel in air, which releases the chemical energy bound up in the fuel) and has these gases push on a piston. The piston then drives the crankshaft, which transmits power to the wheels, thus moving the vehicle forward. Cooler, lower pressure gases exit from the cylinder after their energy had been extracted.

A refrigerator is used to keep food cool. It accomplishes this by taking electrical power and using this power to operate a compressor that increases the pressure of a vapor. Before the vapor is compressed, it is cooler than the interior of the refrigerator, and so it can remove heat from inside the refrigerator to cool the interior. After it is compressed, the vapor is hotter than the room temperature, and it is able to release the excess heat to the air outside the refrigerator. So, in this case, electrical power is used to change the state of the refrigerant so that it can accomplish the task of moving energy from a cooler space inside the refrigerator to a warmer space outside the refrigerator.

There are a vast number of devices and systems that are encountered every day that use thermodynamics to some extent, some of which are shown in **Figure 1.5**. A furnace to heat a building, an air conditioner to cool a building, the radiator on an engine, the sun heating the earth, a light bulb illuminating (and heating) a room, a bicycle being ridden, and a computer generating heat while performing its tasks are all such examples. All around you, energy is changing forms. Energy is moving throughout the world. Thermodynamics describes these energy motions and transformations. Although conventional thermodynamic analysis is not needed to analyze many things in everyday life, keep in mind that thermodynamics is fundamental to how the world functions.

Thermodynamics, and thermodynamic analysis, is defined by four scientific laws. These laws will be introduced when appropriate throughout the book. Scientific laws are not absolutely proven principles, but rather are concepts that are well established through observation and have never been shown to be incorrect. Occasionally, a law may need to be refined as our knowledge of the world deepens, but the basic principle usually remains unchanged. (For example, the law of the conservation of energy had to be modified to include mass for nuclear processes when Einstein showed that mass and energy were equivalent.) If one of the four laws upon which thermodynamics is based is ever shown to be incorrect, future scientists and engineers will need to reformulate the basics upon which thermodynamics rests. However, this is extremely unlikely.

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FIGURE 1.5 Examples of thermodynamics in the world today: an industrial furnace, the sun heating the earth, and human-powered bicycles.

Thermodynamics is one of the basic sciences that engineers use daily as they apply scientific principles to solve problems to aid humanity. This doesn't mean that every engineer will be performing thermodynamic analyses every day of his or her career, but some engineers do frequently design and analyze devices and processes by relying on the principles of thermodynamics. Others will only occasionally need to invoke thermodynamic principles in their careers. Still others rarely use thermodynamics directly, but thermodynamics still informs their work and may influence their work in ways that are not immediately apparent. As such, it is important for all engineers to be fluent in the basics of thermodynamics.

Before we can explore the principles of thermodynamics, we must first define and describe a number of basic concepts upon which our subsequent presentations will be based. This is the focus of the next section.

1.1 BASIC CONCEPTS: SYSTEMS, PROCESSES, AND PROPERTIES

1.1.1 The Thermodynamic System

At the basis of all thermodynamic analysis is a construct known as the ***thermodynamic system***. A thermodynamic system is the volume of space that contains the object(s) that are the focus of the thermodynamic analysis. The system is defined by the person performing the analysis and should be made as simple as possible. Unnecessary complexity should be avoided because it will either result in an incorrect analysis or will lead to significant amounts of additional work on the part of the person performing the analysis.

As shown in **Figure 1.6**, a thermodynamic system is delineated by a system boundary; everything inside the system boundary (which we will represent with a dashed line) is the system, and everything outside the boundary is considered the *surroundings*. **Figure 1.7** shows several possible systems that could all be considered the system for analyzing a particular problem. The quantity to be determined is the amount of heat needed to heat liquid water in a kettle on a stove. In Figure 1.7a, the system is proposed to be only the water in the kettle. In Figure 1.7b, the system is proposed to be the water and the kettle. In Figure 1.7c, the system is proposed to be the water, kettle, and the air above the water inside the pot. All three of these systems could be used to analyze the problem. However, the systems in (b) and (c) add complexity to the fundamental problem of determining the amount of heat that is added to the

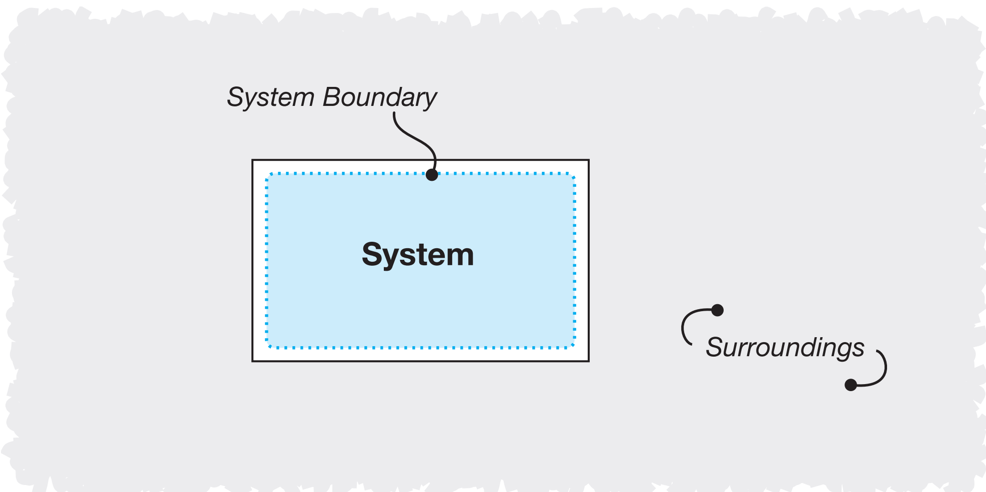

FIGURE 1.6 Example of a thermodynamic system, the system boundary (represented by a dashed line), and the surroundings.

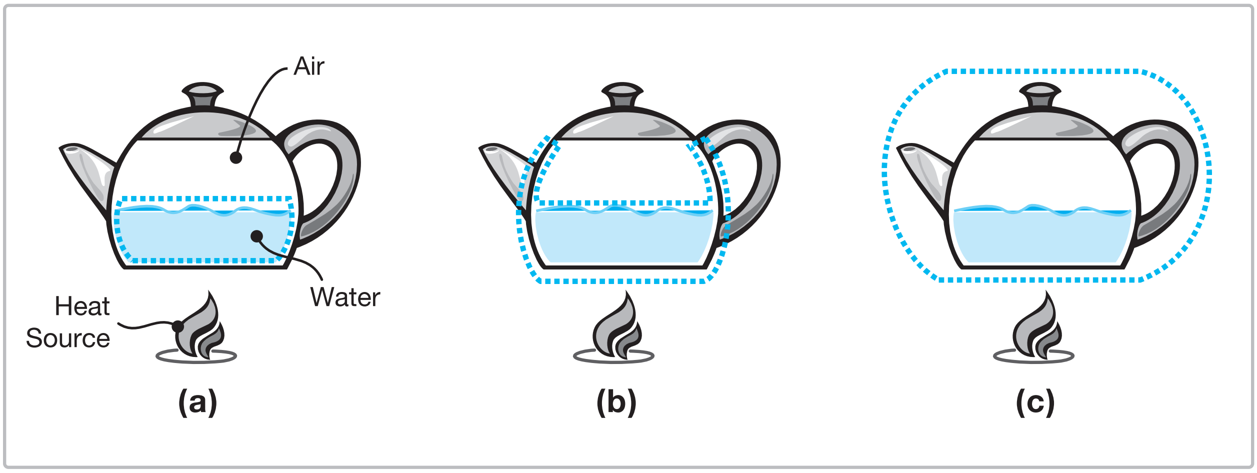

FIGURE 1.7 Examples of how the choice of the thermodynamic system changes the problem to be analyzed: (a) the system as only the water, (b) the system as the water and kettle, and (c) the system as the kettle, its contents, and its immediate surroundings.

water alone. In system (b), we would need to determine how much heat was added to both the water and the kettle, and then further analysis would be needed to determine how much heat was added to the water itself. In system (c), the problem would be further complicated by needing to determine how much heat was also added to the air, and then again separating out only the heat added to the water. So, although all three systems could be used for the problem, it is best to take care when defining the extent of the system so that the smallest volume possible is used in the analysis. This will reduce the amount of extra work that is necessary for finding the solution.

There are three types of systems; the types of systems are differentiated by whether or not mass and/or energy can cross the system boundary:

Isolated System: Neither mass nor energy can cross the system boundary.
Closed System: Energy can cross the system boundary, but mass cannot.
Open System: Both mass and energy can cross the system boundary.

Sometimes, a closed system is referred to as a "control mass," whereas sometimes an open system is referred to as a "control volume." However, in this book we will refer to each by the name of "closed" or "open" system, respectively.

In determining what type of system is to be employed for an analysis, we need to consider the important characteristics of the problem on the time scale likely to be employed. It is likely that given enough time, some small amount of mass may diffuse across the solid boundary of a closed system; however, if the amount of mass flowing across the system boundary is negligible over the time frame of the problem, it is likely best to view the system as a closed system. For example, if we have a bicycle tire filled with air, and the tire has no obvious leaks, it is safe to treat the system as a closed system if the time period under consideration is no more than a day or two. But if we are considering the tire over the course of a year, we may need to consider the impact of air very slowly leaving the tire—which would make it an open system.

Isolated systems will play a minor role in this book but are important in more advanced thermodynamics studies. One type of system that could be considered an isolated system is an insulated thermos bottle, after it has been closed, as shown in **Figure 1.8**. Suppose the bottle is filled with hot coffee at the start of the day. The bottle is closed, and then a short time later the bottle is opened and some coffee is poured out. The conditions of the coffee would change

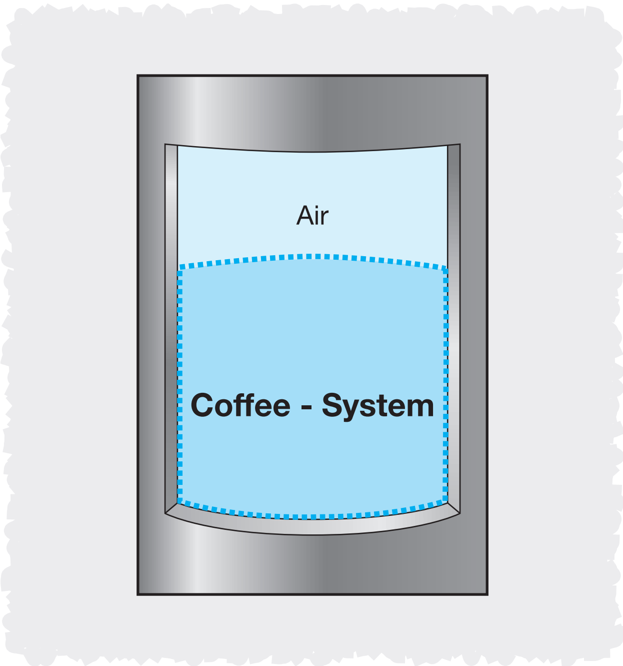

FIGURE 1.8 A cutaway diagram of an insulated bottle containing coffee and air, with the system being only the coffee.

little in that short time, and so between the time that the bottle was filled and the time when some coffee was poured out, the bottle could be considered an isolated system (as neither mass nor energy crossed the system boundary). The coffee would cool at a rate that is slow enough that the energy leaving the bottle could be ignored for relatively short periods of time. Although the choice of an isolated system may work well for a half hour or hour time duration, the system would probably be a poor choice for analyzing the coffee over the time period of a day. Over that longer period of time, the coffee will noticeably cool, and a closed system would be a better choice for modeling the system.

Another example of an isolated system is the entire universe, although performing a thermodynamic analysis of the entire universe is beyond the scope of this book. As far as we understand the universe, it contains all of the mass and energy that exists, and so mass and energy cannot cross the system boundary.

There are many more practical examples of closed systems, and some of these are shown in **Figure 1.9**. Solid objects generally are considered closed systems, unless they are specifically losing mass. A liquid or gas inside a closed container also is typically viewed as a closed system. The contents inside objects such as sealed

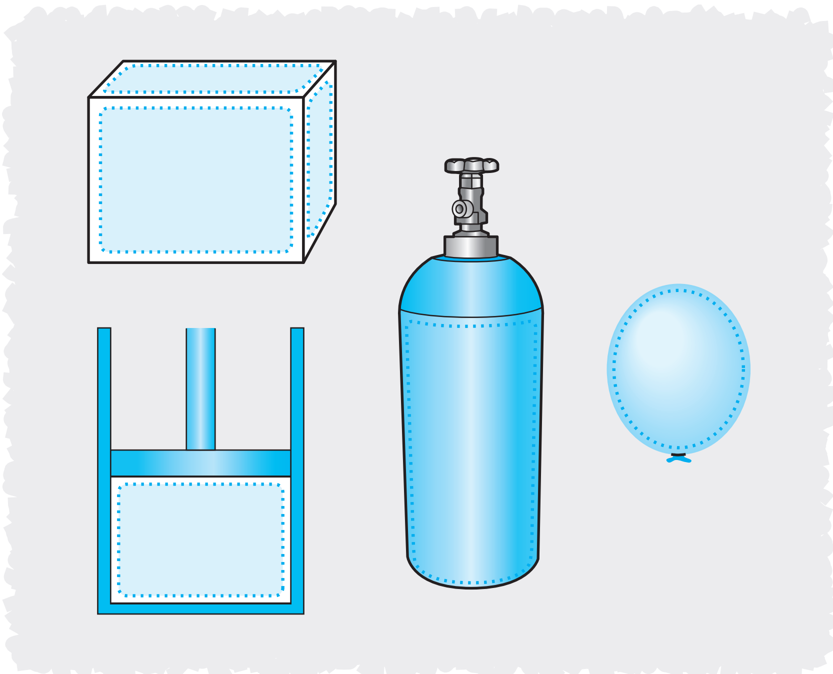

FIGURE 1.9 Examples of closed systems: a solid block of metal, the gas inside a tank, the air inside a balloon, and the gas in a piston–cylinder device.

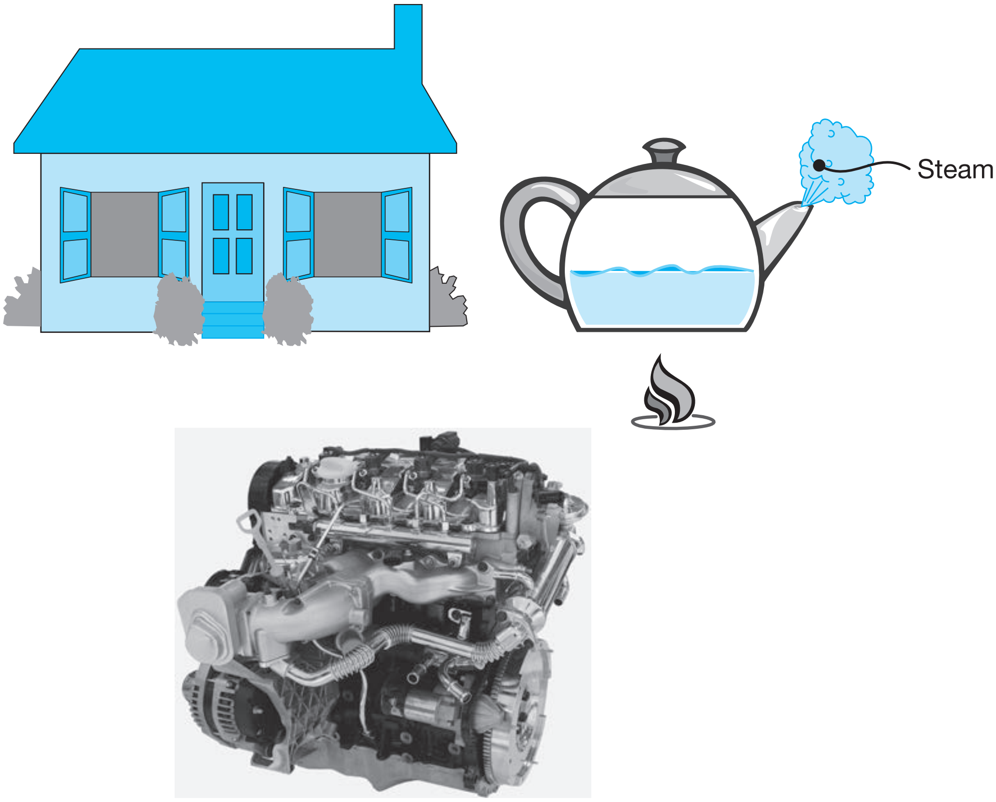

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FIGURE 1.10 Examples of open systems: a house with open windows, steam escaping from a kettle, and an automobile engine.

balloons are considered closed systems because, even though their volume changes, the mass inside the balloon doesn't change. Similarly, a piston–cylinder assembly containing a fixed mass of a gas or liquid will be considered a closed system.

Any system that clearly has mass being added to or removed from it is viewed as an open system. **Figure 1.10** provides a few of the many possible examples of open systems. A garden hose, a house with open windows, an air compressor, an automobile engine, and a kettle containing escaping boiling water are all examples of open systems. It should be noted that closed systems can be viewed as special applications of open systems. A thermodynamic analysis of a generic open system contains all the elements that would be seen in a closed system analysis; however, the closed system analysis will allow terms involving mass flow into and out of the system to be eliminated.

When determining the type of system to be used, it is important to consider the application of the object under consideration. For example, if we are in the act of filling or emptying a thermos bottle, we are dealing with what is clearly an open system rather than a potentially isolated system. Or, consider a kitchen refrigerator as shown in **Figure 1.11**. Assuming that the door is well sealed, the mass inside the refrigerator is fixed when the refrigerator door is closed. Energy in the form of electricity is still flowing into the refrigerator, and energy in the form of heat is being rejected to the environment as the refrigerant cools. (Heat is also slowly flowing through the walls to the interior of the refrigerator, but this heat can often be neglected for a well-built refrigerator.) Because energy can cross the system boundary but mass cannot, this would be viewed as a closed system. Now, consider if the door is open so that food can be

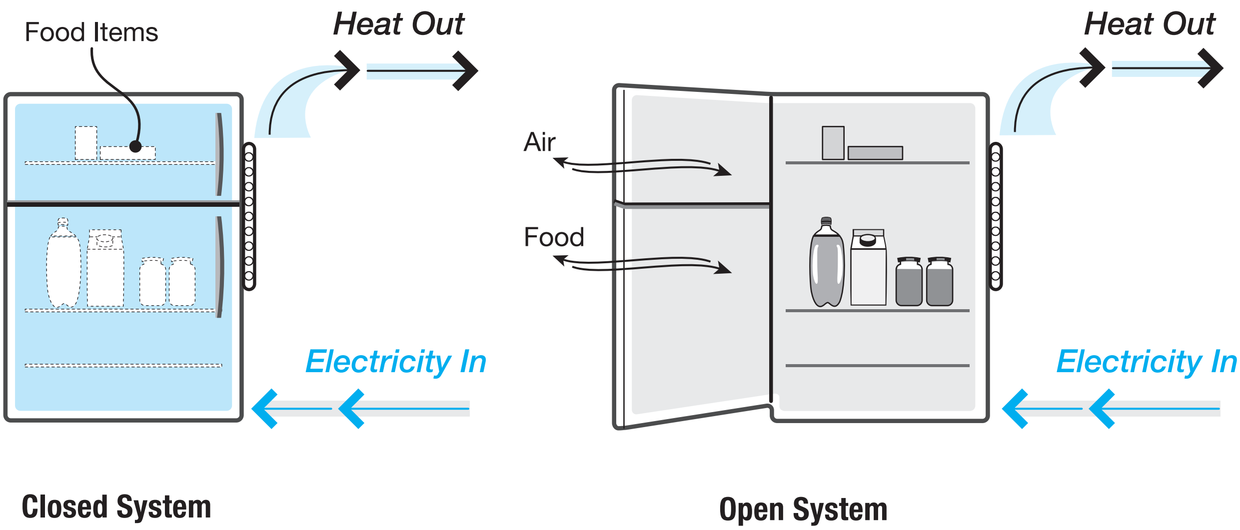

FIGURE 1.11 A refrigerator viewed as a closed system and as an open system.

added or removed from the refrigerator. Both air and the mass contained in the food can cross the system boundary; therefore, a refrigerator with an open door would be more appropriately viewed as an open system.

Alternatively, consider a piston–cylinder device inside an automobile engine, such as in Figure 1.12. When the intake and exhaust valves are closed, the mass trapped inside the cylinder is fixed, and the system is closed. But, if we open the exhaust valve, the gases inside the cylinder can flow out of the cylinder and into the exhaust manifold, making the piston–cylinder device an open system. Therefore, the choice of the type of system to use depends on the portion of the engine cycle under consideration.

Previously, we said that a garden hose is an open system. However, suppose that the valve that allows water to flow into the hose is shut. At this point, as long as the hose does not leak, there is a fixed mass of water that resides inside the hose. Some water may slowly evaporate, but because little mass if actively flowing into or out of the hose, the hose would be best considered a closed system. So, keep in mind that we cannot always determine whether a system is open or closed just by identifying the object under consideration, but rather we should also learn the nature of the process impacting the system.

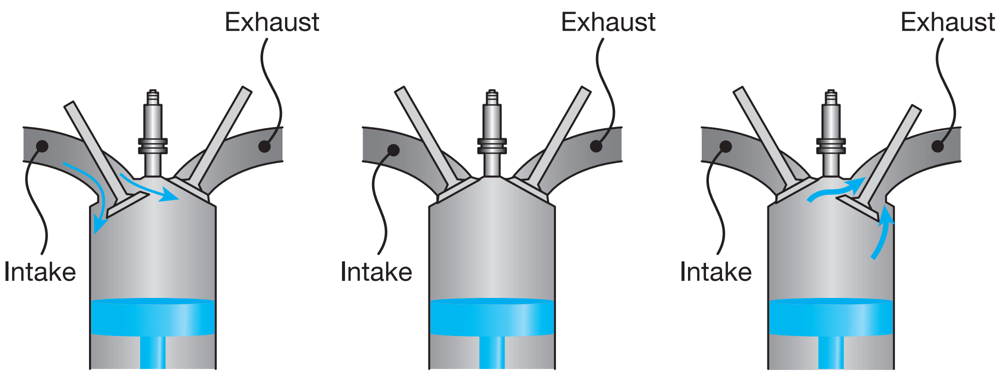

FIGURE 1.12 An engine cylinder as an open system (with intake valve open), as a closed system (with both valves closed), and as an open system (exhaust valve open).

1.1.2 The Thermodynamic Process

A thermodynamic system exists in a particular state, as described by the properties of the system, at a particular time. If the system is undergoing a change in state, the system is undergoing a thermodynamic process. A ***thermodynamic process*** is the action of changing a thermodynamic system from one state to another and is described by the series of thermodynamic states that a system experiences as it transforms from the "initial state" to the "final state." This is a rather formal definition of what is intuitively a rather simple concept. Essentially, a process is what happens to a system when mass and/or energy is added to or removed from the system, or as the mass or energy inside the system undergoes an internal transformation. Examples of processes include the heating or cooling a system, the compressing of a system or its expansion, and the changes in a system as electricity flows into it. Having an object accelerate as it falls from a height is an example of a process involving an internal transformation of energy, as will be described in Chapter 2. Normally, we show the progression of a thermodynamic process by drawing a diagram that illustrates how two of the system's properties vary during the process. **Figure 1.13**, for example, shows the thermodynamic process of heating air in a rigid (fixed volume) container by visually illustrating the relationship between the pressure and temperature for this process.

Often systems undergo a series of processes. As an example, consider the gases inside a piston–cylinder assembly in an automobile engine with the intake and exhaust valves closed. These processes are shown in **Figure 1.14**. First, the air and fuel mixture is compressed by the piston. Then a spark is used to ignite

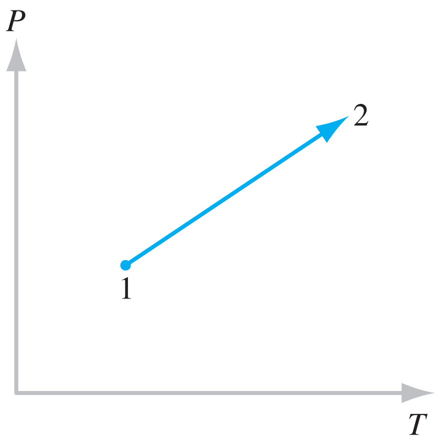

FIGURE 1.13 A pressure vs. temperature (P-T) diagram of a thermodynamic process.

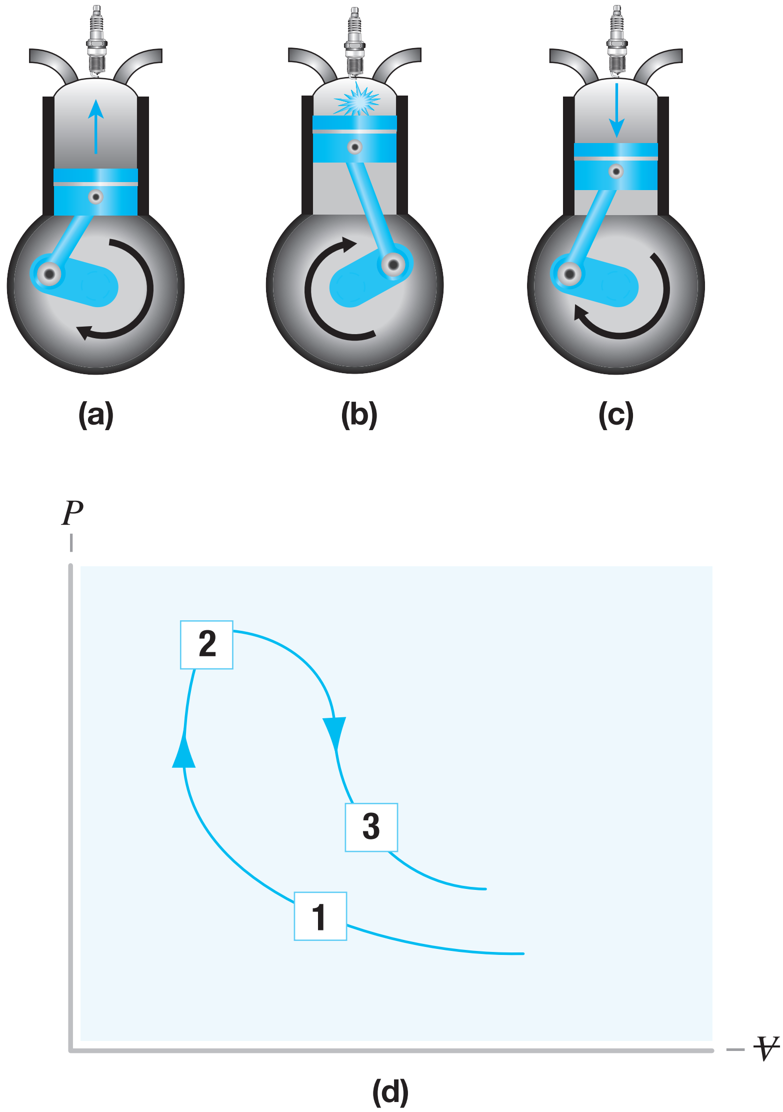

FIGURE 1.14 Three processes that occur during automobile engine operation: (a) the compression stroke, (b) the combustion process, and (c) the expansion stroke. (d) The processes are then shown on a pressure vs. volume (P-$\forall$) diagram.

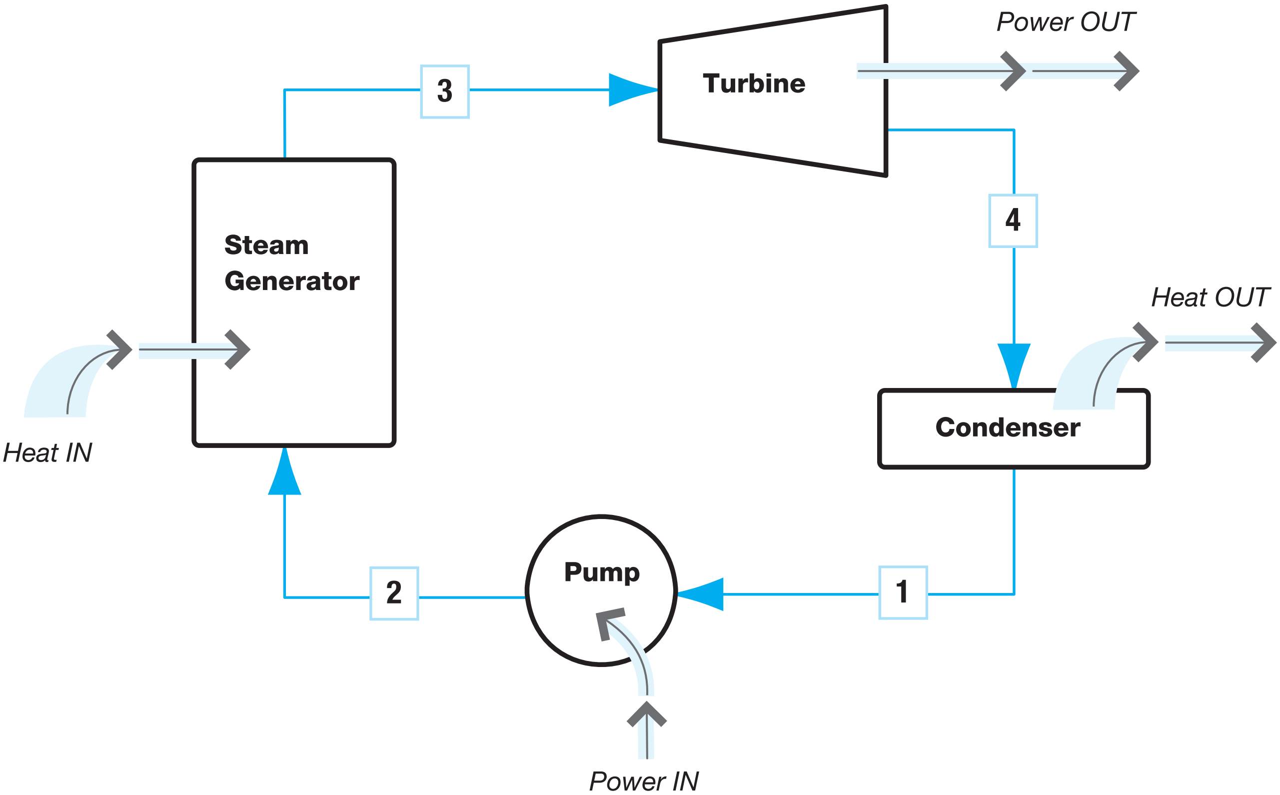

FIGURE 1.15 A schematic diagram of a basic Rankine cycle for steam power plants.

the mixture, which causes a rapid increase in temperature and pressure. The increased pressure pushes on the piston as the gases undergo an expansion process. From this description, we can see that the gases experience a series of three processes with the valves closed.

A special case for a series of processes occurs when the initial state of the first process is the same as the final state of the last process. If a system's initial state and final state are identical before and after a series of processes, it is said that the processes make up a ***thermodynamic cycle***. Cycles play an important role in thermodynamics, both in the theoretical development of various concepts and in the practical application of thermodynamics to everyday systems. An example of a cycle is a simple steam power plant as shown in **Figure 1.15**. Here, liquid water is sent through a pump, which increases the pressure of the liquid water. The high-pressure liquid water then is heated and boils to produce high-pressure steam. The steam passes through a turbine, which generates power. The low-pressure steam is then sent through a condenser, which uses low-temperature external cooling water to remove heat from the steam and thereby allow it to condense to a low-pressure liquid. This low-pressure liquid is then sent into the pump, and the cycle repeats itself. In order for the cycle to repeat continually, the water must enter the pump at the same state each time it completes one loop through the processes. So the water undergoes four processes, for which the initial and end states are the same.

1.1.3 The Concept of Thermodynamic Equilibrium

Equilibrium, in general, is defined as a state of balance due to the canceling of the actions by opposing forces. There are many different types of equilibrium, some of which you may already be familiar with. Mechanical equilibrium is the state that exists when a system undergoes no acceleration because the mechanical forces acting on the system are balanced. In thermodynamics, we often will view mechanical equilibrium as the state at which the pressure in a system is uniform. Thermal equilibrium is the state when two or more systems are at the same temperature, or when a single system has a uniform temperature.

Thermodynamic equilibrium is the state that exists when a system is in a combination of thermal, mechanical, chemical, and phase equilibriums. A system that is in thermodynamic equilibrium does not have the capacity to spontaneously change its state; for a system in thermodynamic equilibrium to change its state, it must experience a driving force from outside the system.

In this book, we will study equilibrium thermodynamics. There is another branch of thermodynamics known as nonequilibrium thermodynamics that is beyond the scope of this book and that does not have as many practical applications for most engineers. In equilibrium thermodynamics, we assume that our systems are in a state of thermodynamic equilibrium. You may note, though, that as a system proceeds from one state to another during a process, it may not be at equilibrium every instant of time. For example, if a container of water is heated on a stove, the water at the bottom of the container near the heat source may be warmer than the water at the top of the container. Given sufficient time, the system will all be at the same temperature, but at a given instant in time, the system may not technically be at thermal equilibrium. In such situations, we normally consider the system to be passing through a series of quasi-equilibrium states. Although such states are not strictly in equilibrium, the deviations from equilibrium experienced in these states are insignificant in terms of the overall analysis of the problem, and the deviations exist for relatively short periods of time. Although these deviations from equilibrium may cause errors in a very detailed analysis of a system, they generally do not cause significant errors in an engineering analysis or design of a system.

1.1.4 Thermodynamic Properties

We need a way to describe the state of a thermodynamic system. The thermodynamic properties of a system are the tools that are used to describe the state of a system. A ***thermodynamic property*** is a quantity whose numerical value is independent of how the state of a system was achieved and only depends on the system's local thermodynamic equilibrium state. This is an important distinction, because it means that anything whose value depends on a specific process that a system undergoes is not a property of the system but is rather a description of the process.

You are undoubtedly already familiar with many properties, such as temperature, pressure, mass, volume, and density. As an example of how temperature fits our definition of a property, consider air in a room. If air in a room is at a particular temperature, a description of the system does not need to explain how that temperature was achieved (via heating or cooling); the system is simply at that temperature. Other properties of note are viscosity, thermal conductivity, emissivity, and many more that will be introduced when appropriate throughout the book. Color also fits the definition of a property, because a system's color can be described numerically through a spectrum describing the wavelengths of light composing the color.

Some properties are considered ***extensive*** properties and some are considered ***intensive*** properties. An extensive property is a property whose value depends on the mass of the system, whereas an intensive property is one whose value is independent of a system's mass. A quick method to use to determine whether a property is extensive or intensive is to mentally divide the system in half and determine if the value of the property in half the system would change. Doing this should yield the result that temperature, pressure, and density are intensive properties, because a system of half the size will have the same value of those properties as the original system (i.e., dividing a system in half should have no impact on its temperature). However, mass and volume are extensive properties because each would have different values in a system half the size of the initial system (i.e., the volume of a system half the size of the initial system is clearly half of the initial volume).

Extensive properties can be transformed into intensive properties by dividing the extensive property by the mass of the system. Such transformed properties are given the name "specific." For example, the volume of a system, $V\!\!\!/$, can be divided by the mass, m, yielding the specific volume, v:

$$v = V\!\!\!/ / m \tag{1.1}$$

You may note that the specific volume is the inverse of the density, ρ, which is defined as the mass divided by the volume ($\rho = m/V\!\!\!/$).

As will be discussed below, in general it is easier to work with intensive properties of a system in a thermodynamic analysis, and then multiply the value of the property by the system's mass to get the total value of the extensive quantity for that particular system. Working with intensive properties allows us to avoid needing to perform calculations for every possible mass of a system undergoing a process. We can solve the process on an intensive (per unit mass) basis in general and then apply that solution to any specific mass undergoing the process.

Properties of a substance are related to each other through ***equations of state***. Some equations of state, as we will see, are very simple relationships, whereas others are so complicated that they are better calculated through computer programs. An example of a simple equation of state that you are probably familiar with is the ideal gas law:

$$PV\!\!\!/ = mRT \tag{1.2}$$

where P is the pressure, T is the temperature, and R is the gas-specific ideal gas constant, which is equal to the universal ideal gas constant, $\overline{R}$, divided by the molecular mass of the gas, M. The ideal gas law can also be written in terms of the specific volume:

$$Pv = RT \tag{1.3}$$

We will explore the ideal gas law in more detail later.

Considering Eq. (1.3), we can see that for a particular gas, three properties are related through the given equation of state. Two of these properties can be independently set, and the third property will be calculated from knowledge of those other two properties. The properties that can be arbitrarily chosen for a particular system are called ***independent properties***, whereas the properties whose values are subsequently determined through an equation of state are known as ***dependent properties***. In Eq. (1.3), if the pressure, P, and specific volume, v, are chosen as the independent properties, the temperature, T, is a dependent property whose value is determined through the ideal gas law. Similarly, if P and T are known as the independent properties, then v is the dependent property.

Equations (1.2) and (1.3) also provide a concrete example of the benefit of using specific properties. Suppose you were asked to compile a list of information that could be used to find the total volume occupied by a particular gas for a set of pressures and temperatures. If you were to use Eq. (1.2) to calculate the total volume directly, you would need to compile a list for every possible mass of the gas. However, if you used Eq. (1.3), you could prepare one list of specific volumes, and then ask the user of the data to just multiply the given number by the system's particular mass. Clearly, the second approach is simpler.

Below, we will formally introduce the basic, easily measured properties that are commonly used to describe a system. But, first, we need to comment on the nature of the unit systems involved in thermodynamics.

1.1.5 A Note on Units

In engineering practice, there are generally two broad systems of units that are employed. One system, known as the International System (SI), is common throughout much of the world, whereas the other system, known as the English Engineering (EE) system, is mostly limited to use in the United States, although the SI system is becoming more commonly used there as well. The SI system of units is a system that is based upon scientific principles and strongly employs a decimal numbering system. The EE system developed haphazardly over time using measurements of convenience that often lacked consistent universal standards. Although standards have since been developed, unit conversions in the EE system are often nonintuitive and today may appear to have been assigned arbitrary values.

Although you may be more familiar in everyday life with units from the EE system, the SI system is much simpler to use when performing scientific or engineering calculations. As such, in this book we will concentrate on using the SI system because doing so will allow you to focus on understanding the thermodynamic principles rather than being caught up in learning how to convert units. The EE system will be used for some examples and problems to breed familiarity.

To illustrate the intuitive simplicity of the SI system, let us compare the units used in the two systems for a measurement of length. The SI system uses the meter, m, as the base unit of length. If a system is substantially larger than or smaller than a meter, we can apply one of the prefixes shown in **Table 1.1** for the SI system. So, 1 millimeter (mm) equals one thousandth of a meter: 1 mm = 0.001 m. One kilometer (km) equals one thousand meters: 1 km = 1000 m. In common practice, the centimeter (cm) is also used and is equal to one hundredth of a meter: 1 cm = 0.01 m.

For the EE system, the base unit of length is the foot (ft). To convert to larger or smaller sizes, we would employ conversion factors such as 1 ft = 12 inches, and 1 mile = 5280 ft. Although such conversions are possible, they can introduce unnecessary complexity to calculations and can more easily introduce mistakes into the calculations than the SI unit conversions.

The unit of time for both the SI and EE system of units is the second (s). Both systems of units will employ concepts such as milliseconds (ms) for 0.001 s. In addition, both systems consider 1 minute equal to 60 seconds, and 1 hour to be 3600 seconds. These conversions are the only situations where the SI system of units fails to deal exclusively with factors of 10 in unit conversions.

Remember that once the thermodynamic principles are learned, they are applied in the same way no matter which unit system is employed. It is important in both unit systems to be certain that the units employed in equations appropriately cancel so as to give the correct final units.

QUESTION FOR THOUGHT/DISCUSSION

Most of the world uses the SI system of units, whereas the United States generally employs the EE system of units. Would it be a good idea for the United States to adopt the SI system, and what might be needed for this to occur?

TABLE 1.1 Common Prefixes for the SI System of Units

Prefix	Factor	Symbol
Pico	10^{-12}	p
Nano	10^{-9}	n
Micro	10^{-6}	μ
Milli	10^{-3}	m
Centi	10^{-2}	c
Kilo	10^{3}	k
Mega	10^{6}	M
Giga	10^{9}	G
Tera	10^{12}	T

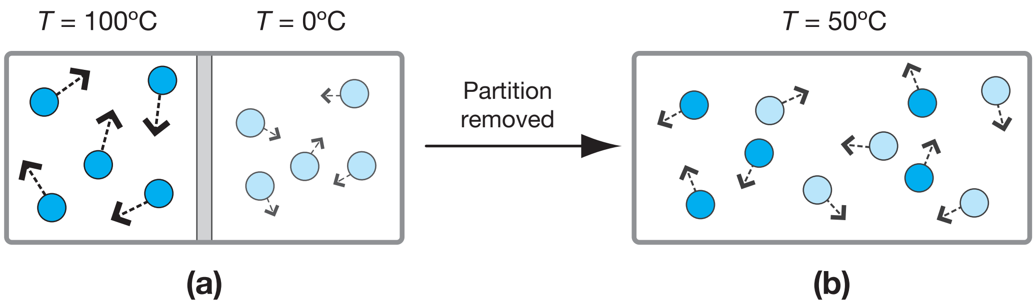

FIGURE 1.16 (a) A box partitioned in half with some molecules at 100°C and some molecules at 0°C. (b) After the hot molecules collide with the cold molecules, the molecules are all at 50°C.

1.2 AN INTRODUCTION TO SOME COMMON PROPERTIES

As mentioned previously, some thermodynamic properties are familiar, commonly encountered, and (rather) easily measured. These are the properties that we often use to describe a system. In this section, we will discuss some of these common properties and the units associated with them.

1.2.1 Temperature

When we think of concepts such as "heat," the first property we often think of is temperature. And although we discuss temperatures freely, we may find it difficult to define the word *temperature*. Temperature is a measure of the molecular motion and the energy associated with the motion inside a system. Systems with low temperatures have relatively slow motions associated with their atoms and molecules, whereas systems with high temperatures have relatively fast motion of their atoms and molecules. In one sense, this is why a hot system will tend to cool when it comes in contact with a cool system (and why the cool system heats up). The fast-moving molecules in the hot system will collide with the slow-moving molecules in the cold system, transferring some energy to the slower-moving molecules. This causes the fast-moving molecules to slow (leading to a decrease in temperature for the hot system) and the slow-moving molecules to speed up (leading to an increase in temperature for the cold system); this process is illustrated in **Figure 1.16**.

There are many methods for measuring the temperature of a system, but the one most commonly recognized is the thermometer (see **Figure 1.17**). If we look at a thermometer, we will see a scale showing a series of marks indicating the "degrees" of the substance. In the SI system of units, the unit of temperature used is the degree Celsius (°C). This system is given logical scientific reference points to define the scale:

0°C corresponds to the freezing point of water at atmospheric pressure.
100°C corresponds to the boiling point of water at atmospheric pressure.

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FIGURE 1.17 A common thermometer for measuring temperature.

In the EE system of units, the unit of temperature is the degree Fahrenheit (°F). The set points used to define this scale are as follows, and are compared to the Celsius scale in **Figure 1.18**:

32°F corresponds to the freezing point of water at a pressure of 1 atmosphere.
212°F corresponds to the boiling point of water at a pressure of 1 atmosphere.

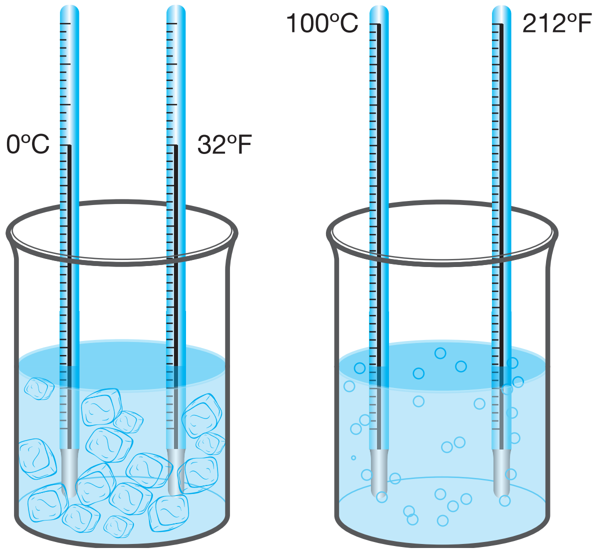

FIGURE 1.18 The image on the left shows the temperature in Celsius and Fahrenheit for ice water, whereas the image on the right shows the same for boiling water at 1 atm.

Clearly, these values do not make much sense scientifically. However, the temperature scale is rather convenient to use for everyday temperature descriptions. If we consider most of the world, a temperature range of 0°F to 100°F is good for describing the range of temperatures that people are likely to experience. Although some people encounter temperatures outside this range, most people live in temperatures that fall within this range for most of the year.

Both scales have fixed temperatures at the same physical points, so a relationship can be derived between the two scales:

$$T(°\text{C}) = \frac{5}{9}[T(°\text{F}) - 32] \tag{1.4}$$

or, equivalently,

$$T(°\text{F}) = \frac{9}{5}T(°\text{C}) + 32 \tag{1.5}$$

Both of these temperature scales are based on an arbitrarily set 0 point (zero point), which makes them *relative* scales. Although relative scales are perfectly adequate for comparing the temperatures of different systems, and although they are adequate for determining a change in temperature, relative scales can cause significant problems when performing calculations involving a specific temperature. Consider the ideal gas law, Eq. (1.2), written in a form to solve for the mass of a system:

$$m = P\forall/RT$$

Now, suppose we wish to determine the mass of a system whose temperature is that of the freezing point of water at atmospheric pressure. If we used the SI system of units and degrees Celsius, we would obtain an infinite mass for the system, whereas the EE system of units and degrees Fahrenheit would give a finite mass. Clearly, there is a problem if an infinite mass and a finite mass can be calculated for the same system just because of the units used for temperature. Similarly, if the temperature scale gave a temperature below zero, the mass of the system would be negative. To avoid the problems that can result from using a relative temperature scale, an absolute temperature scale can be used.

If we return to the idea of what temperature is—a measure of molecular motion in a system—then we can develop a concept of a temperature scale that would not be based on an arbitrary zero point. If we cool a system, the molecules in the system will slow. The cooler the system becomes, the slower the molecules will move. At some point, all molecular-level motion will cease. At the point where all motion ceases, we can define a temperature scale to have a temperature of zero. Such a scale is called an absolute temperature scale, because the scale is based on a true definition of zero motion. It is not possible to have a lower temperature than this "absolute zero" because motion cannot become slower once the molecules have stopped.

The absolute temperature scale in the SI system of units is the Kelvin (K) scale. One Kelvin (1 K) is equal in magnitude to 1°C. Absolute zero occurs at −273.15°C, and this corresponds to 0 K. Therefore, the relationship between the Celsius and Kelvin temperature scales is

$$T(\text{K}) = T(°\text{C}) + 273.15 \tag{1.6}$$

In practice, the 273.15 is often rounded to 273. The size of a degree Celsius and the size of a Kelvin are identical, so the difference in temperature is identical numerically for the Kelvin and Celsius scales, as shown in Example 1.1.

▶ EXAMPLE 1.1

Determine the difference in temperature in both °C and K between a system at 30°C and a system at 70°C.

Given: $T_A = 30°C$, $T_B = 70°C$

Find: ΔT in both °C and K

Solution: We will consider two systems, A and B, with the given indicated temperatures: $T_A = 30°C$, $T_B = 70°C$. The difference in temperature is $\Delta T = T_B - T_A$.

In degrees Celsius, the difference in temperature is equal to

$$\Delta T = 70°C - 30°C = \mathbf{40°C}$$

Each temperature can be converted to the Kelvin scale.

$$T_A = 30 + 273.15 = 303.15 \text{ K} = 303 \text{ K}$$

$$T_B = 70 + 273.15 = 343.15 \text{ K} = 343 \text{ K}$$

The difference in temperature in Kelvin is

$$\Delta T = 343 \text{ K} - 303 \text{ K} = \mathbf{40\ K}$$

Analysis: Numerically the difference in temperature is the same because the size of each unit is the same. In practice, this means that either scale can be used when considering differences in temperature. In addition, if the value of some quantity has units of "unit/K," the value is the same in terms of "unit/°C," and vice versa.

In the EE system of units, the absolute temperature scale is the Rankine (R) scale. As in the SI system, the magnitude of the unit 1 R equals the magnitude of 1°F. Absolute zero occurs at −459.67°F, which corresponds to 0 R. Therefore, the relationship between the Fahrenheit and Rankine temperature scales is

$$T(\text{R}) = T(°\text{F}) + 459.67 \tag{1.7}$$

The 459.67 is often rounded to 460 in practice. The same concepts discussed for the SI temperature scales regarding the implications of the size of the units hold true for the Rankine and Fahrenheit temperature scales.

It should be noted that the temperature in Kelvin and the temperature in Rankine are related through

$$T(\text{K}) = \frac{5}{9}T(\text{R}) \tag{1.8}$$

▶ EXAMPLE 1.2

A system has a temperature of 25°C. Determine the value of this temperature in °F, K, and R.

Given: $T(°C) = 25°C$

Find: $T(°F)$, $T(K)$, $T(R)$

Solution: With $T(°C) = 25°C$, Eq. (1.5) can be used to find the temperature of the system in °F:

$$T(°\text{F}) = \frac{9}{5}T(°\text{C}) + 32 = \frac{9}{5}(25) + 32 = \mathbf{77°F}$$

Equation (1.6) can be used to find the temperature of the system in Kelvin:

$$T(\text{K}) = T(^\circ\text{C}) + 273.15 = 25 + 273.15 = 298.15\ \text{K} = \mathbf{298\ K}$$

Equation (1.8), rewritten to solve for $T(\text{R})$, can be used to find the temperature of the system in Rankine:

$$T(\text{R}) = \frac{9}{5}T(\text{K}) = \frac{9}{5}(298.15) = 536.67\ \text{R} = \mathbf{537\ R}$$

These different values are illustrated in **Figure 1.19.**

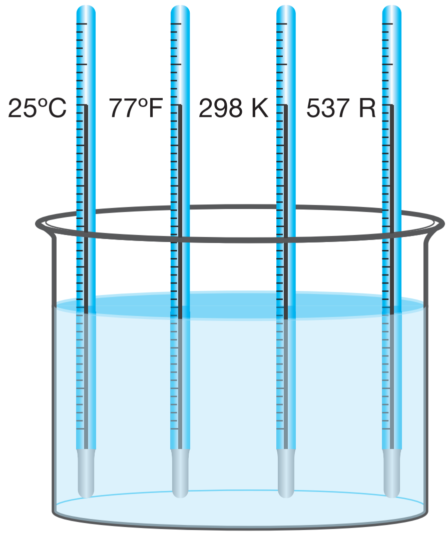

FIGURE 1.19 Four thermometers showing the same temperature in four temperature scales.

Today, the absolute temperature scales are defined through the absolute 0 point and the triple point of water. (The triple point of water is the temperature at which the solid, liquid, and vapor phase can all coexist.) This temperature is 0.01°C, and so the size of a unit of K in the Kelvin temperature scale is specified through the absolute 0 point and the triple point of water at a temperature of 273.16 K—there are 273.16 evenly sized units of Kelvin between absolute 0 and the triple point of water.

QUESTION FOR THOUGHT/DISCUSSION

Think of some possible scenarios that would give a nonsensical result if you divided by the temperature using a relative temperature scale. How can you use this to remind others to use only absolute temperatures when multiplying or dividing by a temperature?

1.2.2 Mass, Moles, and Force

The property known as ***mass*** specifies the amount of a substance. Mass is represented by the letter m. Somewhat like temperature, mass represents a concept that is easy to understand but difficult to define. The SI unit used for mass is the kilogram (kg), and the EE unit used for mass is the pound-mass (lbm).

A mole represents the amount of a substance that contains an Avogadro's number worth of atoms or molecules of that substance, with Avogadro's number being equal to 6.022×10^{23}. More formally, Avogadro's number is defined as the number of carbon atoms present in 0.012 kg of carbon-12. The number of moles of a substance is represented by the letter n. The ***molecular mass***, M, of a substance is the mass of one mole of the substance:

$$M = m/n$$

However, because we often will be using mass in kilograms, we are normally more concerned with the number of kilomoles of a substance; in such a case, the molecular mass represents the mass in kg of 1 kmole (one thousand moles) of the substance. In this book, we will be concerned primarily with mass rather than moles until we begin to encounter gas mixtures and chemically reacting systems.

From Newton's second law of motion, the force, F, that is exerted by a mass experiencing an acceleration, a, is equal to

$$F = ma \tag{1.9}$$

The SI unit of force is the Newton (N), and by definition 1 N = 1 kg · m/s^2. So, in the SI system of units, the unit for force is derived directly from the definition of force, because the units of acceleration are m/s^2. You should note that the weight, W, of an object is the force exerted by the mass of the object in a gravitational field with an acceleration equal to g: $W = mg$. At sea level on earth, the acceleration due to gravity, g, is 9.81 m/s^2 in SI units, and 32.17 ft/s^2 in EE units. In lieu of knowing a different value for the acceleration due to gravity at other locations, these are the values that should be used by default. Note that the weight of an object can change, but the mass of the object stays constant no matter where it is located. So if an object is moved into a different gravitational field, its weight will change—this is why objects weigh less on the moon than on earth, even though the objects have the same mass.

There is additional complexity in the EE unit system with regard to force. The unit of force in the EE system is the pound-force (lbf). As the use of the units and the concept of mass developed, it was desirable to have an object's mass and weight in pounds be numerically equal at sea level on earth, even though mass and weight are represented by different units. So, if an object has a mass of 50 lbm, it should have a weight of 50 lbf at sea level. However, considering that the acceleration due to gravity is 32.17 ft/s^2, this will clearly not occur if the equation $W = mg$ is used. To account for this, in the EE system of units, a unit conversion factor, g_c, is introduced:

$$g_c = 32.174 \text{ lbm} \cdot \text{ft}/(\text{lbf} \cdot \text{s}^2)$$

In turn, this changes Eq. (1.9) to

$$F = ma/g_c$$

for EE units. In fact, in any equation where there needs to be a conversion between lbm and lbf, the conversion factor g_c must be introduced; this is one of the complications of trying to learn thermodynamics using EE units. In SI units, $g_c = 1$. In this book, because we emphasize SI units, we will be ignoring the use of g_c in the equations, but be aware that the unit conversion will be needed for EE unit calculations.

▶ EXAMPLE 1.3

An object on a distant planet has a weight of 58.5 N. The acceleration due to gravity on the planet is 31.5 m/s^2. Determine the object's mass.

Given: $W = 58.5$ N

$g = 31.5$ m/s^2

Find: m

Solution: Because $W = mg$, we can find

$$m = 58.5 \text{ N}/31.5 \text{ m/s}^2 = 58.5 \text{ kg} \cdot \text{m/s}^2/31.5 \text{ m/s}^2 = \mathbf{1.86 \text{ kg}}$$

▶ EXAMPLE 1.4

On earth at sea level, a block of metal has a weight of 295 lbf. The block is placed on a rocket and delivered to the moon, where the acceleration due to gravity is 5.32 ft/s^2. Determine the weight of the block of metal on the moon.

Given: Earth: $W_e = 295$ lbf, $g_e = 32.17$ ft/s^2

Moon: $g_m = 5.32$ ft/s^2

Find: W_m (Weight on the moon)

Solution: Incorporating the unit conversion factor, g_c, the mass of the object can be found from the given information on the block's weight on the earth.

$$m = W_e g_c / g_e = (295 \text{ lbf})(32.17 \text{ lbm} \cdot \text{ft/lbf} \cdot \text{s}^2)/(32.17 \text{ ft/s}^2) = 295 \text{ lbm}$$

The mass is constant, so using the acceleration due to gravity on the moon, the weight of the block on the moon can be found:

$$W_m = m g_m / g_c = (295 \text{ lbm})(5.32 \text{ ft/s}^2)/(32.17 \text{ lbm} \cdot \text{ft/lbf} \cdot \text{s}^2) = \mathbf{48.8 \text{ lbf}}$$

These different weights are illustrated in Figure 1.20.

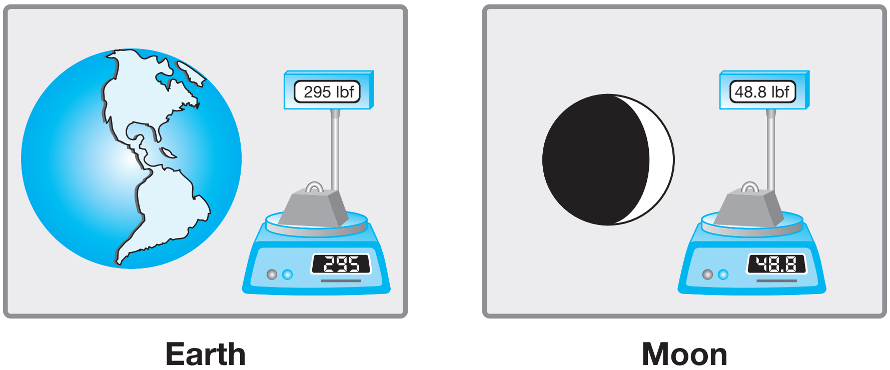

FIGURE 1.20 Scales showing the same object's weight on the earth and on the moon.

1.2.3 Volume and Specific Volume

The ***volume***, $\forall$, of a system is the physical space occupied by the system. Volume represents a three-dimensional spatial region, so the SI unit for volume is the cubic meter: m^3. The EE unit for volume is the cubic foot: ft^3.

As mentioned previously, thermodynamic calculations are typically performed using intensive properties, and the result can then be scaled by multiplying by the system's mass. Volume is an extensive property, whereas the ***specific volume***, v, is the corresponding intensive property. The specific volume is the total volume of the system divided by the system's mass:

$$v = \forall / m$$

The units for specific volume in the SI system are m^3/kg, and the units are ft^3/lbm in the EE system. As noted, the specific volume is the inverse of the density, ρ: $v = 1/\rho$.

1.2.4 Pressure

The last of the easily measured common properties of a system that we often use to describe a system is the pressure, P. The pressure is the force exerted divided by the area, A, over which the force acts. At a particular point in space, the pressure is found as the limit of the force divided by the area as the area approaches that of a point:

$$P = \lim_{A \to A'} \frac{F}{A} \tag{1.10}$$

where A' is the area of the point. In practice, the pressure exerted on a system or by a system will be uniform on a surface, and so in general the pressure will be calculated simply as

$$P = F/A \tag{1.11}$$

In SI units, the unit of pressure is the Pascal (Pa), where 1 Pa = 1 N/m^2. However, if you consider the size of this unit, you would see that it would be equal to the weight on earth of a roughly 0.1 kg object spread over a square meter of space: this is a very small unit of pressure. As such, in thermodynamics we typically will be concerned with units of pressure in kilopascals (kPa) (1000 Pa) and megapascals (MPa) (10^6 Pa). Occasionally, you may see units of pressure in "bar," where 1 bar = 100 kPa = 10^5 Pa. The reason for this unit will become apparent shortly. The standard unit of pressure in EE units is the pound-force per square foot: lbf/ft^2. Often, the pound-force per square inch (lbf/in^2 or psi) will be also used, where 1 lbf/ft^2 = 144 lbf/in^2 due to there being 12 inches in a foot.

Assuming that a system is in equilibrium, mechanical equilibrium requires that the pressure exerted on the outside of a system will be equal to that which the system exerts from the inside. Therefore, the pressure inside a system can be determined to be the net pressure exerted on the system by outside forces. Keep in mind that these forces can include the walls surrounding the system pushing back on the inside of the system; therefore, it may be easier to measure the pressure inside the system rather than adding external pressures exerted on the system.

Atmospheric pressure is the force exerted by the air above some location (the weight of the air) divided by the area over which it is distributed. Standard atmospheric pressure, P_0, is defined as the average air pressure at sea level and is equal to

$$P_0 = 101.325 \text{ kPa} = 14.696 \text{ lbf/in}^2 = 2116.2 \text{ lbf/ft}^2$$

The standard atmospheric pressure is often also referred to as 1 atm, and pressures can be reported in terms of a number of atmospheres. As can be seen, standard atmospheric pressure is approximately 100 kPa, indicating that a pressure given in bar is approximately equal to the number of atmospheres. The local atmospheric pressure, P_{atm}, is often different from standard atmospheric pressure, particularly at an elevation significantly higher than sea level. The air pressure in mountainous areas is considerably less than that at sea level; the difference is significant enough that its effect on the boiling properties of water will change cooking times for some foods.

Measuring a difference in pressure is a relatively easy task. Manometers or other simple pressure gages can be used for this purpose. As shown in **Figure 1.21**, in a manometer, a tube containing a liquid is placed between the two systems whose pressures are to be compared; in this case, a cylinder containing a gas and the atmosphere. The cylinder contains pressurized gas, and this exerts a greater force on one side of the fluid in comparison to the force exerted by the atmosphere on the other side. This causes a difference in height, L, of the liquid between the two legs of the tube. Multiplying L by the density of the liquid and the local acceleration due to gravity

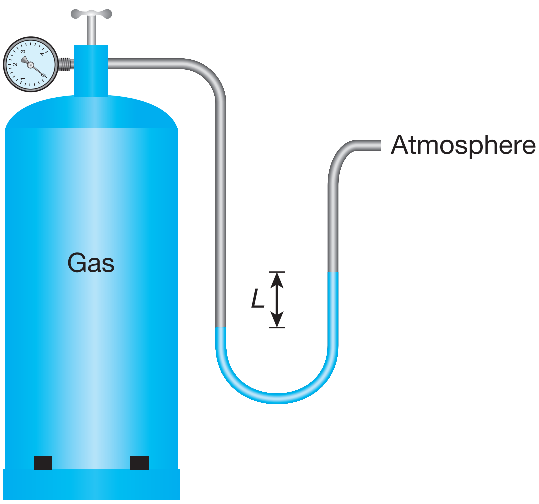

FIGURE 1.21 A manometer as set up to measure the pressure inside a tank of gas.

yields the pressure difference between the two systems. This pressure difference is called the gage pressure, P_g:

$$P_g = \rho g L \tag{1.12}$$

The gage pressure can be measured in other ways as well. Consider the state of the manometer if the gas inside the cylinder has a pressure equal to that of the local atmosphere. In this case, both ends of the tube will experience the same force, and there will be no height difference between the fluid in both legs of the manometer. This indicates that the gage pressure is zero. But is the pressure inside the cylinder equal to zero? No, the pressure is equal to the atmospheric pressure. Therefore, to get the actual pressure of the system, we must combine the gage pressure and the local atmospheric pressure to obtain the absolute pressure, P:

$$P = P_g + P_{\text{atm}} \tag{1.13}$$

The absolute pressure is the pressure that is needed for calculations involving equations of state to find other properties of a system.

Another way to envision the need for the absolute pressure is to consider the problem of determining the mass of air inside a flat bicycle tire. A flat bicycle tire is one whose internal air pressure is identical to the local atmospheric pressure: a tire gage would read zero for a flat tire. But is there still air inside the tire? Yes, there is still air inside the tire, because a vacuum condition has not been formed by a tire losing its air. Recall the ideal gas law (rewritten from Eq. (1.2)):

$$m = P\forall/RT$$

Clearly, the gage pressure of zero cannot be used as the pressure of the air inside the tire, because that would lead to a mass of zero. Instead, the absolute pressure is required in this calculation, where in this case the absolute pressure is equal to the local atmospheric pressure.

As mentioned, the local atmospheric pressure is not necessarily equal to standard atmospheric pressure, although standard atmospheric pressure can be used as a good approximation if other information is not available. It tends to be more difficult, and expensive, to measure the local atmospheric pressure. A typical device used for such a measurement is a barometer, and so the local atmospheric pressure is often called the barometric pressure.

QUESTION FOR THOUGHT/DISCUSSION

What would happen if you placed a well-sealed, fully-inflated bicycle tire into a chamber with a pressure of 15 atm?

▶ EXAMPLE 1.5

A pressure gage on a tank filled with compressed helium reads that the pressure inside the tank is 352 kPa. A barometer in the room containing the tank indicates that the local barometric pressure is 100.2 kPa. Determine the absolute pressure of the helium inside the tank.

Given: $P_g = 352$ kPa (The pressure gage is providing a gage pressure in the tank.)

$P_{\text{atm}} = 100.2$ kPa (The barometer provides the local atmospheric pressure.)

Find: P

Solution: The absolute pressure is the sum of the gage pressure and atmospheric pressure:

$$P = P_g + P_{\text{atm}} = 352 \text{ kPa} + 100.2 \text{ kPa} = \mathbf{452.2\ kPa = 452\ kPa}$$

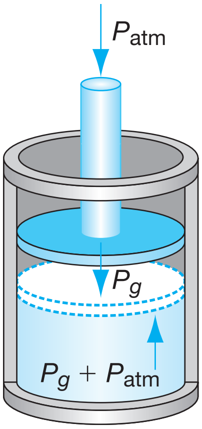

FIGURE 1.22 A diagram showing the pressures exerted on a gas in a piston–cylinder device.

▶ EXAMPLE 1.6

A circular piston in a cylinder has a diameter of 5 cm. The cylinder contains air. A pressure gage inside the cylinder reads a pressure of 300 kPa. The piston is at sea level, where the acceleration due to gravity is 9.81 m/s². Determine the mass of the piston.

Given: $D = 5$ cm $= 0.05$ m, $P_g = 300$ kPa, $g = 9.81$ m/s²

Find: m

Solution: As shown in **Figure 1.22**, the absolute pressure inside the cylinder is equal to the pressure exerted by the weight of the piston plus the local atmospheric pressure. Therefore, the difference in pressure between the air inside the cylinder and outside the cylinder (i.e., the gage pressure) is that caused by the weight of the piston. As such, we do not need to find the absolute pressure in the tank to find the mass of the piston; we just need to equate the gage pressure to what is produced by the piston:

$$P_g = F/A = mg/A$$

The area of the piston is that of a circle:

$$A = \pi D^2/4 = \pi(0.05 \text{ m})^2/4 = 0.00196 \text{ m}^2$$

Keep in mind that the pressure unit that is naturally derived from a force in Newtons is the Pascal. Therefore, $P_g = 300$ kPa $= 300{,}000$ Pa.

$$m = P_g A/g = (300{,}000 \text{ Pa})(0.00196 \text{ m}^2)/(9.81 \text{ m/s}^2)$$
$$= (300{,}000 \text{ N/m}^2)(0.00196 \text{ m}^2)/(9.81 \text{ m/s}^2) = 60.0 \text{ N} \cdot \text{s}^2/\text{m}$$
$$= 60.0 \text{ (kg} \cdot \text{m/s}^2)(\text{s}^2/\text{m}) = \mathbf{60.0 \text{ kg}}$$

Analysis: This problem is a good illustration of the benefit of tracking units in a calculation. Keeping track of the units and canceling the units appropriately will allow for the avoidance of careless mistakes. For example, if we had kept the gage pressure in kPa, the final answer would clearly have been incorrect because the units would not have properly canceled to give a mass in kilograms.

The two previous examples illustrate the use of "engineering accuracy" in the answers for thermodynamics calculations. In general, engineering accuracy is considered a precision of three significant figures in the value. A significant figure is a non-placeholding 0 number in an answer. Numbers such as 10,300, 431, 2.04, and 0.00352 all have three significant figures. In general, it is considered that most quantities can be measured to three significant figures of precision and that most objects can be built to such specifications without an excessive amount of effort. Clearly, some applications need more precision, and some need less. But in general in this course, we will be seeking to provide answers to three significant figures of precision and will assume that given quantities were known to that precision, even if they are not given to that level (such as the diameter of "5 cm" in Example 1.6).

There are some special thermodynamic processes that have one property held constant. A constant-temperature process is also known as an ***isothermal process***. A constant-pressure process is also known as an ***isobaric process***. Less commonly, a constant-volume process is sometimes referred to as an ***isochoric process***.

1.3 ZEROTH LAW OF THERMODYNAMICS

Now that some of the basic concepts and properties in thermodynamics have been introduced, we are ready to consider one of the four laws that govern thermodynamics. The law is known as the ***Zeroth Law of Thermodynamics***, as it was formally stated after the First Law of Thermodynamics, but was subsequently deemed as more fundamental.

Consider three systems: A, B, and C. The Zeroth Law of Thermodynamics states that if system A is in thermal equilibrium (i.e., has the same temperature) with system B, and system B is in thermal equilibrium with system C, then system A is in thermal equilibrium with system C. This law should seem logical, and because it is so logical it was not formally stated as early as other scientific laws. However, as we shall discuss, the Zeroth Law is at the heart of temperature measurement, and we have already considered that temperature is a very important property in thermodynamics. Therefore, the Zeroth Law was formally stated, and the other laws of thermodynamics rest upon it and rely upon it to provide a basis for correct temperature measurements.

As an example of a temperature measurement device, consider the mercury thermometer shown in **Figure 1.23**. The thermometer is placed in a glass containing water and is made of glass containing mercury. Once the thermometer reaches a steady temperature, we assume we are measuring the temperature of the water. But, in actuality, we are reading the temperature of the mercury inside the glass. To assume that we are reading the temperature of the water, we must assume that the temperature of the mercury (T_{Hg}) is equal to the temperature of the glass (T_g), which in turn is equal to the temperature of the water (T_w). For this to be the case, the mercury must be in thermal equilibrium with the glass, and the glass must be in thermal equilibrium with the water. From the Zeroth Law, we now can state that the mercury is in thermal equilibrium with the water, and indeed measuring the temperature of the mercury is the same as measuring the temperature of the water:

$$T_{Hg} = T_g$$

and $$T_g = T_w$$

so $$T_{Hg} = T_w$$

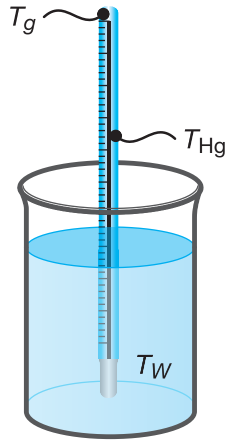

FIGURE 1.23 A mercury thermometer measuring the temperature of water. The three systems (the mercury, the glass, and the water) are all in thermal equilibrium, so the temperature of the mercury (what is being read) is the same as the temperature of the water.

Notice that reaching thermal equilibrium is a requirement for this temperature measurement concept to work. If we stored the mercury thermometer in a refrigerator and then took it out and placed it into a glass of boiling water, looking at the temperature of the mercury as shown by the thermometer immediately after placing it into the water would not yield the water temperature. Thermal equilibrium between the three systems would not have been reached at that point, and the Zeroth Law indicates that the mercury temperature is not the water temperature until the thermal equilibrium conditions are met.

1.4 PHASES OF MATTER

A ***pure substance*** is a substance that is chemically homogeneous—a substance that has a uniform chemical composition throughout. A pure substance can be either a single-molecule substance (such as water, nitrogen, and oxygen) or it can be a mixture of substances that has a constant composition throughout (such as air, which is a mixture of gases that has the same composition throughout a reasonably sized system). A ***phase*** of matter is a quantity of matter of a pure substance that is physically homogeneous. So a phase is chemically and physically uniform throughout. There are a relatively small number of phases of matter, three of which are of primary concern to engineers: solid, liquid, and gas. The plasma phase is important in some applications, and phases such as a Bose-Einstein condensate are primarily of interest at a scientific, but not necessarily practical, level.

The solid phase is characterized by a quantity of matter whose atoms or molecules are in a fixed lattice structure. The atoms or molecules are spaced closely together and held in place by intermolecular attractive forces. A solid maintains its shape without the aid of a container. As a solid is heated, the molecules will oscillate more and more inside the lattice structure and eventually will have enough energy to break free of the lattice. This is a melting process if the molecules move into the liquid phase, and a sublimation process if the molecules move into the gas phase.

The liquid phase still has molecules spaced closely together, but the molecules are not in a fixed lattice structure. The molecules are free to move inside the phase and are not forced into a position next to another particular molecule: the molecules can translate and rotate. The intermolecular forces are not as strong as with the solid phase, but are strong enough to keep the molecules in a somewhat orderly and structured environment. As more energy is added to the liquid, the molecules can gain enough energy to overcome the intermolecular forces binding the liquid together, and the boiling process to a gas occurs.

The gas phase is characterized by free atoms or molecules moving in random directions unattached to other molecules. The spacing between the molecules is great, and intermolecular forces are very small. Interactions between molecules in a gas occur primarily through random collisions as the molecules move in different directions. Sometimes, the gas phase will be referred to as the vapor phase. These phases are identical, with the term ***vapor*** being more typically applied to substances that are relatively close to their boiling/condensation point with the liquid phase. Gas is a term that is more commonly reserved for substances that are commonly experienced as a gas, even though we know that they could exist in other phases. So, we often will refer to hydrogen gas, or nitrogen gas, or carbon dioxide gas, because these substances are typically, in everyday life, experienced only in the gas phase. However, the gaseous phase of water is often called "water vapor" because we experience water in liquid and gaseous (and solid) forms often.

The phases can also change as a result of energy being removed from the material. A gas will condense into a liquid (or directly to a solid under the appropriate conditions), and a liquid will freeze into a solid. If energy is added to the material, the phase changes can occur in the opposite direction. For a substance, the temperatures at which these processes occur are dependent on the pressure of the system and do not depend on the direction of the phase change. So, at a pressure of 1 atm, pure water will change from the solid phase (ice) to the liquid phase through melting at 0°C, and liquid water will change to ice through freezing at 0°C as well. Similarly, liquid water at 1 atm will boil to the gas phase (water vapor) at 100°C, and water vapor will condense to liquid water at 100°C. These temperatures are different at different pressures, as illustrated in **Figure 1.24**. For example, the boiling/condensation temperature of water at 200 kPa is 120.2°C, and at 1000 kPa is 179.9°C.

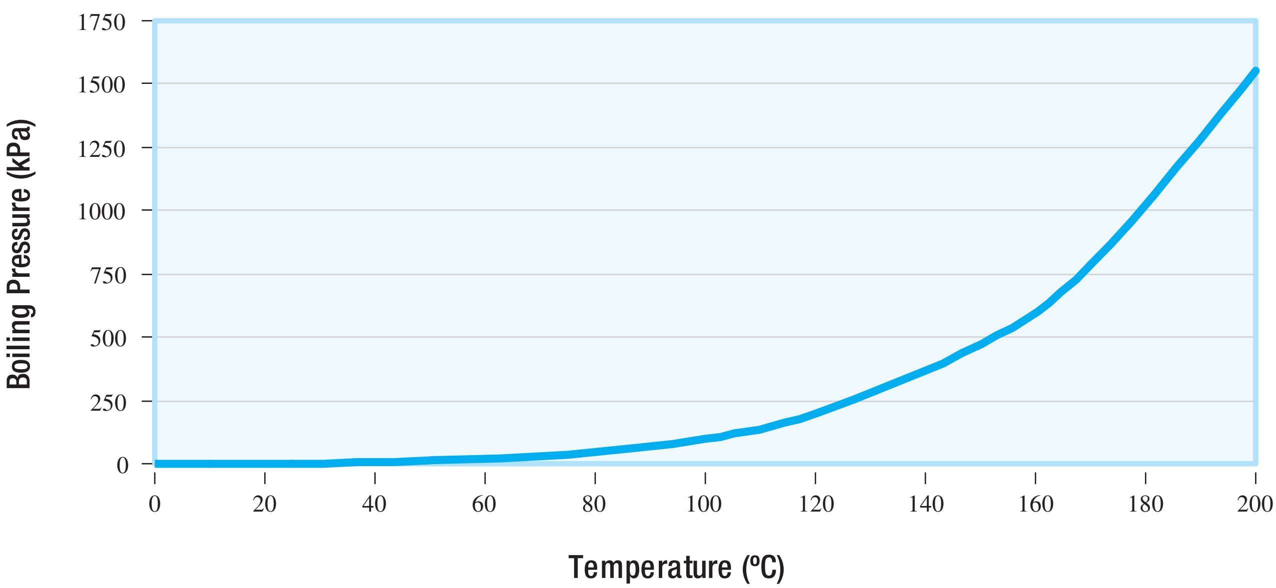

FIGURE 1.24 The boiling pressure of water as a function of temperature.

As will be discussed in greater detail in Chapter 3, a pure substance can exist in a system in more than one phase. A common example of this is a glass of ice water, containing both liquid water and ice, at the same temperature if thermal equilibrium has been reached between the two. When multiple phases of a substance exist inside a system and the masses of each phase are unchanging, the system is considered to be in ***phase equilibrium***. Phase equilibrium is one of the requirements necessary for a system to be considered to be in thermodynamic equilibrium.

QUESTION FOR THOUGHT/DISCUSSION

What are two ways you could stop liquid water at 1 atm and 100°C from boiling?

Summary

In this chapter, we have established the importance of energy in the world and the need for engineers to understand the science that describes energy: thermodynamics. We have described some of the fundamental concepts involving thermodynamic analysis, such as the system, the process, and the concept of thermodynamic properties. The SI and EE unit systems have been introduced, and it should be noted that most of the focus of this book is on using SI units. The basic properties that are used to typically describe systems, such as temperature and pressure, have been discussed. The Zeroth Law of Thermodynamics was presented, and its application to temperature measurement systems was explored. Finally, the idea of a phase of matter was presented.

These are all fundamental concepts, many of which may already be familiar to you through other courses. However, the rest of this book relies on these concepts, and you should be certain you thoroughly understand these principles before moving forward. Some of the principles will be explicitly referred to at future points in the book, but other concepts (such as thermodynamic equilibrium or the Zeroth Law) will be implicitly assumed as being a fundamental component of the development of the principles of thermodynamics.

KEY EQUATIONS

Temperature Scale Conversions:

$$T(°C) = \frac{5}{9}[T(°F) - 32] \quad (1.4)$$

$$T(°F) = \frac{9}{5}T(°C) + 32 \quad (1.5)$$

$$T(K) = T(°C) + 273.15 \quad (1.6)$$

$$T(R) = T(°F) + 459.67 \quad (1.7)$$

Force:

$$F = ma/g_c \quad (1.9)$$

where $g_c = 1$ (SI units) or $g_c = 32.174$ lbm · ft/(lbf · s^2) (EE units)

Absolute Pressure:

$$P = P_g + P_{atm} \quad (1.13)$$

PROBLEMS

1.1 For the following systems, determine whether the system described is best modeled as an isolated, closed, or open system:

- **(a)** steam flowing through a turbine
- **(b)** an incandescent light bulb
- **(c)** a fuel pump in a moving automobile
- **(d)** an anchor of a sunken ship resting 3000 m below the surface of the ocean
- **(e)** the roof of a house

1.2 For the following systems, determine whether the system described is best modeled as an isolated, closed, or open system:

- **(a)** a tree growing in a forest
- **(b)** a television
- **(c)** a laptop computer
- **(d)** the *Voyager 2* spacecraft in its current state
- **(e)** the *Messenger* spacecraft as it moved into orbit around Mercury

1.3 For the following systems, determine whether the system described is best modeled as an isolated, closed, or open system:

- **(a)** an inflated tire
- **(b)** a lawn sprinkler actively in use
- **(c)** a cup filled with liquid water
- **(d)** an engine's radiator
- **(e)** a rock formation 200 m below the surface of the earth

1.4 For the following systems, determine whether the system described is best modeled as an isolated, closed, or open system:

- **(a)** a pump supplying water to a building
- **(b)** a tea kettle containing boiling water
- **(c)** an active volcano
- **(d)** a solid gold bar placed inside a very well-insulated box
- **(e)** a chair

1.5 For the following systems, determine whether the system described is best modeled as an isolated, closed, or open system:

- **(a)** a pulley on an elevator
- **(b)** a bathtub
- **(c)** a human being
- **(d)** a piece of metal being shaped on a lathe
- **(e)** a comet orbiting the sun in the Oort cloud (the cloud of inactive comets located well beyond the orbits of the planets)

1.6 Consider a closed bottle half-filled with water and placed in a refrigerator. Draw diagrams showing the most appropriate system for a thermodynamic analysis that

- **(a)** only considers the water
- **(b)** considers only the water and the air inside the bottle
- **(c)** considers the water and air inside the bottle, and the bottle itself
- **(d)** considers only the bottle and not the contents
- **(e)** considers all the contents of the refrigerator, but not the physical refrigerator

1.7 Consider a fire hose with water flowing through the hose and then through a nozzle at the end of the hose. Draw diagrams showing the most appropriate system for a thermodynamic analysis that

(a) considers only the water in the nozzle of the system
(b) considers the water flowing through the hose and the nozzle
(c) considers both the water flowing through the nozzle and the nozzle itself

1.8 A basketball is about to leave a player's hand for a shot. Draw diagrams showing the most appropriate system for a thermodynamic analysis that

(a) considers only the air inside the basketball
(b) considers only the material making up the basketball, and not the air inside the ball
(c) considers the basketball and the air inside
(d) considers the basketball, the air inside, and the player's hand
(e) considers the entire arena in which the basketball is located

1.9 To condense a flow of steam, liquid cooling water is sent through a pipe, and the steam is passed over the exterior of the pipe. Draw diagrams showing the most appropriate system for a thermodynamic analysis that

(a) considers only the water flowing through the pipe
(b) considers only the steam condensing on the exterior of the pipe
(c) considers only the pipe
(d) considers the pipe, the internal cooling water, and the external condensing steam

1.10 Draw a schematic diagram of the place where you live. Identify any places where mass or energy may flow into or out of the room or building.

1.11 Draw a schematic diagram of an automobile engine. Identify any locations where mass or energy may flow into or out of the engine.

1.12 Draw a schematic diagram of a desktop computer. Identify any locations where mass or energy may flow into or out of the computer.

1.13 Draw a schematic diagram of a highway bridge over a river. Identify any mechanisms that may cause mass or energy to flow into or out of the system of the bridge.

1.14 Draw a schematic diagram of an airplane in flight. Identify any locations where mass or energy may flow into or out of the airplane.

1.15 A closed system undergoes a constant volume (isochoric) process at 0.25 m^3/kg, as the pressure changes from 100 kPa to 300 kPa. Draw this process on a P-v (pressure vs. specific volume) diagram.

1.16 A system undergoes an isothermal process at 30°C as the specific volume changes from 0.10 m^3/kg to 0.15 m^3/kg. Draw this process on a T-v (temperature vs. specific volume) diagram.

1.17 A system undergoes an isobaric process from 50°C to 30°C, at a pressure of 200 kPa. Draw this process on a P-T (pressure vs. temperature) diagram.

1.18 A system undergoes a process described by Pv = constant, from an initial state of 100 kPa and 0.25 m^3/kg, to a final specific volume of 0.20 m^3/kg. Determine the final pressure, and draw this process on a P-v (pressure vs. specific volume) diagram.

1.19 Draw on a P-v diagram the following three sequential processes that a system undergoes:

(a) a constant-pressure expansion from an initial state of 500 kPa and 0.10 m^3/kg to a specific volume of 0.15 m^3/kg
(b) a constant-specific-volume depressurization to a pressure of 300 kPa
(c) a process following Pv = constant to a final pressure of 400 kPa

1.20 Draw a T-v diagram of the following three sequential processes that a system undergoes:

(a) a constant-specific-volume heating from 300 K and 0.80 m^3/kg to a temperature of 450 K
(b) an isothermal compression to a specific volume of 0.60 m^3/kg
(c) an isochoric cooling to 350 K

1.21 Draw a P-T diagram of a system undergoing the following two sequential processes:

(a) an isothermal compression from 500 K and 250 kPa to a pressure of 500 kPa
(b) an isobaric cooling to a temperature of 350 K

1.22 Draw a P-v diagram of a closed system undergoing the following four sequential processes:

(a) an isobaric compression from 200 kPa and 0.50 m^3/kg to a specific volume of 0.20 m^3/kg
(b) a constant-volume expansion to a specific volume of 0.30 m^3/kg
(c) a constant-volume depressurization to a pressure of 125 kPa
(d) a constant-pressure expansion to a specific volume of 0.30 m^3/kg

1.23 A thermodynamic cycle consists of the following three processes. Draw the cycle on a T-v diagram.

(a) a constant-volume heating from 0.10 m^3/kg and 300 K to 500 K
(b) an isothermal expansion to a specific volume of 0.15 m^3/kg
(c) a linear process returning the process to its initial state

1.24 A thermodynamic cycle consists of the following three processes. Draw the cycle on a P-v diagram.

(a) an isobaric compression from 300 kPa and 1.20 m^3/kg to a specific volume of 0.80 m^3/kg
(b) a process for which Pv = constant to a specific volume of 1.20 m^3/kg
(c) a constant-volume process resulting in a pressure of 300 kPa

1.25 A thermodynamic cycle involves the following four processes. Draw the cycle on a P-T diagram.

(a) an isobaric heating from 500 K and 400 kPa to a temperature of 700 K
(b) an isothermal compression to a pressure of 800 kPa
(c) an isobaric cooling to a temperature of 500 K
(d) an appropriate isothermal expansion

1.26 The melting point of lead at atmospheric pressure is 601 K. Determine this temperature in °C, °F, and R.

1.27 The melting point of gold at atmospheric pressure is 2405 R. Determine this temperature in °C, °F, and K.

1.28 At a pressure of 5.1 atm, carbon dioxide will condense into a liquid at –57°C. Determine this temperature in °F, K, and R.

1.29 The "normal" temperature for a human being is 98.6°F. Determine this temperature in °C, K, and R.

1.30 The boiling point of ammonia at atmospheric pressure is 239.7 K. Determine this temperature in °C, °F, and R.

1.31 The melting point of aluminum at atmospheric pressure is 1220°F. Determine this temperature in °C, K, and R.

1.32 At atmospheric pressure, the boiling point of methanol is 337.7 K and the boiling point of ethanol is 351.5 K. Convert both of these temperatures to degrees Celsius, and determine the difference in these temperatures in both K and °C.

1.33 At atmospheric pressure, the melting point of pure platinum is 2045 K, and the melting point of silver is 1235 K. Convert both of these temperatures to degrees Celsius, and determine the difference in these temperatures in both K and °C.

1.34 You wish to drop an ice cube into a cup of hot water to cool the water. The temperature of the ice cube is –10°C, and the water temperature is 92°C. Convert both of these temperatures to Kelvin, and determine the difference between the temperatures in both K and °C.

1.35 Oxygen, O_2, has a molecular mass of 32 kg/kmole. How many moles does 17 kg of O_2 represent?

1.36 You determine that 1.2 kmole of a substance has a mass of 14.4 kg. Determine the molecular mass of the substance.

1.37 You are asked if you would like to have a box which contains 3.5 kmole of gold. The only condition of the deal is that you must carry the box away using only your own strength. What is the mass of the gold in the box if the molecular mass of the gold is 197 kg/kmole? Do you think you will be able to accept this deal?

1.38 Suppose that one kilomole of any gaseous substance at a given temperature and pressure occupies a volume of 24 m^3. The density of a particular gas at these conditions is 1.28 kg/m^3. How much mass of the gas is present if you have a 2.0-m^3 container full of the gas at the given temperature and pressure, and what is the molecular mass of the gas?

1.39 Burning a hydrocarbon fuel will convert the carbon in the fuel to carbon dioxide. For every kmole of carbon to be burned, you need 1 kmole of oxygen (O_2). This produces 1 kmole of CO_2. If you originally have 2 kg of carbon to be burned, what is the mass of the CO_2 that will be produced? The molecular mass of carbon is 12 kg/kmole, of oxygen is 32 kg/kmole, and of CO_2 is 44 kg/kmole.

1.40 A rock at sea level on earth (where $g = 9.81\ m/s^2$) has a mass of 25 kg. What is the weight of the rock in Newtons?

1.41 On a distant planet, the acceleration due to gravity is 6.84 m/s^2. The weight of an object on that planet is 542 N. What is the mass of the object? If that object is moved to earth, where $g = 9.81\ m/s^2$, what is the weight of the object?

1.42 How much force is needed to accelerate a ball with a mass of 0.5 kg at a rate of 25 m/s^2?

1.43 How much force is needed to accelerate a block with a mass of 1.59 lbm at a rate of 35 ft/s^2?

1.44 An object has a mass of 145 lbm. This object is sent into space and is placed onto the surface of a planet where the acceleration due to gravity is 25 ft/s^2. What is the weight of the object in lbf on the other planet?

1.45 The acceleration due to gravity on Mars is 12.17 ft/s^2. At sea level on earth, an astronaut can lift an object that weighs 125 lbf. What is the mass of an object that the astronaut could lift on Mars?

1.46 A club applies a force of 12 lbf to a rubber ball that has a mass of 1.5 lbm. What is the acceleration experienced by the ball as it encounters the force?

1.47 What force is required to accelerate a 5.0-lbm rock at a rate of 35 ft/s^2?

1.48 The specific volume of steam at 500°C and 500 kPa is 0.7109 m^3/kg. You have a container whose volume is 0.57 m^3, which is full of the steam at 500°C and 500 kPa. Determine the mass of the steam in the container.

1.49 A solid block of unknown composition has dimensions of 0.5 m in length, 0.25 m in width, and 0.1 m in height. The weight of the block at sea level (g = 9.81 m/s^2) is 45 N. Determine the specific volume of the block.

1.50 A mixture of liquid water and water vapor occupies a cylindrical tube whose diameter is 0.05 m and whose length is 0.75 m. If the specific volume of the water is 0.00535 m^3/kg, determine the mass of the water present.

1.51 The density of several metals is as follows: lead: 11,340 kg/m^3; tin: 7310 kg/m^3; aluminum: 2702 kg/m^3. You are given a small box (0.1 m × 0.1 m × 0.075 m) and are told that it is filled with one of these metals. Unable to open the box and unable to read the label on the box, you decide to weigh the box to determine the metal inside. You find that the weight of the box is 53.8 N. Determine the density and specific volume of the box, and choose the likely metal inside.

1.52 A person with a mass of 81 kg stands on a small platform whose base is 0.25 m × 0.25 m. Determine the pressure exerted on the ground below the platform by the person.

1.53 A wall of area 2.5 m^2 is hit by a gust of wind. The force exerted by the wind on the wall is 590 kN. Determine the pressure exerted by the wind on the wall.

1.54 A press applies a pressure of 800 kPa uniformly over an area of 0.025 m^2. What is the total force applied by the press?

1.55 A manometer is used to determine the pressure difference between the atmosphere and a tank of liquid. The fluid used in the manometer is water, with a density of 1000 kg/m^3. The manometer is located at sea level, where g = 9.81 m/s^2. The difference in height between the liquid in the two legs of the manometer is 0.25 m. Determine the pressure difference.

1.56 A mercury (ρ = 13,500 kg/m^3) manometer is used to measure the pressure difference between two tanks containing fluids. The difference in height of the mercury in the two legs is 10 cm. Determine the difference in pressure between the tanks.

1.57 You choose to use a mercury (ρ = 13,500 kg/m^3) manometer to check the accuracy of a pressure gage on a compressed nitrogen gas tank. The manometer is set up between the tank and the atmosphere, and the height difference for the mercury in the two legs is 1.52 m. The pressure gage to be checked reads a pressure of 275 kPa for the gage pressure of the tank. Is the pressure gage accurate?

1.58 Compressed gas tanks often have gage pressures of at least 1 MPa. Suppose you wished to use a manometer to measure the gage pressure of a compressed air tank whose pressure was at least 1 MPa. The manometer would be set up between the tank and the atmosphere. What is the minimum length of tube needed for such a measurement if the liquid in the manometer is (a) mercury (ρ = 13,500 kg/m^3), (b) water (ρ = 1000 kg/m^3), and (c) engine oil (ρ = 880 kg/m^3)? Do these seem to be practical devices for such a measurement?

1.59 A manometer using a liquid with a density of 625 lbm/ft^3 is set up to measure the pressure difference between two locations in a flow system. The height of the manometer liquid is 0.52 ft. What is the pressure difference between the two locations?

1.60 The pressure gage on a tank of compressed nitrogen reads 785 kPa. A barometer is used to measure the local atmospheric pressure as 99 kPa. What is the absolute pressure in the tank?

1.61 The pressure gage on a tank of compressed air reads 120 psi. The local atmospheric pressure is measured as 14.5 psi. What is the absolute pressure in the tank?

1.62 A pressure gage is used to measure the pressure of air inside a piston–cylinder device. The diameter of the cylinder is 8 cm. While the piston is at rest, the gage measures the pressure to be 40 kPa. A barometer measures the atmospheric pressure to be 100 kPa. A weight with a mass of 20 kg is placed on the top of the piston, and the piston moves until it reaches a new equilibrium point. What is the new gage pressure and the new absolute pressure of the air in the cylinder when this new equilibrium is reached?

1.63 The absolute pressure of air in a piston–cylinder device is 220 kPa. The local atmospheric pressure is 99 kPa. If the acceleration due to gravity is 9.79 m/s^2, and if the diameter of the cylinder is 0.10 m, what is the mass of the piston?

1.64 Air is located in a piston–cylinder device. The diameter of the cylinder is 12 cm, the mass of the piston is 5 kg, and the acceleration due to gravity is 9.80 m/s^2. The local atmospheric pressure is 100.5 kPa. Determine the mass of a set of weights that needs to be added to the top of the piston so that the absolute pressure of the air in the cylinder is 250 kPa.

1.65 A tank of liquid exerts a pressure of 300 kPa on a plug on the bottom of the tank. The local atmospheric pressure is 99 kPa. The diameter of the circular plug is 2.5 cm. What is the additional force that needs to be applied to the plug to keep the plug in place?

1.66 What is the absolute pressure of air located in a piston–cylinder device for a cylinder of diameter 0.5 ft, with a piston mass of 150 lbm, and with local atmospheric pressure of 14.65 psi? The device is located at sea level on earth.

1.67 Consider a piston–cylinder device initially at equilibrium with the air pressure inside the cylinder being 150 kPa. It is desired to raise the pressure of the air to 300 kPa by adding air to the cylinder, without changing the location of the piston. If the piston has a diameter of 8 cm, how much mass needs to be added to the piston to keep the piston in the same location with the higher pressure? Assume standard acceleration due to gravity at sea level on earth.

CHAPTER 2

The Nature of Energy

Learning Objectives

Upon completion of Chapter 2, you will be able to

2.1 Explain the nature of energy and the different forms that energy can take;

2.2 Identify the methods of transporting energy into or out of a system;

2.3 Recognize the three modes of heat transfer;

2.4 Describe and compute the many modes of work; and

2.5 Express an approach and framework for solving thermodynamic problems.

2.1 WHAT IS ENERGY?

Energy is something that most people inherently understand, but it is very hard to define. The *Oxford English Dictionary* defines *energy* as the "ability or capacity to produce an effect." Considering this definition, a substance or object with energy has the ability to change itself or its surroundings. For example, a substance with energy can move, or it can do work, or it can heat some other substance. Energy is a property of a substance. The quantity of energy that a substance has is not related to how the state of the substance was reached, but rather is only a function of the local thermodynamic equilibrium state. In this chapter, we will describe some of these concepts in more detail.

Energy is also of great interest in the world today. Modern society has developed because of the ability of humans to harness the energy in the world around us. The use of energy surrounds us every day. Energy is used to heat or cool buildings. Energy is used by vehicles to transport people and goods. Energy is used in computers, lights, and every electrical device in our homes and offices. Energy is used to manufacture everything we see around us. As a result, the supply and cost of energy is often paramount in our minds. Many engineers deal with energy on an everyday basis. Some engineers work on producing electricity or transportation fuels. Some engineers seek new ways to harness nature's energy. Other engineers try to make devices more efficient users of energy so that the energy that is available can last longer. Although not every engineer works in such areas, the efficient use of energy touches the jobs of most engineers at least intermittently, and not necessarily in obvious ways. Consider that it might be natural for a bridge designer to seek to use less material in their bridges in order to keep costs down. How does using less material reduce costs? As one consideration, it requires energy to turn raw materials into the steel and concrete