SEVENTH EDITION

Principles of Engineering Thermodynamics

Moran • Shapiro • Boettner • Bailey

SI Version

7th Edition

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How to Use This Book Effectively

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

Examples

- Numerous annotated solved examples are provided that feature the *solution methodology* presented in Sec. 1.9 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 are intended to allow you to gain a deeper understanding of the text material, think critically, and test yourself.
- A large number of end-of-chapter problems also are provided under the heading *Problems: Developing engineering skills.* The problems are sequenced to coordinate with the subject matter and are listed in increasing order of difficulty. The problems are also classified under headings to expedite the process of selecting review problems to solve. Answers to selected problems are provided on the student companion site that accompanies this book: *www.wiley.com/go/global/moran.*
- Because one purpose of this book is to help you prepare to use thermodynamics in engineering practice, design considerations related to thermodynamics are included. Every chapter has a set of problems under the heading *Design & open ended problems: exploring engineering practice* that provide brief design experiences to help you develop creativity and engineering judgment. They also provide opportunities to develop your communication skills.

Further Study Aids

- Each chapter opens with an introduction giving the *engineering context,* stating the *chapter objective*, and listing the *learning objectives.*
- 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.*
- Key words are listed in the margins and coordinated with the text material at those locations.
- Key equations are set off by a double horizontal bar, as, for example, Eq. 1.8.
- *Take Note...* in the margin identifies where we refine our problem-solving methodology, as on p. 9, or introduce conventions such as rounding the temperature 273.15 K to 273 K, as on p. 18.
- The icon 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 and facing page.

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/lb · °R = 4.1868 kJ/kg · K

Constants

Universal Gas Constant

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

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

$T(°R) = 1.8\, T(K)$
$T(°C) = T(K) - 273.15$
$T(°F) = T(°R) - 459.67$

Preface

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

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

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

Core Text Features

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

- ► Develops an intuitive understanding of thermodynamics by focusing on physical explanations. See, for example, the introduction to the control volume energy balance on p. 155 and the Carnot Corollary discussion on p. 226.
- ► Develops basic principles in an engaging, readable way using applications of contemporary interest. See, as examples, *Bio...connections* on pp. 4, 155, 172, *Energy & Environment* on pp. 33, 66, 229, and *Horizons* on pp. 37, 120, 160.
- ► Teaches students to model systems and solve engineering problems involving thermodynamics. Our methodology also teaches students to think systematically and helps them reduce errors. See Sec. 1.9 and all solved examples.
- ► Provides a substantial selection of problems in every chapter organized to help students develop engineering skills in three modes:
  - ► **Conceptual.** See *Exercises: things engineers think about.*
  - ► **Skill Building.** See *Problems: developing engineering skills.*
  - ► **Design.** See *Design & open ended problems: exploring engineering practice.*

  Many of the conceptual and design problems build on the engaging *Bio...connections, Energy & Environment*, and *Horizons* discussions placed throughout the text.
- ► Prepares students to use thermodynamics in engineering practice through
  - ► **Sound developments of the application areas.** Included in Chaps. 8–14 are comprehensive developments of power and refrigeration cycles, psychrometrics,

and combustion from which instructors can choose various levels of coverage ranging from short introductions to in-depth studies.

- **Emphasis on engineering design and analysis.** Specific text material on the design process is included in Sec. 1.8: *Engineering Design and Analysis* and Sec. 7.7: *Thermoeconomics.* Each chapter also provides carefully crafted *Design and open ended problems* that allow students to develop an appreciation of engineering practice and to enhance a variety of skills such as creativity, formulating and solving problems, making engineering judgments, and communicating ideas.

- Employs an effective development of the second law of thermodynamics. The text features the *entropy balance* (Chap. 6), recognized globally as the most effective way for students to learn how to apply the second law. Also, the presentation of *exergy analysis* (Chaps. 7 and 13) has become the state-of-the-art model for learning that subject matter.
- Uses software to enhance problem solving for deeper learning. In every chapter, end-of-chapter problems are identified by a special icon to signal the use of computer software. All of these problems can be solved using *Interactive Thermodynamics (IT)*, the interactive software program available with the text. Tutorials on the use of *IT* are given in several places throughout the text, beginning in Sec. 3.7. As in previous editions, the text presentation is carefully structured so instructors wanting to omit the use of software can do so seamlessly.
- Encourages flexibility in units. The text allows an SI or mixed SI/English presentation. Careful use of units and systematic application of unit conversion factors is emphasized throughout the text. A handy set of conversion factors is inserted inside the front cover of the book for easy access.
- Provides many text features that are proven to enhance student learning. We recognize that the first course in thermodynamics covers a lot of material in a short period of time. To help students learn and study the material more effectively, we have included a variety of features to assist them. For easy reference, these features are inserted inside the front cover under the heading "How to Use This Book Effectively".

New in the Seventh Edition

- Each chapter begins with a set of **Learning Objectives.**
- Each solved example concludes with a list of the **Skills Developed** in solving the example that reinforce specific skills related to the learning objectives.
- Each solved example has a follow-up **Quick Quiz** that gives the student an immediate check of understanding of an important skill.
- A set of **Key Equations** has been added at the close of each chapter for easy reference and to assist in studying.
- Engaging new features called **Bio...connections, Energy & Environment,** and **Horizons** have been introduced throughout. They tie the subject matter to contemporary applications in biomedicine, bioengineering, energy resource use, environmental engineering, and emerging technologies.
- **End-of-Chapter problems** in each of three modes: conceptual, skill building, and design have been **substantially refreshed.** Some build on the engaging *Bio...connections, Energy & Environment,* and *Horizons* discussions introduced in this edition. The skill-building problems are classified under headings to assist instructors and students alike in problem selection. These problems range from confidence-building exercises illustrating basic skills to more challenging ones that may

involve several components and require high-order thinking. As in previous editions, a generous collection of problems is provided.

- **New and revised class-tested content** contributes to student learning and instructor effectiveness:
  - The discussion of pressure measurement has been expanded with new content on manometers and barometers in Sec. 1.6.1.
  - A discussion of *net* radiant exchange between two surfaces has been added in Sec. 2.4.2.
  - Example 3.6 considers the measurement of the calorie value of cooking oil.
  - More detailed modeling considerations are provided in Secs. 4.6–4.10 for nozzles and diffusers, turbines, compressors and pumps, heat exchangers, and throttling devices, respectively.
  - Example 4.6 considers the analysis of a pumping system.
  - An *entropy statement of the second law* has been introduced in Sec. 5.2.3. This allows instructors to elect an axiomatic approach to the second law, bypass much of the Chap. 5 detail, and go quickly to the entropy and entropy balance developments of Chap. 6 if they choose.
  - The discussion of entropy and probability has been expanded with new content in Secs. 6.1.3 and 6.8.2 to provide a brief introduction that relates to technologies involving microscopic analysis.
  - By focusing on physical explanations and stressing the relationship of exergy to fossil fuel use, the introduction to exergy analysis in Secs. 7.1–7.5 has been placed in a more digestible, abbreviated form.
  - Ideal gas model *reviews* have been added at key locations in Sec. 6.5 (Table 6.1) and in Sec. 9.1 (Table 9.1).
- In response to users and to student needs, **class-tested changes** have been introduced. Many contribute to a more *just-in-time* presentation.
  - To emphasize the central role of effective modeling in engineering analysis, we introduce the more descriptive term *Engineering Model* in our solution methodology (Sec. 1.9) in lieu of the term *Assumptions.*
  - The introduction to *quasiequilibrium processes* has moved from Chap. 1 to Sec. 2.2.5.
  - The introduction to *thermodynamic cycles* has moved from Chap. 1 to Sec. 2.6.
  - The discussion of *phase* and *pure substance* has moved from Chap. 1 to Sec. 3.1.1.
  - The discussions of the *constant-volume gas thermometer* and *gas scale of temperature* has moved from Chap. 1 to Sec. 5.8.2.
  - The development of the *Clausius integral* has moved from Chap. 6 to Sec. 5.11. This brings all introductory cycle-related second law content into Chap. 5 and allows Chap. 6 to deal exclusively with entropy and the entropy balance.
- The software accompanying the text, *Interactive Thermodynamics: IT,* has been significantly enhanced with an up-to-date graphical user interface and text-editing features, an equation editor for easier entry of mathematical notation, and *Excel* input of *IT* subroutines. Brief tutorials of *IT* are included within the text and the use of *IT* is illustrated within some of the solved examples. For instructors preferring to use *Engineering Equation Solver (EES)*, detailed *EES* solutions to the computer problems are provided on the instructor's companion website: *www.wiley.com/go/global/moran,* making it easy to choose that software as an alternative.

Supplements

The following supplements are available with the text:

- Instructors who have adopted the text for their course can visit *www.wiley.com/go/global/moran* and click on the instructor companion site to find:
  - Figures from the text suitable for creating presentations and/or exams.
  - PowerPoint lecture slides.
  - Detailed solutions to all end-of-chapter problems.
  - Electronic files of solutions to all computer problems in both *Interactive Thermodynamics (IT)* and *Engineering Equation Solver (EES)* formats.
- *Interactive Thermodynamics (IT) software*. Available online from the Book Companion Site at *www.wiley.com/go/global/moran*.

Ways to Meet Different Course Needs

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

<table>
<tr><th>Type of course</th><th>Intended audience</th><th>Chapter coverage</th></tr>
<tr><td rowspan="2">Surveys</td><td>Nonmajors</td><td>• <u>Principles</u>. Chaps. 1–6.
• <u>Applications</u>. Selected topics from Chaps. 8–10 (omit compressible flow in Chap. 9).</td></tr>
<tr><td>Majors</td><td>• <u>Principles</u>. Chaps. 1–6.
• <u>Applications</u>. Same as above plus selected topics from Chaps. 12 and 13.</td></tr>
<tr><td>Two-course sequences</td><td>Majors</td><td>• <u>First course</u>. Chaps. 1–7. (Chap. 7 may be deferred to second course or omitted.)
• <u>Second course</u>. Selected topics from Chaps. 8–14 to meet particular course needs.</td></tr>
</table>

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

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Answers to Selected Problems: Visit the student companion site at *www.wiley.com/go/global/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 the introduction is brief, and further elaboration is provided in subsequent chapters.

Learning Objectives

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

✔ demonstrate understanding of several fundamental concepts used throughout the book . . . including closed system, control volume, boundary and surroundings, property, state, process, the distinction between extensive and intensive properties, and equilibrium.

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

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

1.2 Defining Systems

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

system

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

surroundings

boundary

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

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

1.2.1 Closed Systems

closed system

isolated system

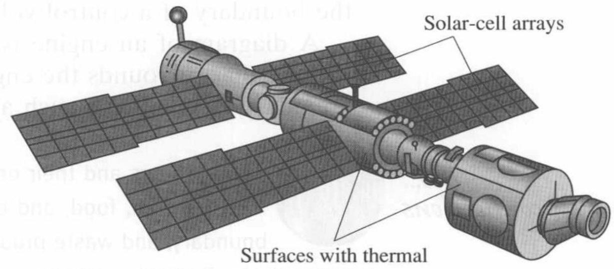
A ***closed system*** is defined when a particular quantity of matter is under study. A closed system always contains the same matter. There can be no transfer of mass across its boundary. A special type of closed system that does not interact in any way with its surroundings is called an ***isolated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

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

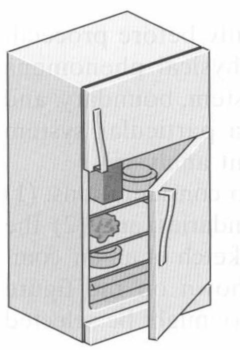
Table 1.1

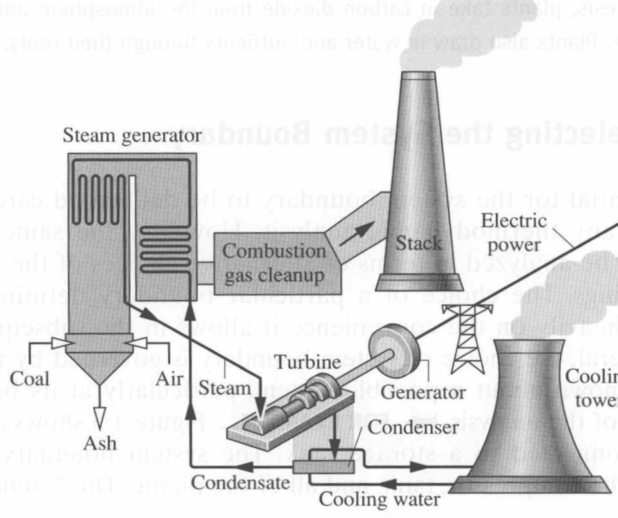
Selected Areas of Application of Engineering Thermodynamics

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

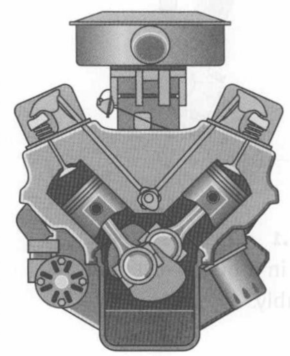


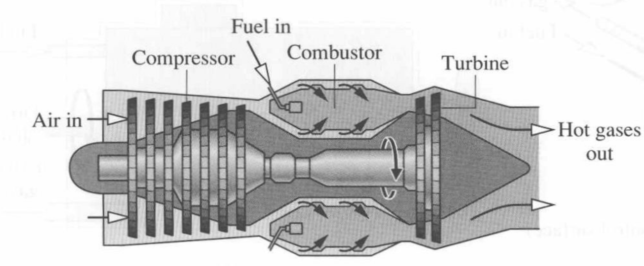
International Space Station


Refrigerator

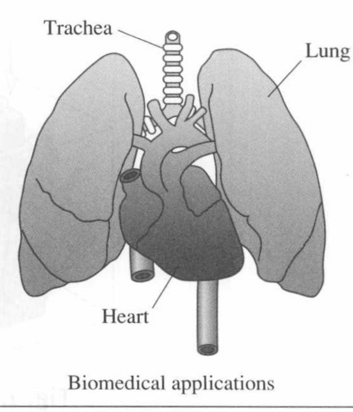


Electrical power plant


Automobile engine



Turbojet engine



Biomedical applications

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

1.2.2 Control Volumes

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

control volume

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

Bio... connections

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

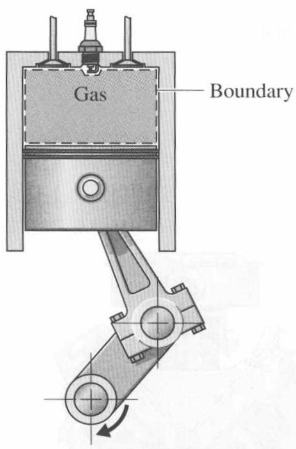


Fig. 1.1 Closed system: A gas in a piston–cylinder assembly.

1.2.3 Selecting the System Boundary

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

In general, the choice of system boundary is governed by two considerations: (1) what is known about a possible system, particularly at its boundaries, and (2) the objective of the analysis. ➡ **FOR EXAMPLE...** Figure 1.5 shows a sketch of an air compressor connected to a storage tank. The system boundary shown on the figure encloses the compressor, tank, and all of the piping. This boundary might be selected

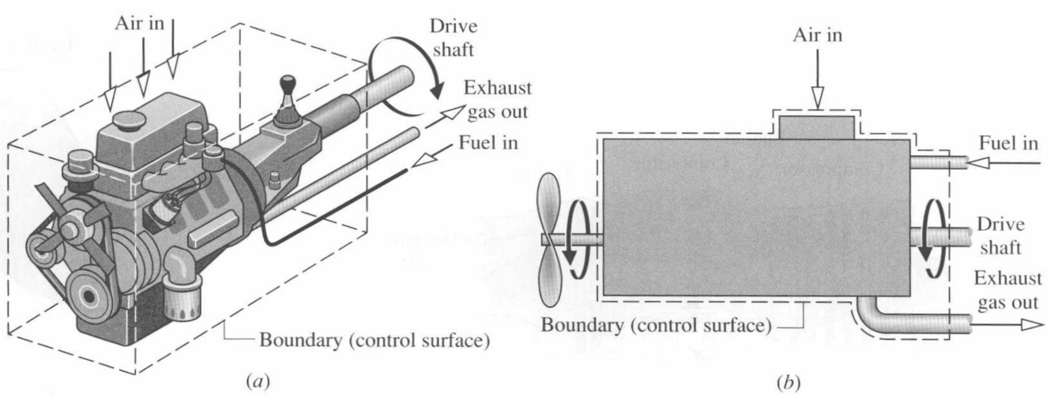


Fig. 1.2 Example of a control volume (open system). An automobile engine.