MORAN | SHAPIRO | BOETTNER | BAILEY

Principles of Engineering Thermodynamics

Eighth Edition

EXCLUSIVE CONTENT

SI VERSION

WILEY

How to Use This Book Effectively

This book is organized by chapters and sections within chapters. For a listing of contents, see pp. xi–xviii. Fundamental concepts and associated equations within each section lay the foundation for applications of engineering thermodynamics provided in solved examples, end-of-chapter problems and exercises, and accompanying discussions. **Boxed material** within sections of the book allows you to explore selected topics in greater depth, as in the boxed discussion of properties and nonproperties on p. 8.

Contemporary issues related to thermodynamics are introduced throughout the text with three unique features: **ENERGY & ENVIRONMENT** discussions explore issues related to energy resource use and the environment, as in the discussion of hybrid vehicles on p. 32. **BIOCONNECTIONS** discussions tie topics to applications in bioengineering and biomedicine, as in the discussion of control volumes of living things and their organs on p. 5.

Horizons link subject matter to emerging technologies and thought-provoking issues, as in the discussion of nanotechnology on p. 13.

Other core features of this book that facilitate your study and contribute to your understanding include:

Examples

- Numerous annotated solved examples are provided that feature the **solution methodology** presented in Sec. 1.9 and illustrated in Example 1.1. We encourage you to study these examples, including the accompanying comments.
- Each solved example concludes with a list of the **Skills Developed** in solving the example and a ***Quick*Quiz** that allows an immediate check of understanding.
- Less formal examples are given throughout the text. They open with ▶ FOR EXAMPLE and close with ◀ ◀ ◀ ◀ ◀. These examples also should be studied.

Exercises

- Each chapter has a set of discussion questions under the heading ▶ EXERCISES: THINGS ENGINEERS THINK ABOUT that may be done on an individual or small-group basis. They allow you to gain a deeper understanding of the text material, think critically, and test yourself.
- A large number of end-of-chapter problems also are provided under the heading ▶ PROBLEMS: DEVELOPING ENGINEERING SKILLS. The problems are sequenced to coordinate with the subject matter and are listed in increasing order of difficulty. The problems are also classified under headings to expedite the process of selecting review problems to solve. Answers to selected problems are provided on the **student companion website** that accompanies this book.
- Because one purpose of this book is to help you prepare to use thermodynamics in engineering practice, design considerations related to thermodynamics are included. Every chapter has a set of problems under the heading ▶ DESIGN & OPEN ENDED PROBLEMS: EXPLORING ENGINEERING PRACTICE that provide opportunities for practicing creativity, formulating and solving design and open-ended problems, using the Internet and library resources to find relevant information, making engineering judgments, and developing communications skills. See, for example, problem 1.10D on p. 29.

Further Study Aids

- Each chapter opens with an introduction giving the **engineering context**, stating the **chapter objective**, and listing the **learning outcomes**.
- Each chapter concludes with a ▶ CHAPTER SUMMARY AND STUDY GUIDE that provides a point of departure to study for examinations.
- For easy reference, each chapter also concludes with lists of ▶ KEY ENGINEERING CONCEPTS and ▶ KEY EQUATIONS.
- Important terms are listed in the margins and coordinated with the text material at those locations.
- Important equations are set off by a color screen, as for Eq. 1.8.
- **TAKE NOTE...** in the margin provides just-in-time information that illuminates the current discussion, as on p. 6, or refines our problem-solving methodology, as on p. 10 and p. 20.
- A in the margin identifies an animation that reinforces the text presentation at that point. Animations can be viewed by going to the **student companion website** for this book. See **TAKE NOTE...** on p. 6 for further detail about accessing animations.
- in the margin denotes end-of-chapter problems where the use of appropriate computer software is recommended.
- For quick reference, conversion factors and important constants are provided on the next page.
- A list of symbols is provided on the inside back cover.

Conversion Factors

Mass and Density

1 kg = 2.2046 lb
1 g/cm^3 = 10^3 kg/m^3
1 g/cm^3 = 62.428 lb/ft^3
1 lb = 0.4536 kg
1 lb/ft^3 = 0.016018 g/cm^3
1 lb/ft^3 = 16.018 kg/m^3

Length

1 cm = 0.3937 in.
1 m = 3.2808 ft
1 in. = 2.54 cm
1 ft = 0.3048 m

Velocity

1 km/h = 0.62137 mile/h
1 mile/h = 1.6093 km/h

Volume

1 cm^3 = 0.061024 in.^{3}
1 m^3 = 35.315 ft^3
1 L = 10^{-3} m^3
1 L = 0.0353 ft^3
1 in.^{3} = 16.387 cm^3
1 ft^3 = 0.028317 m^3
1 gal = 0.13368 ft^3
1 gal = 3.7854×10^{-3} m^3

Force

1 N = 1 kg · m/s^2
1 N = 0.22481 lbf
1 lbf = 32.174 lb · ft/s^2
1 lbf = 4.4482 N

Pressure

1 Pa = 1 N/m^2
= 1.4504×10^{-4} lbf/in.^{2}
1 bar = 10^5 N/m^2
1 atm = 1.01325 bar
1 lbf/in.^{2} = 6894.8 Pa
1 lbf/in.^{2} = 144 lbf/ft^2
1 atm = 14.696 lbf/in.^{2}

Energy and Specific Energy

1 J = 1 N · m = 0.73756 ft · lbf
1 kJ = 737.56 ft · lbf
1 kJ = 0.9478 Btu
1 kJ/kg = 0.42992 Btu/lb
1 ft · lbf = 1.35582 J
1 Btu = 778.17 ft · lbf
1 Btu = 1.0551 kJ
1 Btu/lb = 2.326 kJ/kg
1 kcal = 4.1868 kJ

Energy Transfer Rate

1 W = 1 J/s = 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

Specific Heat

1 kJ/kg · K = 0.238846 Btu/lb · °R
1 kcal/kg · K = 1 Btu/lb · °R
1 Btu/h · °R = 4.1868 kJ/kg · K

Others

1 ton of refrigeration = 200 Btu/min = 211 kJ/min
1 volt = 1 watt per ampere

Constants

Universal Gas Constant

$$\bar{R} = \begin{cases} 8.314 \text{ kJ/kmol} \cdot \text{K} \\ 1545 \text{ ft} \cdot \text{lbf/lbmol} \cdot {}^\circ\text{R} \\ 1.986 \text{ Btu/lbmol} \cdot {}^\circ\text{R} \end{cases}$$

Standard Acceleration of Gravity

$$g = \begin{cases} 9.80665 \text{ m/s}^2 \\ 32.174 \text{ ft/s}^2 \end{cases}$$

Standard Atmospheric Pressure

$$1 \text{ atm} = \begin{cases} 1.01325 \text{ bar} \\ 14.696 \text{ lbf/in.}^2 \\ 760 \text{ mm Hg} = 29.92 \text{ in. Hg} \end{cases}$$

Temperature Relations

$T(^\circ\text{R}) = 1.8\, T(\text{K})$
$T(^\circ\text{C}) = T(\text{K}) - 273.15$
$T(^\circ\text{F}) = T(^\circ\text{R}) - 459.67$

How to Use This Book Effectively

This book is organized by chapters and sections within chapters. For a listing of contents, see pp. xi–xviii. Fundamental concepts and associated equations within each section lay the foundation for applications of engineering thermodynamics provided in solved examples, end-of-chapter problems and exercises, and accompanying discussions. **Boxed material** within sections of the book allows you to explore selected topics in greater depth, as in the boxed discussion of properties and nonproperties on p. 8.

Contemporary issues related to thermodynamics are introduced throughout the text with three unique features: **ENERGY & ENVIRONMENT** discussions explore issues related to energy resource use and the environment, as in the discussion of hybrid vehicles on p. 32. **BIOCONNECTIONS** discussions tie topics to applications in bioengineering and biomedicine, as in the discussion of control volumes of living things and their organs on p. 5.

Horizons link subject matter to emerging technologies and thought-provoking issues, as in the discussion of nanotechnology on p. 13.

Other core features of this book that facilitate your study and contribute to your understanding include:

Examples

- Numerous annotated solved examples are provided that feature the **solution methodology** presented in Sec. 1.9 and illustrated in Example 1.1. We encourage you to study these examples, including the accompanying comments.
- Each solved example concludes with a list of the **Skills Developed** in solving the example and a ***Quick*Quiz** that allows an immediate check of understanding.
- Less formal examples are given throughout the text. They open with **▶ FOR EXAMPLE** and close with ◀ ◀ ◀ ◀ ◀. These examples also should be studied.

Exercises

- Each chapter has a set of discussion questions under the heading **▶ EXERCISES: THINGS ENGINEERS THINK ABOUT** that may be done on an individual or small-group basis. They allow you to gain a deeper understanding of the text material, think critically, and test yourself.
- A large number of end-of-chapter problems also are provided under the heading **▶ PROBLEMS: DEVELOPING ENGINEERING SKILLS**. The problems are sequenced to coordinate with the subject matter and are listed in increasing order of difficulty. The problems are also classified under headings to expedite the process of selecting review problems to solve. Answers to selected problems are provided on the **student companion website** that accompanies this book.
- Because one purpose of this book is to help you prepare to use thermodynamics in engineering practice, design considerations related to thermodynamics are included. Every chapter has a set of problems under the heading **▶ DESIGN & OPEN ENDED PROBLEMS: EXPLORING ENGINEERING PRACTICE** that provide opportunities for practicing creativity, formulating and solving design and open-ended problems, using the Internet and library resources to find relevant information, making engineering judgments, and developing communications skills. See, for example, problem 1.10D on p. 29.

Further Study Aids

- Each chapter opens with an introduction giving the **engineering context**, stating the **chapter objective**, and listing the **learning outcomes**.
- Each chapter concludes with a **▶ CHAPTER SUMMARY AND STUDY GUIDE** that provides a point of departure to study for examinations.
- For easy reference, each chapter also concludes with lists of **▶ KEY ENGINEERING CONCEPTS** and **▶ KEY EQUATIONS**.
- Important terms are listed in the margins and coordinated with the text material at those locations.
- Important equations are set off by a color screen, as for Eq. 1.8.
- **TAKE NOTE...** in the margin provides just-in-time information that illuminates the current discussion, as on p. 6, or refines our problem-solving methodology, as on p. 10 and p. 20.
- A in the margin identifies an animation that reinforces the text presentation at that point. Animations can be viewed by going to the **student companion website** for this book. See **TAKE NOTE...** on p. 6 for further detail about accessing animations.
- For quick reference, conversion factors and important constants are provided on the next page.
- A list of symbols is provided on the inside back cover.

Conversion Factors

Mass and Density

$1 \text{ kg} = 2.2046 \text{ lb}$
$1 \text{ g/cm}^3 = 10^3 \text{ kg/m}^3$
$1 \text{ g/cm}^3 = 62.428 \text{ lb/ft}^3$
$1 \text{ lb} = 0.4536 \text{ kg}$
$1 \text{ lb/ft}^3 = 0.016018 \text{ g/cm}^3$
$1 \text{ lb/ft}^3 = 16.018 \text{ kg/m}^3$

Length

1 cm = 0.3937 in.
1 m = 3.2808 ft
1 in. = 2.54 cm
1 ft = 0.3048 m

Velocity

1 km/h = 0.62137 mile/h
1 mile/h = 1.6093 km/h

Volume

$1 \text{ cm}^3 = 0.061024 \text{ in.}^3$
$1 \text{ m}^3 = 35.315 \text{ ft}^3$
$1 \text{ L} = 10^{-3} \text{ m}^3$
$1 \text{ L} = 0.0353 \text{ ft}^3$
$1 \text{ in.}^3 = 16.387 \text{ cm}^3$
$1 \text{ ft}^3 = 0.028317 \text{ m}^3$
$1 \text{ gal} = 0.13368 \text{ ft}^3$
$1 \text{ gal} = 3.7854 \times 10^{-3} \text{ m}^3$

Force

$1 \text{ N} = 1 \text{ kg} \cdot \text{m/s}^2$
$1 \text{ N} = 0.22481 \text{ lbf}$
$1 \text{ lbf} = 32.174 \text{ lb} \cdot \text{ft/s}^2$
$1 \text{ lbf} = 4.4482 \text{ N}$

Pressure

$1 \text{ Pa} = 1 \text{ N/m}^2$
$= 1.4504 \times 10^{-4} \text{ lbf/in.}^2$
$1 \text{ bar} = 10^5 \text{ N/m}^2$
$1 \text{ atm} = 1.01325 \text{ bar}$
$1 \text{ lbf/in.}^2 = 6894.8 \text{ Pa}$
$1 \text{ lbf/in.}^2 = 144 \text{ lbf/ft}^2$
$1 \text{ atm} = 14.696 \text{ lbf/in.}^2$

Energy and Specific Energy

$1 \text{ J} = 1 \text{ N} \cdot \text{m} = 0.73756 \text{ ft} \cdot \text{lbf}$
$1 \text{ kJ} = 737.56 \text{ ft} \cdot \text{lbf}$
1 kJ = 0.9478 Btu
1 kJ/kg = 0.42992 Btu/lb
$1 \text{ ft} \cdot \text{lbf} = 1.35582 \text{ J}$
$1 \text{ Btu} = 778.17 \text{ ft} \cdot \text{lbf}$
1 Btu = 1.0551 kJ
1 Btu/lb = 2.326 kJ/kg
1 kcal = 4.1868 kJ

Energy Transfer Rate

1 W = 1 J/s = 3.413 Btu/h
1 kW = 1.341 hp
1 Btu/h = 0.293 W
1 hp = 2545 Btu/h
$1 \text{ hp} = 550 \text{ ft} \cdot \text{lbf/s}$
1 hp = 0.7457 kW

Specific Heat

$1 \text{ kJ/kg} \cdot \text{K} = 0.238846 \text{ Btu/lb} \cdot {}^\circ\text{R}$
$1 \text{ kcal/kg} \cdot \text{K} = 1 \text{ Btu/lb} \cdot {}^\circ\text{R}$
$1 \text{ Btu/h} \cdot {}^\circ\text{R} = 4.1868 \text{ kJ/kg} \cdot \text{K}$

Others

1 ton of refrigeration = 200 Btu/min = 211 kJ/min
1 volt = 1 watt per ampere

Constants

Universal Gas Constant

$$\bar{R} = \begin{cases} 8.314 \text{ kJ/kmol} \cdot \text{K} \\ 1545 \text{ ft} \cdot \text{lbf/lbmol} \cdot {}^\circ\text{R} \\ 1.986 \text{ Btu/lbmol} \cdot {}^\circ\text{R} \end{cases}$$

Standard Acceleration of Gravity

$$g = \begin{cases} 9.80665 \text{ m/s}^2 \\ 32.174 \text{ ft/s}^2 \end{cases}$$

Standard Atmospheric Pressure

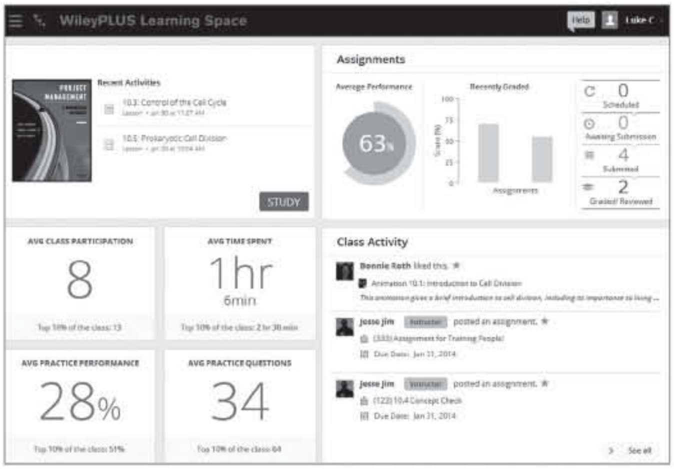
$$1 \text{ atm} = \begin{cases} 1.01325 \text{ bar} \\ 14.696 \text{ lbf/in.}^2 \\ 760 \text{ mm Hg} = 29.92 \text{ in. Hg} \end{cases}$$

Temperature Relations

$T({}^\circ\text{R}) = 1.8\, T(\text{K})$
$T({}^\circ\text{C}) = T(\text{K}) - 273.15$
$T({}^\circ\text{F}) = T({}^\circ\text{R}) - 459.67$

WileyPLUS Learning Space

An easy way to help your students **learn**, **collaborate**, and **grow**.



Personalized Experience

Students create their own study guide while they interact with course content and work on learning activities.

Flexible Course Design

Educators can quickly organize learning activities, manage student collaboration, and customize their course—giving them full control over content as well as the amount of interactivity between students.

Clear Path to Action

With visual reports, it's easy for both students and educators to gauge problem areas and act on what's most important.

Instructor Benefits

- Assign activities and add your own materials
- Guide students through what's important in the interactive e-textbook by easily assigning specific content
- Set up and monitor collaborative learning groups
- Assess learner engagement
- Gain immediate insights to help inform teaching

Student Benefits

- Instantly know what you need to work on
- Create a personal study plan
- Assess progress along the way
- Participate in class discussions
- Remember what you have learned because you have made deeper connections to the content

We are dedicated to supporting you from idea to outcome.

WILEY

PRINCIPLES OF ENGINEERING THERMODYNAMICS

SI Version

EIGHTH EDITION

MICHAEL J. MORAN

The Ohio State University

HOWARD N. SHAPIRO

Wayne State University

DAISIE D. BOETTNER

Colonel, U.S. Army

MARGARET B. BAILEY

Rochester Institute of Technology

WILEY

Cover photo from © Janaka Dharmasena/Shutterstock

Founded in 1807, John Wiley & Sons, Inc. has been a valued source of knowledge and understanding for more than 200 years, helping people around the world meet their needs and fulfill their aspirations. Our company is built on a foundation of principles that include responsibility to the communities we serve and where we live and work. In 2008, we launched a Corporate Citizenship Initiative, a global effort to address the environmental, social, economic, and ethical challenges we face in our business. Among the issues we are addressing are carbon impact, paper specifications and procurement, ethical conduct within our business and among our vendors, and community and charitable support. For more information, please visit our website: www.wiley.com/go/citizenship.

ISBN: 978-1-118-96088-2

Printed in Asia

10 9 8 7 6 5 4 3 2 1

Preface

A Textbook for the 21st Century

In the twenty-first century, engineering thermodynamics plays a central role in developing improved ways to provide and use energy, while mitigating the serious human health and environmental consequences accompanying energy—including air and water pollution and global climate change. Applications in bioengineering, biomedical systems, and nanotechnology also continue to emerge. This book provides the tools needed by specialists working in all such fields. For non-specialists, this book provides background for making decisions about technology related to thermodynamics—on the job and as informed citizens.

Engineers in the twenty-first century need a solid set of analytical and problem-solving skills as the foundation for tackling important societal issues relating to engineering thermodynamics. The eighth edition develops these skills and significantly expands our coverage of their applications to provide

- current context for the study of thermodynamic principles.
- relevant background to make the subject meaningful for meeting the challenges of the decades ahead.
- significant material related to existing technologies in light of new challenges.

In the eighth edition, we build on the **core features** that have made the text the global leader in engineering thermodynamics education. (The present discussion of core features centers on new aspects; see the Preface to the seventh edition for more.) We are known for our clear and concise explanations grounded in the fundamentals, pioneering pedagogy for effective learning, and relevant, up-to-date applications. Through the creativity and experience of our newly expanded author team, and based on excellent feedback from instructors and students, we continue to enhance what has become the leading text in the field.

New in the Eighth Edition

In a major departure from previous editions of this book and all other texts intended for the same student population, we have introduced ***animations*** that strengthen students' understanding of basic phenomena and applications. The eighth edition also features a **crisp new interior design** aimed at helping students

- better understand and apply the subject matter, and
- fully appreciate the relevance of the topics to engineering practice and to society.

This edition also provides, inside the front cover under the heading **How to Use This Book Effectively**, an updated roadmap to core features of this text that make it so effective for student learning. To fully understand all of the many features we have built into the book, be sure to see this important element.

In this edition, several enhancements to improve student learning have been introduced or upgraded:

- New **animations** are offered at key subject matter locations to improve student learning. When viewing the animations, students will develop deeper understanding by visualizing key processes and phenomena.
- Special text elements feature important illustrations of engineering thermodynamics applied to our environment, society, and world:
  - *New* **ENERGY & ENVIRONMENT** presentations explore topics related to energy resource use and environmental issues in engineering.
  - *Updated* **BIOCONNECTIONS** discussions tie textbook topics to contemporary applications in biomedicine and bioengineering.
  - Additional Horizons features have been included that link subject matter to thought-provoking 21st century issues and emerging technologies.

  Suggestions for additional reading and sources for topical content presented in these elements can be provided on request.
- End-of-chapter problems in each of the three modes, **conceptual, skill building, and design,** have been extensively revised and hundreds of new problems added.
- New and revised class-tested material contributes to student learning and instructor effectiveness:
  - Significant new content explores how thermodynamics contributes to meeting the challenges of the 21st century.
  - Key aspects of fundamentals and applications within the text have been enhanced.
- In response to instructor and student needs, class-tested changes that contribute to a more **just-in-time** presentation have been introduced:

- **TAKE NOTE...** entries in the margins are expanded throughout the textbook to improve student learning. For example, see p. 10.
- **Boxed material** allows students and instructors to explore topics in greater depth. For example, see p. 8.
- New **margin terms** at many locations aid in navigating subject matter.

Supplements

The following supplements are available with the text:

- Outstanding *Instructor* and *Student* companion websites (visit www.wiley.com/college/moran) that greatly enhance teaching and learning:
  - Instructor Companion Site: Assists instructors in delivering an effective course with resources including
    - animations—new in this edition.
    - chapter-by-chapter summary of Special Features, including
      - the subject of each solved example,
      - the topics of all **ENERGY & ENVIRONMENT**, **BIOCONNECTIONS**, and Horizons features,
      - the themes of the accompanying **DESIGN & OPEN ENDED PROBLEMS**
    - a complete solution manual that is easy to navigate.
    - solutions to computer-based problems for use with both *IT: Interactive Thermodynamics* as well as *EES: Engineering Equation Solver*.
    - image galleries with text images available in various helpful electronic formats.
    - chapter summary information, including Key Terms and Key Equations.
    - chapter learning outcomes.
  - Student Companion Site: Helps students learn the subject matter with resources including
    - animations—new in this edition.
    - answers to selected problems.
    - chapter summary information, including Key Terms and Key Equations.
    - chapter learning outcomes.
    - chapter-by-chapter summary of Special Features as listed in the Instructor Companion Site.
- *Interactive Thermodynamic: IT* software is available as a stand-alone product or with the textbook. *IT* is a highly valuable learning tool that allows students to develop engineering models, perform "what-if" analyses, and examine principles in more detail to enhance their learning. Brief tutorials of *IT* are included within the text, and the use of *IT* is illustrated within selected solved examples.
- *WileyPLUS* is an online set of instructional, practice, and course management resources, including the full text, for students and instructors.

Visit www.wiley.com/college/moran or contact your local Wiley representative for information on the above-mentioned supplements.

Ways to Meet Different Course Needs

In recognition of the evolving nature of engineering curricula, and in particular of the diverse ways engineering thermodynamics is presented, the text is structured to meet a variety of course needs. The following table illustrates several possible uses of the textbook assuming a semester basis (3 credits). Courses could be taught using this textbook to engineering students with appropriate background beginning in their second year of study.

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

Acknowledgments

We thank the many users of our previous editions, located at hundreds of universities and colleges in the United States, Canada, and worldwide, who continue to contribute to the development of our text through their comments and constructive criticism.

The following colleagues have assisted in the development of this edition. We greatly appreciate their contributions:

John Abbitt, University of Florida

Ralph Aldredge, University of California, Davis

Leticia Anaya, University of North Texas

Kendrick Aung, Lamar University

Justin Barone, Virginia Polytechnic Institute and State University

William Bathie, Iowa State University

Cory Berkland, The University of Kansas

Leonard Berkowitz, California State Polytechnic University, Pomona

Eugene F. Brown, Virginia Polytechnic Institute and State University

David L. Ernst, Texas Tech University

Sebastien Feve, Iowa State University

Timothy Fox, California State University, Northridge

Nick Glumac, University of Illinois at Urbana-Champaign

Tahereh S. Hall, Virginia Polytechnic Institute and State University

Daniel W. Hoch, University of North Carolina–Charlotte

Timothy J. Jacobs, Texas A&M University

Fazal B. Kauser, California State Polytechnic University, Pomona

MinJun Kim, Drexel University

Joseph F. Kmec, Purdue University

Feng C. Lai, University of Oklahoma

Kevin Lyons, North Carolina State University

Pedro Mago, Mississippi State University

Raj M. Manglik, University of Cincinnati

Thuan Nguyen, California State Polytechnic University, Pomona

John Pfotenhauer, University of Wisconsin–Madison

Paul Puzinauskas, University of Alabama

Muhammad Mustafizur Rahman, University of South Florida

Jacques C. Richard, Texas A&M University

Charles Ritz, California State Polytechnic University, Pomona

Francisco Ruiz, Illinois Institute of Technology

Iskender Sahin, Western Michigan University

Will Schreiber, University of Alabama

Enrico Sciubba, University of Rome (Italy)

Tien-Mo Shih, University of Maryland

Larry Sobel, Raytheon Missile Systems

Thomas Twardowski, Widener University

V. Ismet Ugursal, Dalhousie University, Nova Scotia

Angela Violi, University of Michigan

K. Max Zhang, Cornell University

The views expressed in this text are those of the authors and do not necessarily reflect those of individual contributors listed, the Ohio State University, Wayne State University, Rochester Institute of Technology, the United States Military Academy, the Department of the Army, or the Department of Defense.

We also acknowledge the efforts of many individuals in the John Wiley and Sons, Inc., organization who have contributed their talents and energy to this edition. We applaud their professionalism and commitment.

We continue to be extremely gratified by the reception this book has enjoyed over the years. With this edition we have made the text more effective for teaching the subject of engineering thermodynamics and have greatly enhanced the relevance of the subject matter for students who will shape the 21st century. As always, we welcome your comments, criticisms, and suggestions.

Michael J. Moran
moran.4@osu.edu

Howard N. Shapiro
hshapiro@wayne.edu

Daisie D. Boettner
BoettnerD@aol.com

Margaret B. Bailey
Margaret.Bailey@rit.edu

Contents

Answers to Selected Problems: Visit the student companion site at *www.wiley.com/college/moran.*

1

Getting Started

Introductory Concepts and Definitions

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

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

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

▶ LEARNING OUTCOMES

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

- demonstrate understanding of several fundamental concepts used throughout the book . . . including closed system, control volume, boundary and surroundings, property, state, process, the distinction between extensive and intensive properties, and equilibrium.
- apply SI Engineering units, including units for specific volume, pressure, and temperature.
- work with the Kelvin and Celsius temperature scales.
- apply the problem-solving methodology used in this book.

1.1 Using Thermodynamics

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

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

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

1.2 Defining Systems

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

system

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

surroundings
boundary

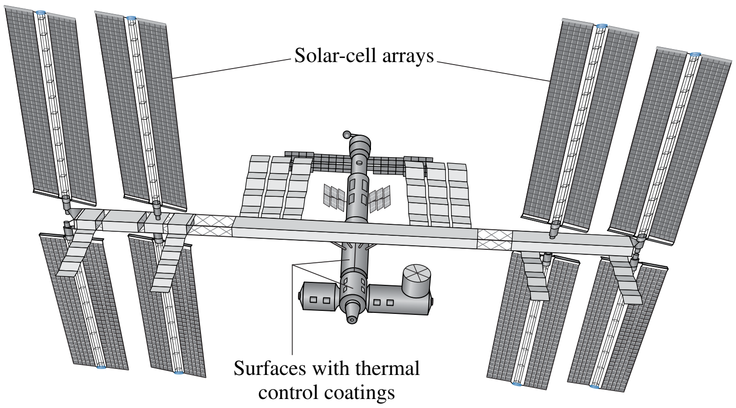
Everything external to the system is considered to be part of the system's **surroundings**. The system is distinguished from its surroundings by a specified **boundary**, which may be at rest or in motion. You will see that the interactions between a system and its surroundings, which take place across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

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

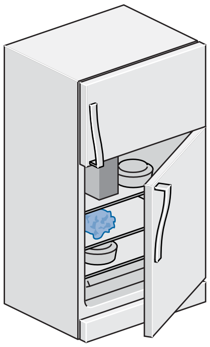
TABLE 1.1

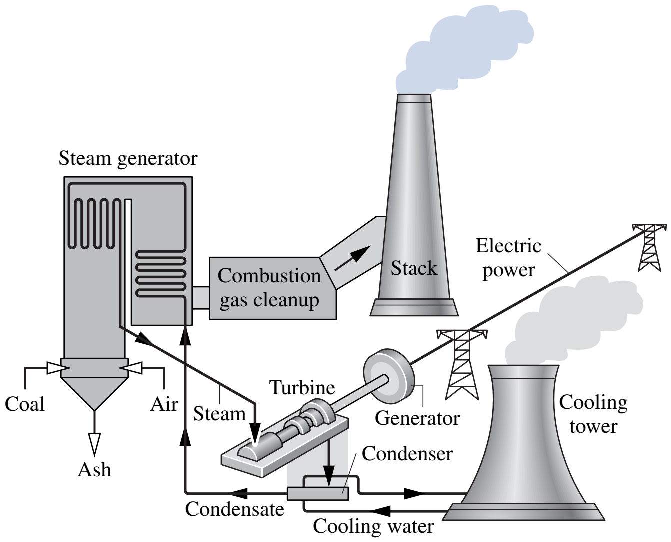
Selected Areas of Application of Engineering Thermodynamics

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

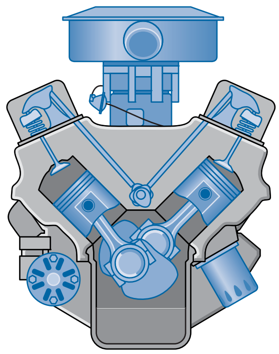


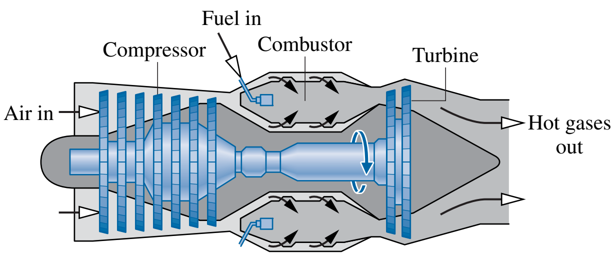
International Space Station


Refrigerator

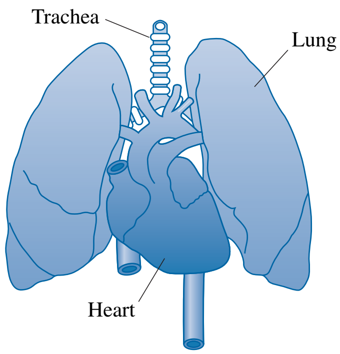


Electrical power plant


Vehicle engine



Turbojet engine



Biomedical applications

TABLE 1.2

Predictions of Life in 2050

At home

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

Transportation

- Plug-in hybrid vehicles and all-electric vehicles dominate.
- Hybrid vehicles mainly use biofuels.
- Use of public transportation within and between cities is common.
- An expanded passenger railway system is widely used.

Lifestyle

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

Power generation

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

1.2.1 Closed Systems

closed system

isolated system

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

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

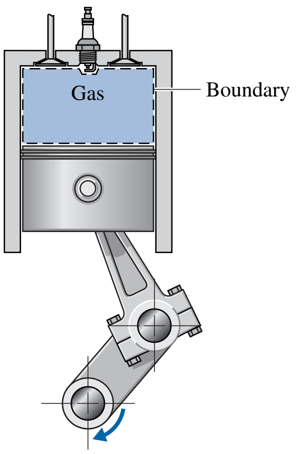


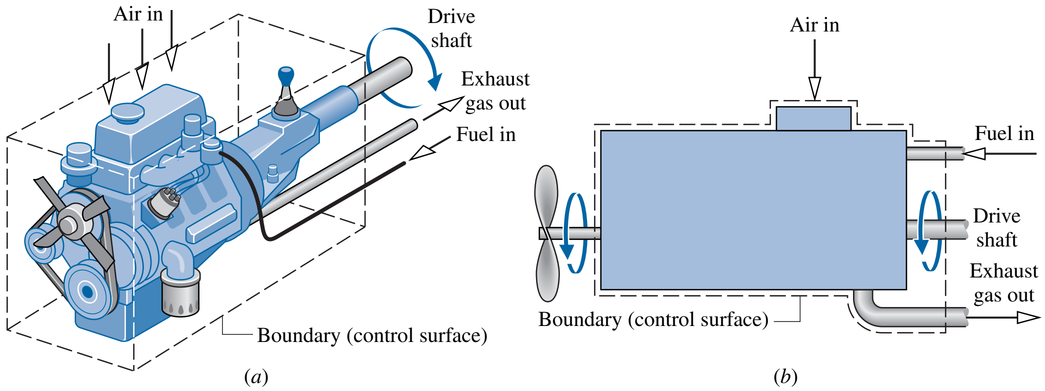
Fig. 1.1 Closed system: A gas in a piston–cylinder assembly.

1.2.2 Control Volumes

control volume

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

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



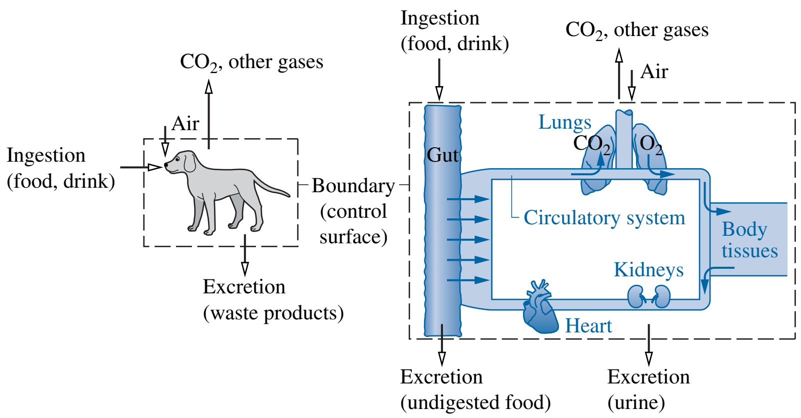
(*a*) (*b*)

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

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

1.2.3 Selecting the System Boundary

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



(*a*) (*b*)

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

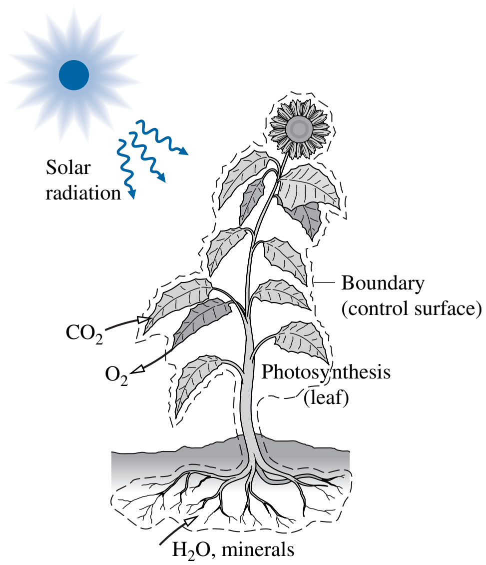


Fig. 1.4 Example of a control volume (open system) in botany.

TAKE NOTE...
Animations reinforce many of the text presentations. You can view these animations by going to the **student companion site** for this book.

Animations are keyed to specific content by an icon in the margin.

The first of these icons appears directly below. In this example, the label **System_Types** refers to the text content while **A.1–Tabs a,b&c** refers to the particular animation **(A.1)** and the tabs **(Tabs a,b&c)** of the animation recommended for viewing now to enhance your understanding.

System_Types
A.1 – Tabs a, b & c

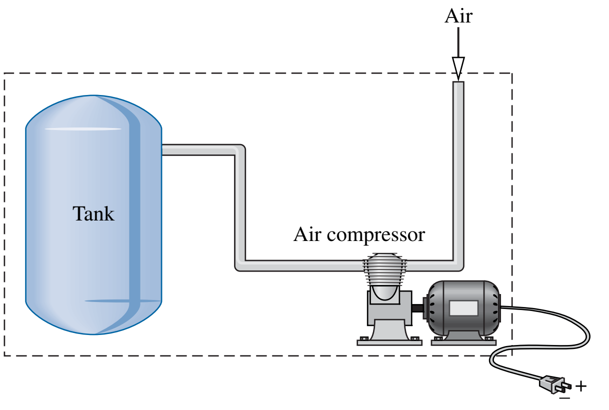


Fig. 1.5 Air compressor and storage tank.

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

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

1.3 Describing Systems and Their Behavior

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

1.3.1 Macroscopic and Microscopic Views of Thermodynamics

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

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

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

1.3.2 Property, State, and Process

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

property

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

state

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

process

steady state

Many properties are considered during the course of our study of engineering thermodynamics. Thermodynamics also deals with quantities that are not properties, such as mass flow rates and energy transfers by work and heat. Additional examples of quantities that are not properties are provided in subsequent chapters. For a way to distinguish properties from *non*properties, see the box on p. 8.

Prop_State_Process
A.2 – Tab a

1.3.3 Extensive and Intensive Properties

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

extensive property

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

intensive property

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

Ext_Int_Properties
A.3 – Tab a

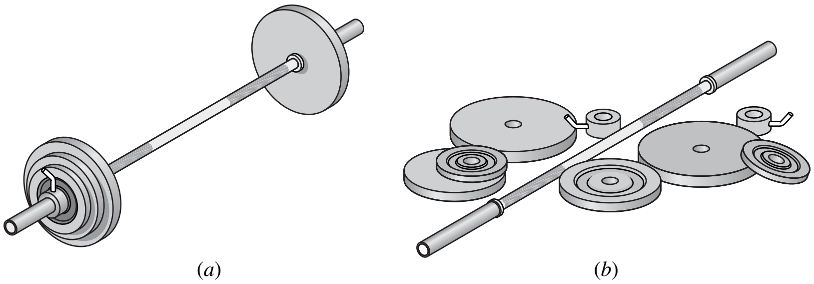


Fig. 1.6 Figure used to discuss the extensive and intensive property concepts.

Distinguishing Properties from Nonproperties

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

1.3.4 Equilibrium

equilibrium

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

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

equilibrium state

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

There is no requirement that a system undergoing a process be in equilibrium *during* the process. Some or all of the intervening states may be nonequilibrium states. For many such processes we are limited to knowing the state before the process occurs and the state after the process is completed.

1.4 Measuring Mass, Length, Time, and Force

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

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

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

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

base unit

1.4.1 SI Units

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

SI base units

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

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

TABLE 1.3

Units for Mass, Length, Time, and Force

	SI	
Quantity	**Unit**	**Symbol**
mass	kilogram	kg
length	meter	m
time	second	s
force	newton ($= 1\ \text{kg} \cdot \text{m/s}^2$)	N