

# FUNDAMENTALS OF ENGINEERING THERMODYNAMICS

SEVENTH EDITION



MICHAEL J. MORAN | HOWARD N. SHAPIRO  
DAISIE D. BOETTNER | MARGARET B. BAILEY





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# FUNDAMENTALS OF ENGINEERING THERMODYNAMICS

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# Preface

Professors Moran and Shapiro are delighted to welcome two new co-authors for the seventh edition of Fundamentals of Engineering Thermodynamics. **Dr. Daisie D. Boettner**, PE, professor of mechanical engineering at the United States Military Academy at West Point, and **Dr. Margaret B. Bailey**, PE, professor of mechanical engineering at the Rochester Institute of Technology, bring outstanding experience in engineering education, research, and service to the team. Their perspectives enrich the presentation and build upon our existing strengths in exciting new ways.

## A Textbook for the 21<sup>st</sup> 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 seventh 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 seventh 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 sixth 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 Seventh 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 seventh 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 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 meet 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. 8.
  - **Boxed material** allows students and instructors to explore topics in greater depth. For example, see p. 188.
  - 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 web sites (visit [www.wiley.com/college/moran](http://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.
- sample syllabi on semester and quarter bases.

- errata for both the text and problems.
- chapter summary information, including Key Terms and Key Equations.
- chapter learning outcomes.
- correlation guides to ease transition between editions of this text and for switching to this edition from another book.
- text Preface.
- Student Companion Site: Helps students learn the subject matter with resources including
  - animations—new in this edition.
  - answers to selected problems.
  - errata for both the text and 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.
  - text Preface.

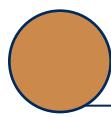
- *Interactive Thermodynamic: IT software* is available as a stand-alone product or with the textbook. *IT* is a highly-valuable learning tool that allows students to develop engineering models, perform “what-if” analyses, and examine principles in more detail to enhance their learning. Brief tutorials 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](http://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	<ul style="list-style-type: none"><li>• <u>Principles</u>. Chaps. 1–6.</li><li>• <u>Applications</u>. Selected topics from Chaps. 8–10 (omit compressible flow in Chap. 9).</li></ul>
	Majors	<ul style="list-style-type: none"><li>• <u>Principles</u>. Chaps. 1–6.</li><li>• <u>Applications</u>. Same as above plus selected topics from Chaps. 12 and 13.</li></ul>
Two-course sequences	Majors	<ul style="list-style-type: none"><li>• <u>First course</u>. Chaps. 1–7. (Chap. 7 may be deferred to second course or omitted.)</li><li>• <u>Second course</u>. Selected topics from Chaps. 8–14 to meet particular course needs.</li></ul>



# Acknowledgments

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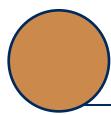
We continue to be extremely gratified by the reception this book has enjoyed over the years. With this edition we have made the text more effective for teaching the subject of engineering thermodynamics and have greatly enhanced the relevance of the subject matter for students who will shape the 21st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

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<p><b>Answers to Selected Problems:</b> Visit the student companion site at <a href="http://www.wiley.com/college/moran">www.wiley.com/college/moran</a>.</p>	

# **FUNDAMENTALS OF ENGINEERING THERMODYNAMICS**

**SEVENTH EDITION**



Fluids such as air and water exert **pressure**, introduced in Sec. 1.6. © Jeffrey Warrington/Alamy

**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.

# 1

# Getting Started

## *Introductory Concepts and Definitions*

### ► 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 and English Engineering units, including units for specific volume, pressure, and temperature.
- ▶ work with the Kelvin, Rankine, Celsius, and Fahrenheit 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 in the United States 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.

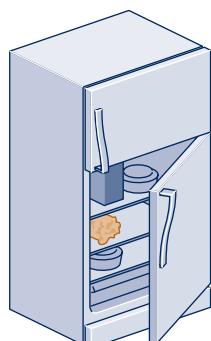
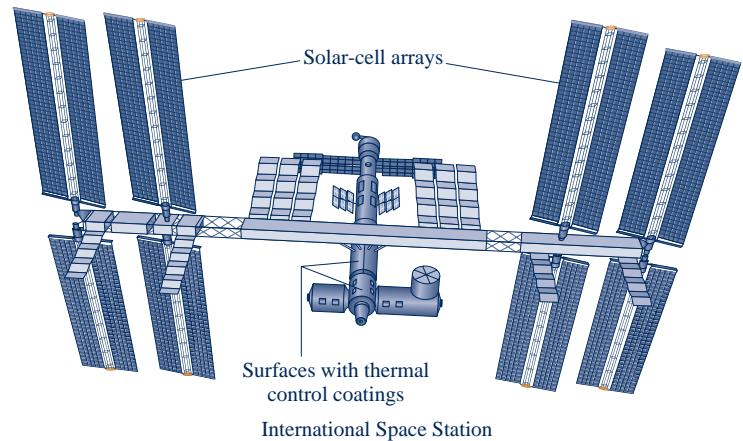
**surroundings**  
**boundary**

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.

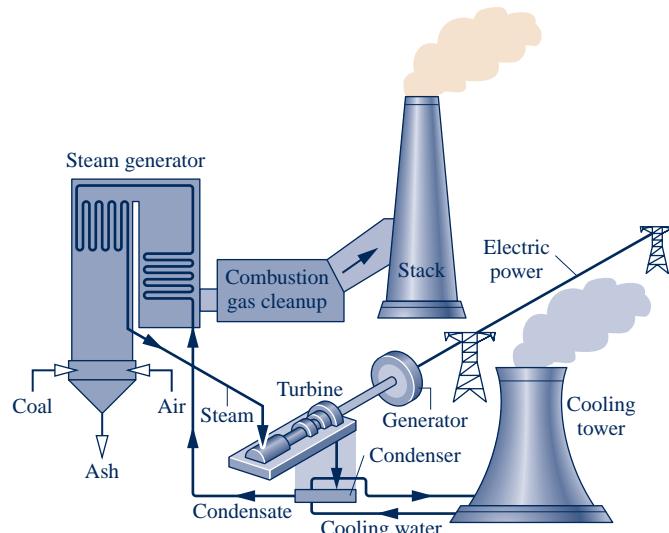
Two basic kinds of systems are distinguished in this book. These are referred to, respectively, as *closed systems* and *control volumes*. A closed system refers to a fixed quantity of matter, whereas a control volume is a region of space through which mass may flow. The term *control mass* is sometimes 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**

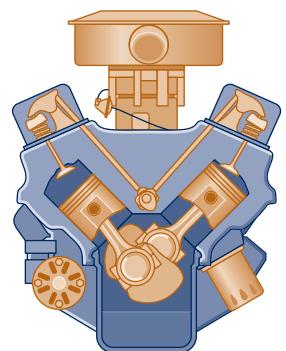
Aircraft and rocket propulsion  
 Alternative energy systems  
   Fuel cells  
   Geothermal systems  
   Magnetohydrodynamic (MHD) converters  
   Ocean thermal, wave, and tidal power generation  
   Solar-activated heating, cooling, and power generation  
   Thermoelectric and thermionic devices  
   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



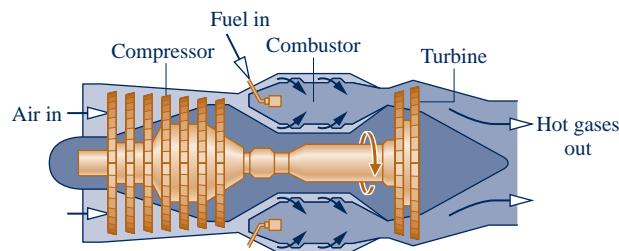
Refrigerator



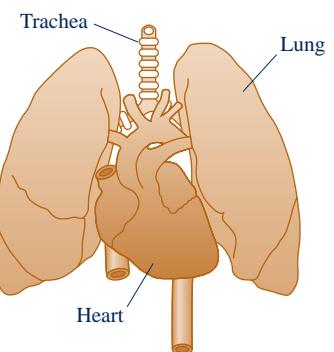
Electrical power plant



Vehicle engine



Turbojet engine



Biomedical applications

**TABLE 1.2****Predictions of Life in the United States 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*

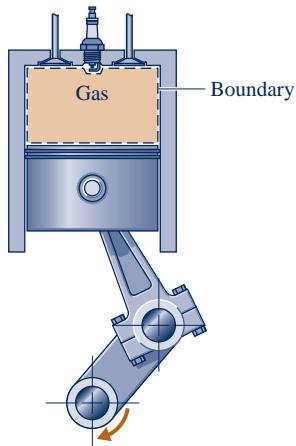
- Plug-in hybrid vehicles and all-electric vehicles dominate.
- Hybrid vehicles mainly use biofuels.
- Use of public transportation within and between cities is common.
- An expanded passenger railway system is widely used.

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

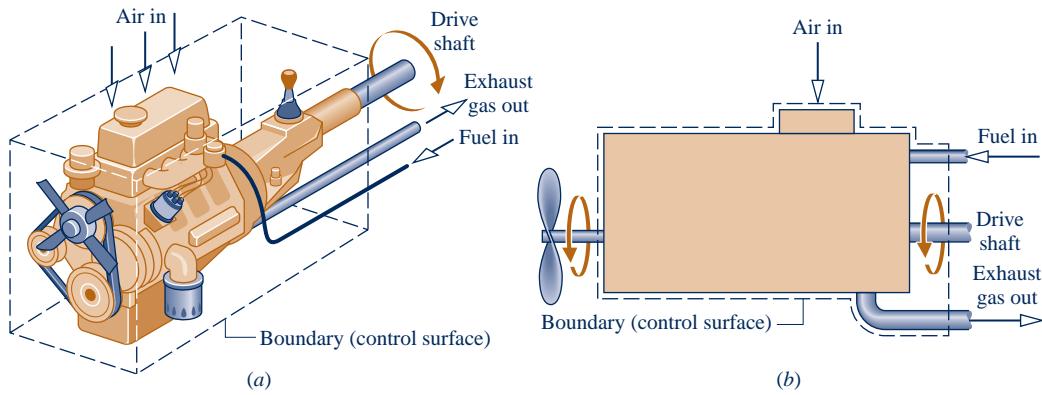
A **closed system** is defined when a particular quantity of matter is under study. A closed system always contains the same matter. There can be no transfer of mass across its boundary. A special type of closed system that does not interact in any way with its surroundings is called an **isolated system**.

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.

**1.2.2 • Control Volumes**

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. 1.2a. 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. 1.2b often suffices for engineering analysis.



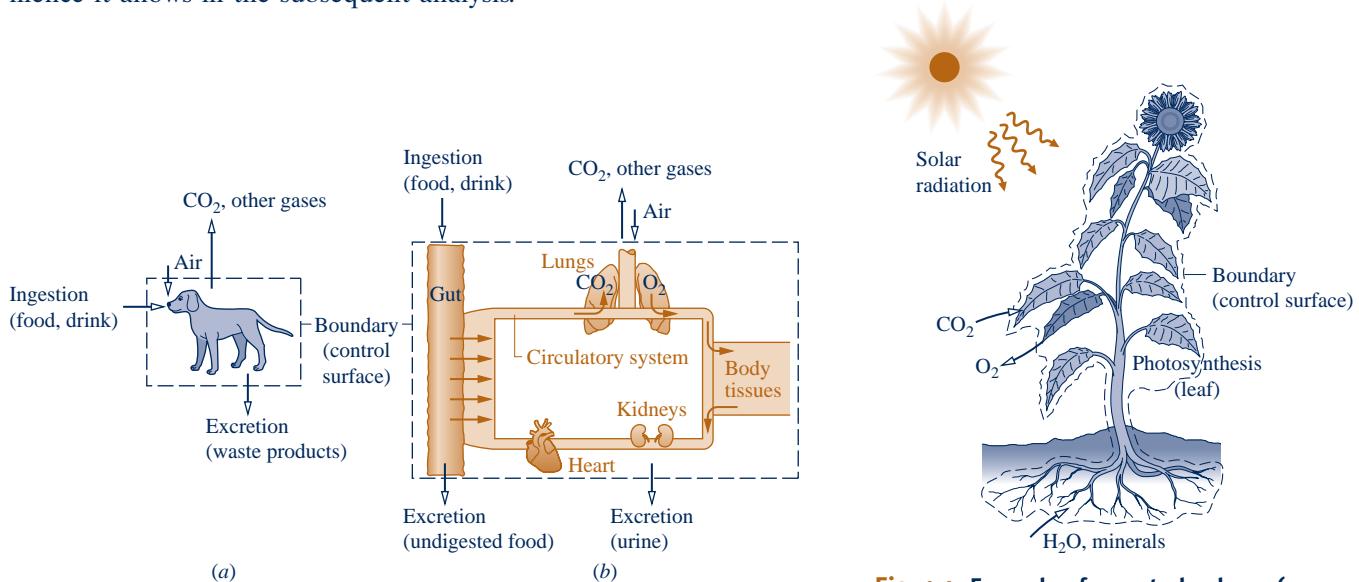
**Fig. 1.2** Example of a control volume (open system). An automobile engine.



**BIO CONNECTIONS** Living things and their organs can be studied as control volumes. For the pet shown in Fig. 1.3a, air, food, and drink essential to sustain life and for activity enter across the boundary, and waste products exit. A schematic such as Fig. 1.3b 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.



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

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

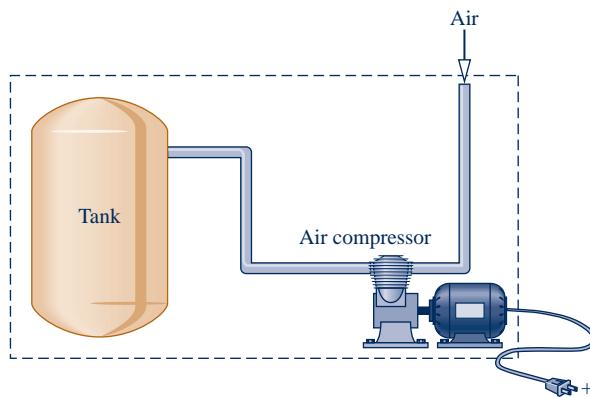
**TAKE NOTE...**

**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.

**A** **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**

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. 10.

**steady state**

**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**

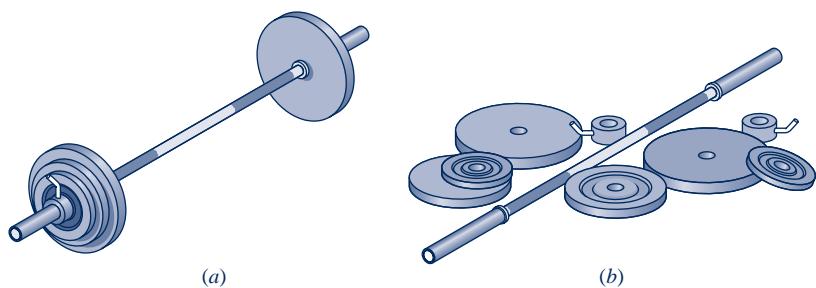
**Intensive** properties are not additive in the sense previously considered. Their values are independent of the size or extent of a system and may vary from place to place within the system at any moment. Thus, intensive properties may be functions of both position and time, whereas extensive properties 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**.

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.

#### equilibrium state

## 1.4 Measuring Mass, Length, Time, and Force

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

Because physical quantities are related by definitions and laws, a relatively small number of physical quantities suffice to conceive of and measure all others. These 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

Quantity	SI		English	
	Unit	Symbol	Unit	Symbol
mass	kilogram	kg	pound mass	lb
length	meter	m	foot	ft
time	second	s	second	s
force	newton	N	pound force $(= 32.1740 \text{ lb} \cdot \text{ft/s}^2)$	lbf

The SI unit of force, called the newton, is a secondary unit, defined in terms of the base units for mass, length, and time. Newton's second law of motion states that the net force acting on a body is proportional to the product of the mass and the acceleration, written  $F \propto ma$ . The newton is defined so that the proportionality constant in the expression is equal to unity. That is, Newton's second law is expressed as the equality

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

The newton, N, is the force required to accelerate a mass of 1 kilogram at the rate of 1 meter per second per second. With Eq. 1.1

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

### TAKE NOTE...

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

**► FOR EXAMPLE** to illustrate the use of the SI units introduced thus far, let us determine the weight in newtons of an object whose mass is 1000 kg, at a place on the earth's surface where the acceleration due to gravity equals a *standard* value defined as  $9.80665 \text{ m/s}^2$ . Recalling that the weight of an object refers to the force of gravity, and is calculated using the mass of the object,  $m$ , and the local acceleration of gravity,  $g$ , with Eq. 1.1 we get

$$\begin{aligned} F &= mg \\ &= (1000 \text{ kg})(9.80665 \text{ m/s}^2) = 9806.65 \text{ kg} \cdot \text{m/s}^2 \end{aligned}$$

This force can be expressed in terms of the newton by using Eq. 1.2 as a *unit conversion factor*. That is,

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

Since weight is calculated in terms of the mass and the local acceleration due to gravity, the weight of an object can vary because of the variation of the acceleration of gravity with location, but its mass remains constant.

**► FOR EXAMPLE** if the object considered previously were on the surface of a planet at a point where the acceleration of gravity is one-tenth of the value used in the above calculation, the mass would remain the same but the weight would be one-tenth of the calculated value.  $\blacktriangleleft \blacktriangleleft \blacktriangleleft \blacktriangleleft \blacktriangleleft$

SI units for other physical quantities are also derived in terms of the SI base units. Some of the derived units occur so frequently that they are given special names and symbols, such as the newton. SI units for quantities pertinent to thermodynamics are given as they are introduced in the text. Since it is frequently necessary to work with extremely large or small values when using the SI unit system, a set of standard prefixes is provided in Table 1.4 to simplify matters. For example, km denotes kilometer, that is,  $10^3 \text{ m}$ .

TABLE 1.4

### SI Unit Prefixes

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

### 1.4.2 English Engineering Units

Although SI units are the worldwide standard, at the present time many segments of the engineering community in the United States regularly use other units. A large portion of America's stock of tools and industrial machines and much valuable engineering data utilize units other than SI units. For many years to come, engineers in the United States will have to be conversant with a variety of units.

In this section we consider a system of units that is commonly used in the United States, called the English Engineering system. The **English base units** for mass, length, and time are listed in Table 1.3 and discussed in the following paragraphs. English units for other quantities pertinent to thermodynamics are given as they are introduced in the text.

### English base units

The base unit for length is the foot, ft, defined in terms of the meter as

$$1 \text{ ft} = 0.3048 \text{ m} \quad (1.3)$$

The inch, in., is defined in terms of the foot

$$12 \text{ in.} = 1 \text{ ft}$$

One inch equals 2.54 cm. Although units such as the minute and the hour are often used in engineering, it is convenient to select the second as the English Engineering base unit for time.

The English Engineering base unit of mass is the pound mass, lb, defined in terms of the kilogram as

$$1 \text{ lb} = 0.45359237 \text{ kg} \quad (1.4)$$

The symbol lbf also may be used to denote the pound mass.

Once base units have been specified for mass, length, and time in the English Engineering system of units, a force unit can be defined, as for the newton, using Newton's second law written as Eq. 1.1. From this viewpoint, the English unit of force, the pound force, lbf, is the force required to accelerate one pound mass at  $32.1740 \text{ ft/s}^2$ , which is the standard acceleration of gravity. Substituting values into Eq. 1.1

$$1 \text{ lbf} = (1 \text{ lb})(32.1740 \text{ ft/s}^2) = 32.1740 \text{ lb} \cdot \text{ft/s}^2 \quad (1.5)$$

With this approach force is regarded as *secondary*.

The pound force, lbf, is not equal to the pound mass, lb, introduced previously. Force and mass are fundamentally different, as are their units. The double use of the word "pound" can be confusing, however, and care must be taken to avoid error.

**► FOR EXAMPLE** to show the use of these units in a single calculation, let us determine the weight of an object whose mass is 1000 lb at a location where the local acceleration of gravity is  $32.0 \text{ ft/s}^2$ . By inserting values into Eq. 1.1 and using Eq. 1.5 as a unit conversion factor, we get

$$F = mg = (1000 \text{ lb})\left(32.0 \frac{\text{ft}}{\text{s}^2}\right)\left|\frac{1 \text{ lbf}}{32.1740 \text{ lb} \cdot \text{ft/s}^2}\right| = 994.59 \text{ lbf}$$

This calculation illustrates that the pound force is a unit of force distinct from the pound mass, a unit of mass. ◀◀◀◀◀

## 1.5 Specific Volume

Three measurable intensive properties that are particularly important in engineering thermodynamics are specific volume, pressure, and temperature. Specific volume is considered in this section. Pressure and temperature are considered in Secs. 1.6 and 1.7, respectively.

From the macroscopic perspective, the description of matter is simplified by considering it to be distributed continuously throughout a region. The correctness of this idealization, known as the *continuum* hypothesis, is inferred from the fact that for an extremely large class of phenomena of engineering interest the resulting description of the behavior of matter is in agreement with measured data.

When substances can be treated as continua, it is possible to speak of their intensive thermodynamic properties "at a point." Thus, at any instant the density  $\rho$  at a point is defined as

$$\rho = \lim_{V' \rightarrow V} \left( \frac{m}{V} \right) \quad (1.6)$$

where  $V'$  is the smallest volume for which a definite value of the ratio exists. The volume  $V'$  contains enough particles for statistical averages to be significant. It is the smallest

volume for which the matter can be considered a continuum and is normally small enough that it can be considered a “point.” With density defined by Eq. 1.6, density can be described mathematically as a continuous function of position and time.

The density, or local mass per unit volume, is an intensive property that may vary from point to point within a system. Thus, the mass associated with a particular volume  $V$  is determined in principle by integration

$$m = \int_V \rho dV \quad (1.7)$$

and *not* simply as the product of density and volume.

### specific volume

The **specific volume**  $v$  is defined as the reciprocal of the density,  $v = 1/\rho$ . It is the volume per unit mass. Like density, specific volume is an intensive property and may vary from point to point. SI units for density and specific volume are  $\text{kg/m}^3$  and  $\text{m}^3/\text{kg}$ , respectively. However, they are also often expressed, respectively, as  $\text{g/cm}^3$  and  $\text{cm}^3/\text{g}$ . English units used for density and specific volume in this text are  $\text{lb/ft}^3$  and  $\text{ft}^3/\text{lb}$ , respectively.

### molar basis

In certain applications it is convenient to express properties such as specific volume on a molar basis rather than on a mass basis. A mole is an amount of a given substance numerically equal to its molecular weight. In this book we express the amount of substance on a **molar basis** in terms of the kilomole (kmol) or the pound mole (lbtmol), as appropriate. In each case we use

$$n = \frac{m}{M} \quad (1.8)$$

The number of kilomoles of a substance,  $n$ , is obtained by dividing the mass,  $m$ , in kilograms by the molecular weight,  $M$ , in  $\text{kg/kmol}$ . Similarly, the number of pound moles,  $n$ , is obtained by dividing the mass,  $m$ , in pound mass by the molecular weight,  $M$ , in  $\text{lb/lbtmol}$ . When  $m$  is in grams, Eq. 1.8 gives  $n$  in gram moles, or *mol* for short. Recall from chemistry that the number of molecules in a gram mole, called Avogadro’s number, is  $6.022 \times 10^{23}$ . Appendix Tables A-1 and A-1E provide molecular weights for several substances.

To signal that a property is on a molar basis, a bar is used over its symbol. Thus,  $\bar{v}$  signifies the volume per kmol or lbtmol, as appropriate. In this text, the units used for  $\bar{v}$  are  $\text{m}^3/\text{kmol}$  and  $\text{ft}^3/\text{lbtmol}$ . With Eq. 1.8, the relationship between  $\bar{v}$  and  $v$  is

$$\bar{v} = Mv \quad (1.9)$$

where  $M$  is the molecular weight in  $\text{kg/kmol}$  or  $\text{lb/lbtmol}$ , as appropriate.

## 1.6 Pressure

### pressure

Next, we introduce the concept of pressure from the continuum viewpoint. Let us begin by considering a small area  $A$  passing through a point in a fluid at rest. The fluid on one side of the area exerts a compressive force on it that is normal to the area,  $F_{\text{normal}}$ . An equal but oppositely directed force is exerted on the area by the fluid on the other side. For a fluid at rest, no other forces than these act on the area. The **pressure**  $p$  at the specified point is defined as the limit

$$p = \lim_{A \rightarrow A'} \left( \frac{F_{\text{normal}}}{A} \right) \quad (1.10)$$

where  $A'$  is the area at the “point” in the same limiting sense as used in the definition of density.



**Ext\_Int Properties**  
A.3 – Tab d



## Big Hopes For Nanotechnology .....

*Nanoscience* is the study of molecules and molecular structures, called nanostructures, having one or more dimensions less than about 100 nanometers. One nanometer is one billionth of a meter:  $1 \text{ nm} = 10^{-9} \text{ m}$ . To grasp this level of smallness, a stack of 10 hydrogen atoms would have a height of 1 nm, while a human hair has a diameter about 50,000 nm. *Nanotechnology* is the engineering of nanostructures into useful products. At the nanotechnology scale, behavior may differ from our macroscopic expectations. For example, the *averaging* used to assign property values at a point in the

continuum model may no longer apply owing to the interactions among the atoms under consideration. Also at these scales, the nature of physical phenomena such as current flow may depend explicitly on the physical size of devices. After many years of fruitful research, nanotechnology is now poised to provide new products with a broad range of uses, including implantable chemotherapy devices, biosensors for glucose detection in diabetics, novel electronic devices, new energy conversion technologies, and ‘smart materials’, as for example fabrics that allow water vapor to escape while keeping liquid water out.

If the area  $A'$  was given new orientations by rotating it around the given point, and the pressure determined for each new orientation, it would be found that the pressure at the point is the same in all directions *as long as the fluid is at rest*. This is a consequence of the equilibrium of forces acting on an element of volume surrounding the point. However, the pressure can vary from point to point within a fluid at rest; examples are the variation of atmospheric pressure with elevation and the pressure variation with depth in oceans, lakes, and other bodies of water.

Consider next a fluid in motion. In this case the force exerted on an area passing through a point in the fluid may be resolved into three mutually perpendicular components: one normal to the area and two in the plane of the area. When expressed on a unit area basis, the component normal to the area is called the *normal stress*, and the two components in the plane of the area are termed *shear stresses*. The magnitudes of the stresses generally vary with the orientation of the area. The state of stress in a fluid in motion is a topic that is normally treated thoroughly in *fluid mechanics*. The deviation of a normal stress from the pressure, the normal stress that would exist were the fluid at rest, is typically very small. In this book we assume that the normal stress at a point is equal to the pressure at that point. This assumption yields results of acceptable accuracy for the applications considered. Also, the term pressure, unless stated otherwise, refers to **absolute pressure**: pressure with respect to the zero pressure of a complete vacuum.

### 1.6.1 Pressure Measurement

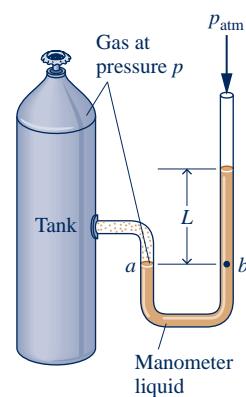
Manometers and barometers measure pressure in terms of the length of a column of liquid such as mercury, water, or oil. The manometer shown in Fig. 1.7 has one end open to the atmosphere and the other attached to a tank containing a gas at a uniform pressure. Since pressures at equal elevations in a *continuous* mass of a liquid or gas *at rest* are equal, the pressures at points  $a$  and  $b$  of Fig. 1.7 are equal. Applying an elementary force balance, the gas pressure is

$$p = p_{\text{atm}} + \rho g L \quad (1.11)$$

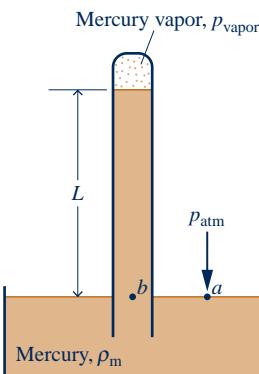
where  $p_{\text{atm}}$  is the local atmospheric pressure,  $\rho$  is the density of the manometer liquid,  $g$  is the acceleration of gravity, and  $L$  is the difference in the liquid levels.

The barometer shown in Fig. 1.8 is formed by a closed tube filled with liquid mercury and a small amount of mercury vapor inverted in an open container of liquid mercury. Since the pressures at points  $a$  and  $b$  are equal, a force balance gives the

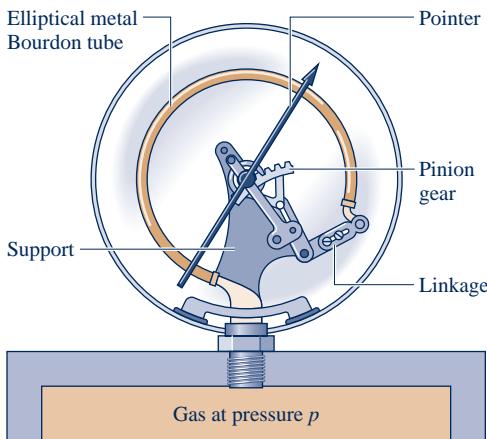
**absolute pressure**



**Fig. 1.7 Manometer.**



**Fig. 1.8 Barometer.**



**Fig. 1.9** Pressure measurement by a Bourdon tube gage.

atmospheric pressure as

$$p_{\text{atm}} = p_{\text{vapor}} + \rho_m g L \quad (1.12)$$

where  $\rho_m$  is the density of liquid mercury. Because the pressure of the mercury vapor is much less than that of the atmosphere, Eq. 1.12 can be approximated closely as  $p_{\text{atm}} = \rho_m g L$ . For short columns of liquid,  $\rho$  and  $g$  in Eqs. 1.11 and 1.12 may be taken as constant.

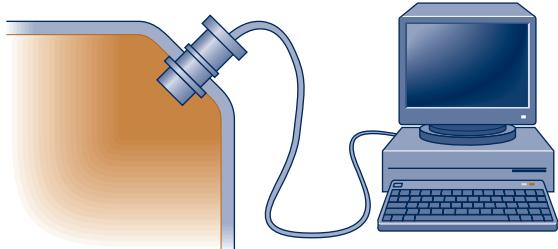
Pressures measured with manometers and barometers are frequently expressed in terms of the length  $L$  in millimeters of mercury (mmHg), inches of mercury (inHg), inches of water (inH<sub>2</sub>O), and so on.

► **FOR EXAMPLE** a barometer reads 750 mmHg. If  $\rho_m = 13.59 \text{ g/cm}^3$  and  $g = 9.81 \text{ m/s}^2$ , the atmospheric pressure, in N/m<sup>2</sup>, is calculated as follows:

$$\begin{aligned} p_{\text{atm}} &= \rho_m g L \\ &= \left[ \left( 13.59 \frac{\text{g}}{\text{cm}^3} \right) \left| \frac{1 \text{ kg}}{10^3 \text{ g}} \right| \left| \frac{10^2 \text{ cm}}{1 \text{ m}} \right|^3 \right] \left[ 9.81 \frac{\text{m}}{\text{s}^2} \right] \left[ (750 \text{ mmHg}) \left| \frac{1 \text{ m}}{10^3 \text{ mm}} \right| \right] \left| \frac{1 \text{ N}}{1 \text{ kg} \cdot \text{m/s}^2} \right| \\ &= 10^5 \text{ N/m}^2 \end{aligned}$$

A Bourdon tube gage is shown in Fig. 1.9. The figure shows a curved tube having an elliptical cross section with one end attached to the pressure to be measured and the other end connected to a pointer by a mechanism. When fluid under pressure fills the tube, the elliptical section tends to become circular, and the tube straightens. This motion is transmitted by the mechanism to the pointer. By calibrating the deflection of the pointer for known pressures, a graduated scale can be determined from which any applied pressure can be read in suitable units. Because of its construction, the Bourdon tube measures the pressure relative to the pressure of the surroundings existing at the instrument. Accordingly, the dial reads zero when the inside and outside of the tube are at the same pressure.

Pressure can be measured by other means as well. An important class of sensors utilize the *piezoelectric effect*: A charge is generated within certain solid materials when they are deformed. This mechanical input/electrical output provides the basis for pressure measurement as well as displacement and force measurements. Another important type of sensor employs a diaphragm that deflects when a force is applied, altering an inductance, resistance, or capacitance. Figure 1.10 shows a piezoelectric pressure sensor together with an automatic data acquisition system.



**Fig. 1.10** Pressure sensor with automatic data acquisition.

## 1.6.2 • Buoyancy

**buoyant force** When a body is completely, or partially, submerged in a liquid, the resultant pressure force acting on the body is called the **buoyant force**. Since pressure increases with depth from the liquid surface, pressure forces acting from below are greater than pressure forces acting from above; thus the buoyant force acts vertically upward. The buoyant force has a magnitude equal to the weight of the displaced liquid (*Archimedes' principle*).

► **FOR EXAMPLE** applying Eq. 1.11 to the submerged rectangular block shown in Fig. 1.11, the magnitude of the net force of pressure acting upward, the buoyant

force, is

$$\begin{aligned} F &= A(p_2 - p_1) = A(p_{\text{atm}} + \rho g L_2) - A(p_{\text{atm}} + \rho g L_1) \\ &= \rho g A(L_2 - L_1) \\ &= \rho g V \end{aligned}$$

where  $V$  is the volume of the block and  $\rho$  is the density of the surrounding liquid. Thus, the magnitude of the buoyant force acting on the block is equal to the weight of the displaced liquid. ▶▶▶▶▶

### 1.6.3 Pressure Units

The SI unit of pressure and stress is the pascal.

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

However, multiples of the pascal: the kPa, the bar, and the MPa are frequently used.

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

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

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

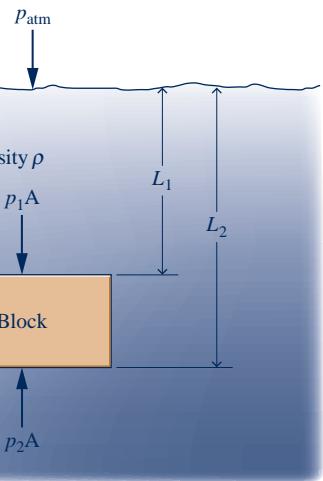
Commonly used English units for pressure and stress are pounds force per square foot, lbf/ft<sup>2</sup>, and pounds force per square inch, lbf/in.<sup>2</sup>

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

$$1 \text{ standard atmosphere (atm)} = \begin{cases} 1.01325 \times 10^5 \text{ N/m}^2 \\ 14.696 \text{ lbf/in.}^2 \\ 760 \text{ mmHg} = 29.92 \text{ inHg} \end{cases} \quad (1.13)$$

Since 1 bar ( $10^5 \text{ N/m}^2$ ) closely equals one standard atmosphere, it is a convenient pressure unit despite not being a standard SI unit. When working in SI, the bar, MPa, and kPa are all used in this text.

Although absolute pressures must be used in thermodynamic relations, pressure-measuring devices often indicate the *difference* between the absolute pressure of a system and the absolute pressure of the atmosphere existing outside the measuring device. The magnitude of the difference is called a **gage pressure** or a **vacuum pressure**. The term gage pressure is applied when the pressure of the system is greater than the local atmospheric pressure,  $p_{\text{atm}}$ .



**Fig. 1.11** Evaluation of buoyant force for a submerged body.

$$p(\text{gage}) = p(\text{absolute}) - p_{\text{atm}}(\text{absolute}) \quad (1.14)$$

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

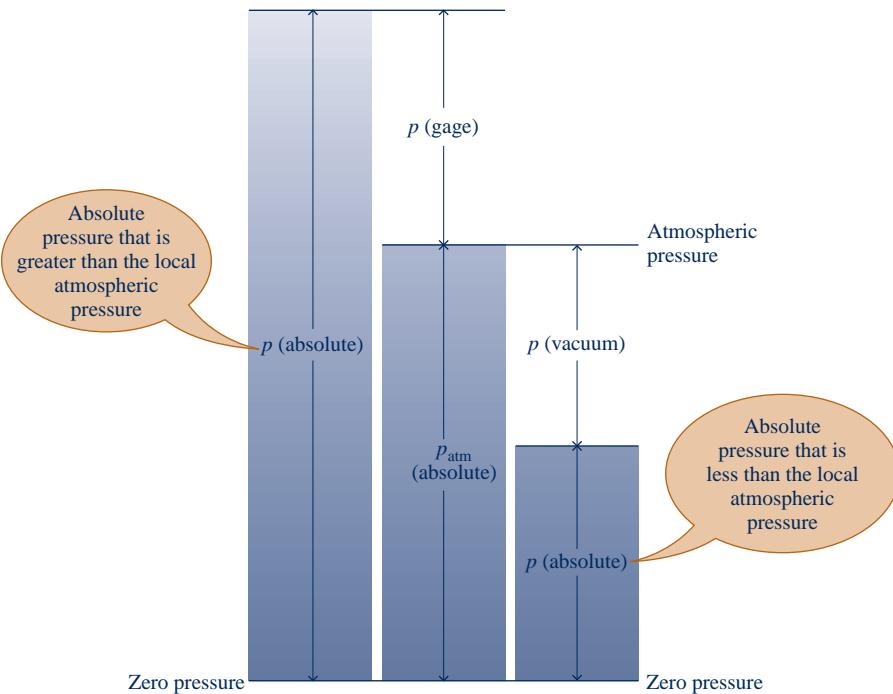
$$p(\text{vacuum}) = p_{\text{atm}}(\text{absolute}) - p(\text{absolute}) \quad (1.15)$$

Engineers in the United States frequently use the letters *a* and *g* to distinguish between absolute and gage pressures. For example, the absolute and gage pressures in pounds force per square inch are written as psia and psig, respectively. The relationship among the various ways of expressing pressure measurements is shown in Fig. 1.12.

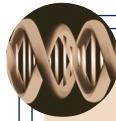
gage pressure  
vacuum pressure

#### TAKE NOTE...

In this book, the term pressure refers to absolute pressure unless indicated otherwise.



**Fig. 1.12 Relationships among the absolute, atmospheric, gage, and vacuum pressures.**



**BIO CONNECTIONS** One in three Americans is said to have high blood pressure. Since this can lead to heart disease, strokes, and other serious medical complications, medical practitioners recommend regular blood pressure checks for everyone. Blood pressure measurement aims to determine the maximum pressure (systolic pressure) in an artery when the heart is pumping blood and the minimum pressure (diastolic pressure) when the heart is resting, each pressure expressed in millimeters of mercury, mmHg. The systolic and diastolic pressures of healthy persons should be less than about 120 mmHg and 80 mmHg, respectively.

The standard blood pressure measurement apparatus in use for decades involving an inflatable cuff, mercury manometer, and stethoscope is gradually being replaced because of concerns over mercury toxicity and in response to special requirements, including monitoring during clinical exercise and during anesthesia. Also, for home use and self-monitoring, many patients prefer easy-to-use automated devices that provide digital displays of blood pressure data. This has prompted biomedical engineers to rethink blood pressure measurement and develop new mercury-free and stethoscope-free approaches. One of these uses a highly-sensitive pressure transducer to detect pressure oscillations within an inflated cuff placed around the patient's arm. The monitor's software uses these data to calculate the systolic and diastolic pressures, which are displayed digitally.

## 1.7 Temperature

In this section the intensive property temperature is considered along with means for measuring it. A concept of temperature, like our concept of force, originates with our sense perceptions. Temperature is rooted in the notion of the “hotness” or “coldness” of objects. We use our sense of touch to distinguish hot objects from cold objects and to arrange objects in their order of “hotness,” deciding that 1 is hotter than 2, 2 hotter



than 3, and so on. But however sensitive human touch may be, we are unable to gauge this quality precisely.

A definition of temperature in terms of concepts that are independently defined or accepted as primitive is difficult to give. However, it is possible to arrive at an objective understanding of *equality* of temperature by using the fact that when the temperature of an object changes, other properties also change.

To illustrate this, consider two copper blocks, and suppose that our senses tell us that one is warmer than the other. If the blocks were brought into contact and isolated from their surroundings, they would interact in a way that can be described as a **thermal (heat) interaction**. During this interaction, it would be observed that the volume of the warmer block decreases somewhat with time, while the volume of the colder block increases with time. Eventually, no further changes in volume would be observed, and the blocks would feel equally warm. Similarly, we would be able to observe that the electrical resistance of the warmer block decreases with time, and that of the colder block increases with time; eventually the electrical resistances would become constant also. When all changes in such observable properties cease, the interaction is at an end. The two blocks are then in **thermal equilibrium**. Considerations such as these lead us to infer that the blocks have a physical property that determines whether they will be in thermal equilibrium. This property is called **temperature**, and we postulate that when the two blocks are in thermal equilibrium, their temperatures are equal.

It is a matter of experience that when two objects are in thermal equilibrium with a third object, they are in thermal equilibrium with one another. This statement, which is sometimes called the **zeroth law of thermodynamics**, is tacitly assumed in every measurement of temperature. Thus, if we want to know if two objects are at the same temperature, it is not necessary to bring them into contact and see whether their observable properties change with time, as described previously. It is necessary only to see if they are individually in thermal equilibrium with a third object. The third object is usually a *thermometer*.

### 1.7.1 Thermometers

Any object with at least one measurable property that changes as its temperature changes can be used as a thermometer. Such a property is called a **thermometric property**. The particular substance that exhibits changes in the thermometric property is known as a *thermometric substance*.

A familiar device for temperature measurement is the liquid-in-glass thermometer pictured in Fig. 1.13a, which consists of a glass capillary tube connected to a bulb filled with a liquid such as alcohol and sealed at the other end. The space above the liquid is occupied by the vapor of the liquid or an inert gas. As temperature increases, the liquid expands in volume and rises in the capillary. The length  $L$  of the liquid in the capillary depends on the temperature. Accordingly, the liquid is the thermometric substance and  $L$  is the thermometric property. Although this type of thermometer is commonly used for ordinary temperature measurements, it is not well suited for applications where extreme accuracy is required.

More accurate sensors known as *thermocouples* are based on the principle that when two dissimilar metals are joined, an electromotive force (emf) that is primarily a function of temperature will exist in a circuit. In certain thermocouples, one thermocouple wire is platinum of a specified purity and the other is an alloy of platinum and rhodium. Thermocouples also utilize copper and constantan (an alloy of copper and nickel), iron and constantan, as well as several other pairs of materials. Electrical-resistance sensors are another important class of temperature measurement devices. These sensors are based on the fact that the electrical resistance of various materials changes in a predictable manner with temperature. The materials used for this purpose are normally conductors (such as platinum, nickel, or copper) or semiconductors.

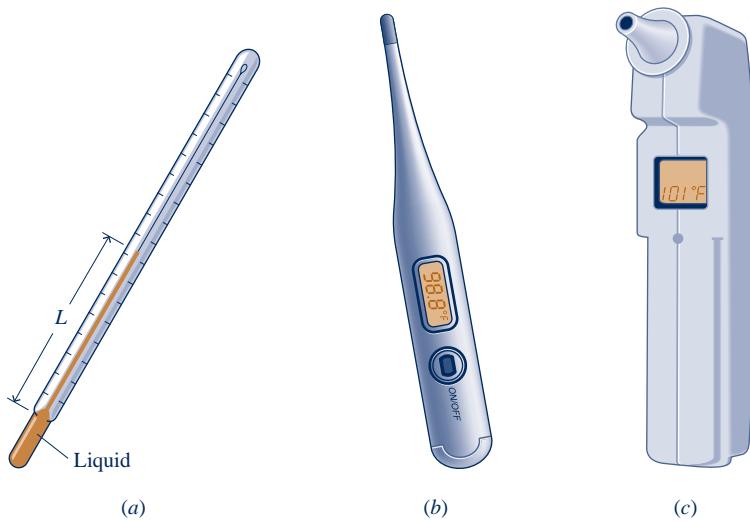
**thermal (heat) interaction**

**thermal equilibrium**

**temperature**

**zeroth law of thermodynamics**

**thermometric property**



**Fig. 1.13 Thermometers.** (a) Liquid-in-glass. (b) Electrical-resistance (c) Infrared-sensing ear thermometer.

Devices using conductors are known as *resistance temperature detectors*. Semiconductor types are called *thermistors*. A battery-powered electrical-resistance thermometer commonly used today is shown in Fig. 1.13b.

A variety of instruments measure temperature by sensing radiation, such as the ear thermometer shown in Fig. 1.13c. They are known by terms such as *radiation thermometers* and *optical pyrometers*. This type of thermometer differs from those previously considered because it is not required to come in contact with the object whose temperature is to be determined, an advantage when dealing with moving objects or objects at extremely high temperatures.



**ENERGY & ENVIRONMENT** The mercury-in-glass fever thermometers, once found in nearly every medicine cabinet, are a thing of the past. The *American Academy of Pediatrics* has designated mercury as too toxic to be present in the home. Families are turning to safer alternatives and disposing of mercury thermometers. Proper disposal is an issue, experts say.

The safe disposal of millions of obsolete mercury-filled thermometers has emerged in its own right as an environmental issue. For proper disposal, thermometers must be taken to hazardous-waste collection stations rather than simply thrown in the trash where they can be easily broken, releasing mercury. Loose fragments of broken thermometers and anything that contacted mercury should be transported in closed containers to appropriate disposal sites.

The present generation of liquid-in-glass fever thermometers for home use contains patented liquid mixtures that are nontoxic, safe alternatives to mercury. Other types of thermometers also are used in the home, including battery-powered electrical-resistance thermometers.

## 1.7.2 • Kelvin and Rankine Temperature Scales

Empirical means of measuring temperature such as considered in Sec. 1.7.1 have inherent limitations.

► **FOR EXAMPLE** the tendency of the liquid in a liquid-in-glass thermometer to freeze at low temperatures imposes a lower limit on the range of temperatures that can be

measured. At high temperatures liquids vaporize, and therefore these temperatures also cannot be determined by a liquid-in-glass thermometer. Accordingly, several *different* thermometers might be required to cover a wide temperature interval. ▶▶▶▶▶

In view of the limitations of empirical means for measuring temperature, it is desirable to have a procedure for assigning temperature values that does not depend on the properties of any particular substance or class of substances. Such a scale is called a *thermodynamic* temperature scale. The **Kelvin scale** is an absolute thermodynamic temperature scale that provides a continuous definition of temperature, valid over all ranges of temperature. The unit of temperature on the Kelvin scale is the kelvin (K). The kelvin is the SI base unit for temperature.

To develop the Kelvin scale, it is necessary to use the conservation of energy principle and the second law of thermodynamics; therefore, further discussion is deferred to Sec. 5.8 after these principles have been introduced. However, we note here that the Kelvin scale has a zero of 0 K, and lower temperatures than this are not defined.

By definition, the **Rankine scale**, the unit of which is the degree rankine ( $^{\circ}\text{R}$ ), is proportional to the Kelvin temperature according to

$$T(^{\circ}\text{R}) = 1.8T(\text{K}) \quad (1.16)$$

**Kelvin scale**

**Rankine scale**

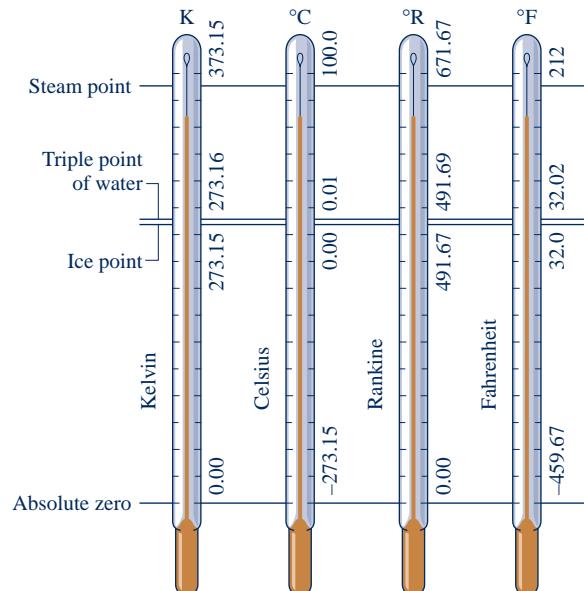
As evidenced by Eq. 1.16, the Rankine scale is also an absolute thermodynamic scale with an absolute zero that coincides with the absolute zero of the Kelvin scale. In thermodynamic relationships, temperature is always in terms of the Kelvin or Rankine scale unless specifically stated otherwise. Still, the Celsius and Fahrenheit scales considered next are commonly encountered.

### 1.7.3 • Celsius and Fahrenheit Scales

The relationship of the Kelvin, Rankine, Celsius, and Fahrenheit scales is shown in Fig. 1.14 together with values for temperature at three fixed points: the triple point, ice point, and steam point.

By international agreement, temperature scales are defined by the numerical value assigned to the easily reproducible **triple point** of water: the state of equilibrium between

**triple point**



**Fig. 1.14** Comparison of temperature scales.

steam, ice, and liquid water (Sec. 3.2). As a matter of convenience, the temperature at this standard fixed point is defined as 273.16 kelvins, abbreviated as 273.16 K. This makes the temperature interval from the *ice point*<sup>1</sup> (273.15 K) to the *steam point*<sup>2</sup> equal to 100 K and thus in agreement over the interval with the Celsius scale, which assigns 100 Celsius degrees to it.

#### Celsius scale

The **Celsius temperature scale** uses the unit degree Celsius ( $^{\circ}\text{C}$ ), which has the same magnitude as the kelvin. Thus, temperature *differences* are identical on both scales. However, the zero point on the Celsius scale is shifted to 273.15 K, as shown by the following relationship between the Celsius temperature and the Kelvin temperature

$$T(^{\circ}\text{C}) = T(\text{K}) - 273.15 \quad (1.17)$$

#### Fahrenheit scale

From this it can be concluded that on the Celsius scale the triple point of water is  $0.01^{\circ}\text{C}$  and that 0 K corresponds to  $-273.15^{\circ}\text{C}$ . These values are shown on Fig. 1.14.

A degree of the same size as that on the Rankine scale is used in the **Fahrenheit scale**, but the zero point is shifted according to the relation

$$T(^{\circ}\text{F}) = T(^{\circ}\text{R}) - 459.67 \quad (1.18)$$

Substituting Eqs. 1.17 and 1.18 into Eq. 1.16, we get

$$T(^{\circ}\text{F}) = 1.8T(^{\circ}\text{C}) + 32 \quad (1.19)$$

This equation shows that the Fahrenheit temperature of the ice point ( $0^{\circ}\text{C}$ ) is  $32^{\circ}\text{F}$  and of the steam point ( $100^{\circ}\text{C}$ ) is  $212^{\circ}\text{F}$ . The 100 Celsius or Kelvin degrees between the ice point and steam point correspond to 180 Fahrenheit or Rankine degrees, as shown in Fig. 1.14.

#### TAKE NOTE...

When making engineering calculations, it's usually okay to round off the last numbers in Eqs. 1.17 and 1.18 to 273 and 460, respectively. This is frequently done in this book.



**BIO CONNECTIONS** *Cryobiology*, the science of life at low temperatures, comprises the study of biological materials and systems (proteins, cells, tissues, and organs) at temperatures ranging from the cryogenic (below about 120 K) to the hypothermic (low body temperature). Applications include freeze-drying pharmaceuticals, cryosurgery for removing unhealthy tissue, study of cold-adaptation of animals and plants, and long-term storage of cells and tissues (called *cryopreservation*).

Cryobiology has challenging engineering aspects owing to the need for refrigerators capable of achieving the low temperatures required by researchers. Freezers to support research requiring cryogenic temperatures in the low-gravity environment of the International Space Station, shown in Table 1.1, are illustrative. Such freezers must be extremely compact and miserly in power use. Further, they must pose no hazards. On-board research requiring a freezer might include the growth of near-perfect protein crystals, important for understanding the structure and function of proteins and ultimately in the design of new drugs.

## 1.8 Engineering Design and Analysis

The word engineer traces its roots to the Latin *ingeniare*, relating to *invention*. Today invention remains a key engineering function having many aspects ranging from developing new devices to addressing complex social issues using technology. In pursuit of many such activities, engineers are called upon to design and analyze things intended to meet human needs. Design and analysis are considered in this section.

<sup>1</sup>The state of equilibrium between ice and air-saturated water at a pressure of 1 atm.

<sup>2</sup>The state of equilibrium between steam and liquid water at a pressure of 1 atm.

## 1.8.1 • Design

Engineering design is a decision-making process in which principles drawn from engineering and other fields such as economics and statistics are applied, usually iteratively, to devise a system, system component, or process. Fundamental elements of design include the establishment of objectives, synthesis, analysis, construction, testing, and evaluation. Designs typically are subject to a variety of **constraints** related to economics, safety, environmental impact, and so on.

**design constraints**

Design projects usually originate from the recognition of a need or an opportunity that is only partially understood initially. Thus, before seeking solutions it is important to define the design objectives. Early steps in engineering design include pinning down quantitative performance specifications and identifying alternative *workable* designs that meet the specifications. Among the workable designs are generally one or more that are “best” according to some criteria: lowest cost, highest efficiency, smallest size, lightest weight, etc. Other important factors in the selection of a final design include reliability, manufacturability, maintainability, and marketplace considerations. Accordingly, a compromise must be sought among competing criteria, and there may be alternative design solutions that are feasible.<sup>3</sup>

## 1.8.2 • Analysis

Design requires synthesis: selecting and putting together components to form a coordinated whole. However, as each individual component can vary in size, performance, cost, and so on, it is generally necessary to subject each to considerable study or analysis before a final selection can be made.

► **FOR EXAMPLE** a proposed design for a fire-protection system might entail an overhead piping network together with numerous sprinkler heads. Once an overall configuration has been determined, detailed engineering analysis is necessary to specify the number and type of the spray heads, the piping material, and the pipe diameters of the various branches of the network. The analysis also must aim to ensure all components form a smoothly working whole while meeting relevant cost constraints and applicable codes and standards. ◀◀◀◀◀

Engineers frequently do analysis, whether explicitly as part of a design process or for some other purpose. Analyses involving systems of the kind considered in this book use, directly or indirectly, one or more of three basic laws. These laws, which are independent of the particular substance or substances under consideration, are

1. the conservation of mass principle
2. the conservation of energy principle
3. the second law of thermodynamics

In addition, relationships among the properties of the particular substance or substances considered are usually necessary (Chaps. 3, 6, 11–14). Newton’s second law of motion (Chaps. 1, 2, 9), relations such as Fourier’s conduction model (Chap. 2), and principles of engineering economics (Chap. 7) also may play a part.

The first steps in a thermodynamic analysis are definition of the system and identification of the relevant interactions with the surroundings. Attention then turns to the pertinent physical laws and relationships that allow the behavior of the system to be described in terms of an **engineering model**. The objective in modeling is to obtain a simplified representation of system behavior that is sufficiently faithful for the purpose

**engineering model**

<sup>3</sup>For further discussion, see A. Bejan, G. Tsatsaronis, and M. J. Moran, *Thermal Design and Optimization*, John Wiley & Sons, New York, 1996, Chap. 1.

of the analysis, even if many aspects exhibited by the actual system are ignored. For example, idealizations often used in mechanics to simplify an analysis and arrive at a manageable model include the assumptions of point masses, frictionless pulleys, and rigid beams. Satisfactory modeling takes experience and is a part of the *art* of engineering.

Engineering analysis is most effective when it is done systematically. This is considered next.

## 1.9 Methodology for Solving Thermodynamics Problems

A major goal of this textbook is to help you learn how to solve engineering problems that involve thermodynamic principles. To this end, numerous solved examples and end-of-chapter problems are provided. It is extremely important for you to study the examples *and* solve problems, for mastery of the fundamentals comes only through practice.

To maximize the results of your efforts, it is necessary to develop a systematic approach. You must think carefully about your solutions and avoid the temptation of starting problems *in the middle* by selecting some seemingly appropriate equation, substituting in numbers, and quickly “punching up” a result on your calculator. Such a haphazard problem-solving approach can lead to difficulties as problems become more complicated. Accordingly, it is strongly recommended that problem solutions be organized using the *five steps* in the box below, which are employed in the solved examples of this text.

- 1 **Known:** State briefly in your own words what is known. This requires that you read the problem carefully *and* think about it.
- 2 **Find:** State concisely in your own words what is to be determined.
- 3 **Schematic and Given Data:** Draw a sketch of the system to be considered. Decide whether a closed system or control volume is appropriate for the analysis, and then carefully identify the boundary. Label the diagram with relevant information from the problem statement.

Record all property values you are given or anticipate may be required for subsequent calculations. Sketch appropriate property diagrams (see Sec. 3.2), locating key state points and indicating, if possible, the processes executed by the system.

The importance of good sketches of the system and property diagrams cannot be overemphasized. They are often instrumental in enabling you to think clearly about the problem.

- 4 **Engineering Model:** To form a record of how you *model* the problem, list all *simplifying assumptions* and *idealizations* made to reduce it to one that is manageable. Sometimes this information also can be noted on the sketches of the previous step. The development of an appropriate model is a key aspect of successful problem solving.
- 5 **Analysis:** Using your assumptions and idealizations, reduce the appropriate governing equations and relationships to forms that will produce the desired results.

It is advisable to work with equations as long as possible before substituting numerical data. When the equations are reduced to final forms, consider them to determine what additional data may be required. Identify the tables, charts, or property equations that provide the required values. Additional property diagram sketches may be helpful at this point to clarify states and processes.

When all equations and data are in hand, substitute numerical values into the equations. Carefully check that a consistent and appropriate set of units is being employed. Then perform the needed calculations.

Finally, consider whether the magnitudes of the numerical values are reasonable and the algebraic signs associated with the numerical values are correct.

The problem solution format used in this text is intended to *guide* your thinking, not substitute for it. Accordingly, you are cautioned to avoid the rote application of these five steps, for this alone would provide few benefits. Indeed, as a particular solution evolves you may have to return to an earlier step and revise it in light of a better understanding of the problem. For example, it might be necessary to add or delete an assumption, revise a sketch, determine additional property data, and so on.

The solved examples provided in the book are frequently annotated with various comments intended to assist learning, including commenting on what was learned, identifying key aspects of the solution, and discussing how better results might be obtained by relaxing certain assumptions.

In some of the earlier examples and end-of-chapter problems, the solution format may seem unnecessary or unwieldy. However, as the problems become more complicated you will see that it reduces errors, saves time, and provides a deeper understanding of the problem at hand.

The example to follow illustrates the use of this solution methodology together with important system concepts introduced previously, including identification of interactions occurring at the boundary.

### ►►►► EXAMPLE 1.1 ►.....

## Using the Solution Methodology and System Concepts

A wind turbine–electric generator is mounted atop a tower. As wind blows steadily across the turbine blades, electricity is generated. The electrical output of the generator is fed to a storage battery.

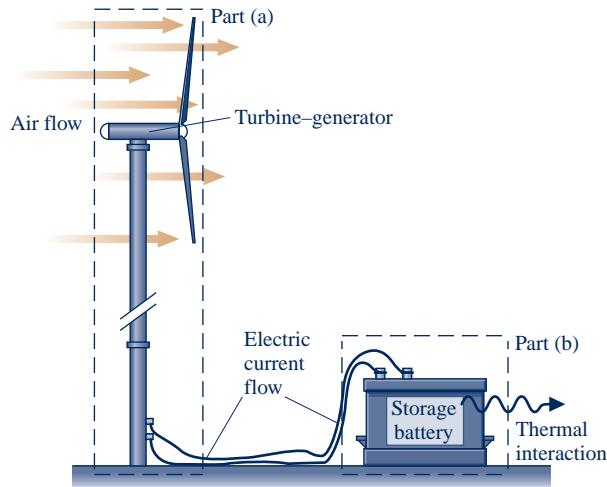
- (a) Considering only the wind turbine–electric generator as the system, identify locations on the system boundary where the system interacts with the surroundings. Describe changes occurring within the system with time.
- (b) Repeat for a system that includes only the storage battery.

### SOLUTION

**Known:** A wind turbine–electric generator provides electricity to a storage battery.

**Find:** For a system consisting of (a) the wind turbine–electric generator, (b) the storage battery, identify locations where the system interacts with its surroundings, and describe changes occurring within the system with time.

### Schematic and Given Data:



### Engineering Model:

1. In part (a), the system is the control volume shown by the dashed line on the figure.
2. In part (b), the system is the closed system shown by the dashed line on the figure.
3. The wind is steady.

Fig. E1.1

### Analysis:

- (a) In this case, the wind turbine is studied as a control volume with air flowing across the boundary. Another principal interaction between the system and surroundings is the electric current passing through the wires. From the macroscopic perspective, such an interaction is not considered a mass transfer, however. With a

steady wind, the turbine-generator is likely to reach steady-state operation, where the rotational speed of the blades is constant and a steady electric current is generated.

- 1 (b) In this case, the battery is studied as a closed system. The principal interaction between the system and its surroundings is the electric current passing into the battery through the wires. As noted in part (a), this interaction is not considered a mass transfer. As the battery is charged and chemical reactions occur within it, the temperature of the battery surface may become somewhat elevated and a thermal interaction might occur between the battery and its surroundings. This interaction is likely to be of secondary importance. Also, as the battery is charged, the state within changes with time. The battery is not at steady state.
  
- 1 Using terms familiar from a previous physics course, the system of part (a) involves the *conversion* of kinetic energy to electricity, whereas the system of part (b) involves energy *storage* within the battery.



### Skills Developed

#### Ability to...

- apply the problem-solving methodology used in this book.
- define a control volume and identify interactions on its boundary.
- define a closed system and identify interactions on its boundary.
- distinguish steady-state operation from nonsteady operation.

### QuickQUIZ

May an *overall* system consisting of the turbine-generator and battery be considered as operating at steady state? Explain. **Ans.** No. A system is at steady state only if *none* of its properties change with time.

## ► CHAPTER SUMMARY AND STUDY GUIDE

In this chapter, we have introduced some of the fundamental concepts and definitions used in the study of thermodynamics. The principles of thermodynamics are applied by engineers to analyze and design a wide variety of devices intended to meet human needs.

An important aspect of thermodynamic analysis is to identify systems and to describe system behavior in terms of properties and processes. Three important properties discussed in this chapter are specific volume, pressure, and temperature.

In thermodynamics, we consider systems at equilibrium states and systems undergoing processes (changes of state). We study processes during which the intervening states are not equilibrium states and processes during which the departure from equilibrium is negligible.

In this chapter, we have introduced SI and English Engineering units for mass, length, time, force, and temperature. You will need to be familiar with both sets of units as you use this book. For *Conversion Factors*, see inside the front cover of the book.

Chapter 1 concludes with discussions of how thermodynamics is used in engineering design and how to solve thermodynamics problems systematically.

This book has several features that facilitate study and contribute to understanding. For an overview, see *How To Use This Book Effectively* inside the front cover of the book.

The following checklist provides a study guide for this chapter. When your study of the text and the end-of-chapter exercises has been completed you should be able to

- write out the meanings of the terms listed in the margin throughout the chapter and understand each of the related concepts. The subset of key concepts listed below is particularly important in subsequent chapters.
- use SI and English units for mass, length, time, force, and temperature and apply appropriately Newton's second law and Eqs. 1.16–1.19.
- work on a molar basis using Eq. 1.8.
- identify an appropriate system boundary and describe the interactions between the system and its surroundings.
- apply the methodology for problem solving discussed in Sec. 1.9.

## ► KEY ENGINEERING CONCEPTS

**system, p. 4**

**surroundings, p. 4**

**boundary, p. 4**

**closed system, p. 6**

**control volume, p. 6**

**property, p. 9**

**state, p. 9**

**process, p. 9**

**extensive property, p. 9**

**intensive property, p. 9**

**equilibrium, p. 10**

**specific volume, p. 14**

**pressure, p. 14**

**temperature, p. 19**

**Kelvin scale, p. 21**

**Rankine scale, p. 21**

## ► KEY EQUATIONS

$n = m/M$	(1.8) p. 14	Relation between amounts of matter on a mass basis, $m$ , and on a molar basis, $n$ .
$T(^{\circ}\text{R}) = 1.8T(\text{K})$	(1.16) p. 21	Relation between the Rankine and Kelvin temperatures.
$T(^{\circ}\text{C}) = T(\text{K}) - 273.15$	(1.17) p. 22	Relation between the Celsius and Kelvin temperatures.
$T(^{\circ}\text{F}) = T(^{\circ}\text{R}) - 459.67$	(1.18) p. 22	Relation between the Fahrenheit and Rankine temperatures.
$T(^{\circ}\text{F}) = 1.8T(^{\circ}\text{C}) + 32$	(1.19) p. 22	Relation between the Fahrenheit and Celsius temperatures.

## ► EXERCISES: THINGS ENGINEERS THINK ABOUT

1. In 1998, owing to a mix-up over units, the NASA Mars Climate Orbiter veered off-course and was lost. What was the mix-up?
2. Operating rooms in hospitals typically have a *positive pressure* relative to adjacent spaces. What does this mean and why is it done?
3. The driver's compartment of race cars can reach  $60^{\circ}\text{C}$  during a race. Why?
4. You may have used the mass unit *slug* in previous engineering or physics courses. What is the relation between the slug and pound mass? Is the slug a convenient mass unit?
5. Based on the macroscopic view, a quantity of air at  $100 \text{ kPa}$ ,  $20^{\circ}\text{C}$  is in equilibrium. Yet the atoms and molecules of the air are in constant motion. How do you reconcile this apparent contradiction?
6. Laura takes an elevator from the tenth floor of her office building to the lobby. Should she expect the air pressure on the two levels to differ much?
7. How do dermatologists remove pre-cancerous skin blemishes *cryosurgically*?
8. When one walks barefoot from a carpet onto a ceramic tile floor, the tiles feel *colder* than the carpet even though each surface is at the same temperature. Explain.
9. Air at  $1 \text{ atm}$ ,  $70^{\circ}\text{F}$  in a closed tank adheres to the *continuum hypothesis*. Yet when sufficient air has been drawn from the tank, the hypothesis no longer applies to the remaining air. Why?
10. Are the *systolic* and *diastolic* pressures reported in blood pressure measurements absolute, gage, or vacuum pressures?
11. When the instrument panel of a car provides the outside air temperature, where is the temperature sensor located?
12. How does a pressure measurement of  $14.7 \text{ psig}$  differ from a pressure measurement of  $14.7 \text{ psia}$ ?
13. What is a *nanotube*?
14. If a system is at steady state, does this mean intensive properties are uniform with position throughout the system *or* constant with time? Both uniform with position *and* constant with time? Explain.

## ► PROBLEMS: DEVELOPING ENGINEERING SKILLS

### Exploring System Concepts

- 1.1** Using the Internet, obtain information about the operation of an application listed or shown in Table 1.1. Obtain sufficient information to provide a full description of the application, together with relevant thermodynamic aspects. Present your findings in a memorandum.
- 1.2** As illustrated in Fig. P1.2, water circulates through a piping system, servicing various household needs. Considering the water heater as a system, identify locations on the system boundary where the system interacts with its surroundings and describe significant occurrences within the system. Repeat for the dishwasher and for the shower. Present your findings in a memorandum.

**1.3** Reef aquariums such as shown in Fig. P1.3 are popular attractions. Such facilities employ a variety of devices, including heaters, pumps, filters, and controllers, to create a healthy environment for the living things residing in the aquarium, which typically include species of fish, together with corals, clams, and anemone. Considering a reef aquarium as a system, identify locations on the system boundary where the system interacts with its surroundings. Using the Internet, describe significant occurrences within the system, and comment on measures for the health and safety of the aquatic life. Present your findings in a memorandum.

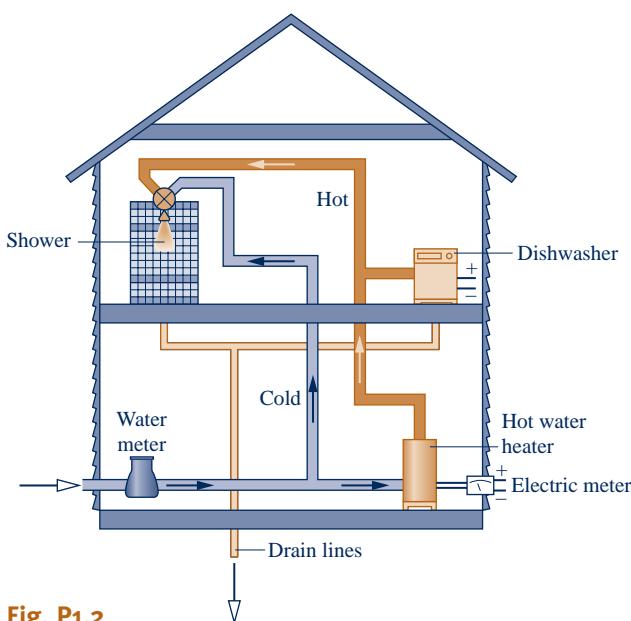


Fig. P1.2



Fig. P1.3

### Working with Units

**1.4** Perform the following unit conversions:

- 1 L to in.<sup>3</sup>
- 650 J to Btu
- 0.135 kW to ft · lbf/s
- 378 g/s to lb/min
- 304 kPa to lbf/in.<sup>2</sup>
- 55 m<sup>3</sup>/h to ft<sup>3</sup>/s
- 50 km/h to ft/s
- 8896 N to ton (=2000 lbf)

**1.5** Perform the following unit conversions:

- 122 in.<sup>3</sup> to L
- 778.17 ft · lbf to kJ
- 100 hp to kW
- 1000 lb/h to kg/s
- 29.392 lbf/in.<sup>2</sup> to bar
- 2500 ft<sup>3</sup>/min to m<sup>3</sup>/s
- 75 mile/h to km/h
- 1 ton (=2000 lbf) to N

### Working with Force and Mass

**1.6** If Superman has a mass of 100 kg on his birth planet Krypton, where the acceleration of gravity is 25 m/s<sup>2</sup>, determine (a) his weight on Krypton, in N, and (b) his mass, in kg, and weight, in N, on Earth where  $g = 9.81 \text{ m/s}^2$ .

**1.7** A person whose mass is 150 lb weighs 144.4 lbf. Determine (a) the local acceleration of gravity, in ft/s<sup>2</sup>, and (b) the person's mass, in lb and weight, in lbf, if  $g = 32.174 \text{ ft/s}^2$ .

**1.8** A gas occupying a volume of 25 ft<sup>3</sup> weighs 3.5 lbf on the moon, where the acceleration of gravity is 5.47 ft/s<sup>2</sup>. Determine its weight, in lbf, and density, in lb/ft<sup>3</sup>, on Mars, where  $g = 12.86 \text{ ft/s}^2$ .

**1.9** Atomic and molecular weights of some common substances are listed in Appendix Tables A-1 and A-1E. Using data from the appropriate table, determine

(a) the mass, in kg, of 20 kmol of each of the following: air, C, H<sub>2</sub>O, CO<sub>2</sub>.

(b) the number of lbmol in 50 lb of each of the following: H<sub>2</sub>, N<sub>2</sub>, NH<sub>3</sub>, C<sub>3</sub>H<sub>8</sub>.

**1.10** In severe head-on automobile accidents, a deceleration of 60 g's or more ( $1 \text{ g} = 32.2 \text{ ft/s}^2$ ) often results in a fatality. What force, in lbf, acts on a child whose mass is 50 lb, when subjected to a deceleration of 60 g's?

**1.11** At the grocery store you place a pumpkin with a mass of 12.5 lb on the produce spring scale. The spring in the scale operates such that for each 4.7 lbf applied, the spring elongates one inch. If local acceleration of gravity is 32.2 ft/s<sup>2</sup>, what distance, in inches, did the spring elongate?

**1.12** A spring compresses in length by 0.14 in. for every 1 lbf of applied force. Determine the mass of an object, in pounds mass, that causes a spring deflection of 1.8 in. The local acceleration of gravity = 31 ft/s<sup>2</sup>.

**1.13** At a certain elevation, the pilot of a balloon has a mass of 120 lb and a weight of 119 lbf. What is the local acceleration of gravity, in ft/s<sup>2</sup>, at that elevation? If the balloon drifts to another elevation where  $g = 32.05 \text{ ft/s}^2$ , what is her weight, in lbf, and mass, in lb?

**1.14** Estimate the magnitude of the force, in lbf, exerted on a 12-lb goose in a collision of duration  $10^{-3}$  s with an airplane taking off at 150 miles/h.

**1.15** Determine the upward applied force, in lbf, required to accelerate a 4.5-lb model rocket vertically upward, as shown in Fig. P1.15, with an acceleration of 3 g's. The only other significant force acting on the rocket is gravity, and  $1 \text{ g} = 32.2 \text{ ft/s}^2$ .

**1.16** An object is subjected to an applied upward force of 10 lbf. The only other force acting on the object is the force of gravity. The acceleration of gravity is 32.2 ft/s<sup>2</sup>. If the object has a mass of 50 lb, determine the net acceleration of the object, in ft/s<sup>2</sup>. Is the net acceleration upward or downward?

**1.17** An astronaut weighs 700 N on Earth where  $g = 9.81 \text{ m/s}^2$ . What is the astronaut's weight, in N, on an orbiting space station where the acceleration of gravity is 6 m/s<sup>2</sup>? Express each weight in lbf.

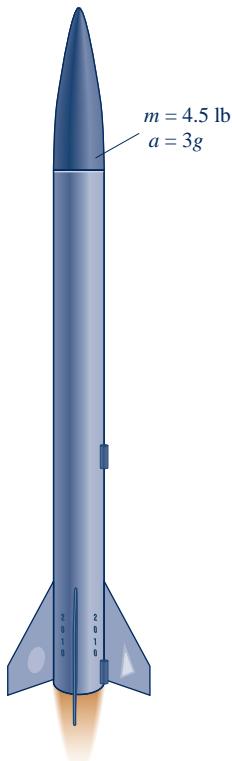


Fig. P1.15

**1.24** The pressure of the gas contained in the piston–cylinder assembly of Fig. 1.1 varies with its volume according to  $p = A + (B/V)$ , where A, B are constants. If pressure is in lbf/ft<sup>2</sup> and volume is in ft<sup>3</sup>, what are the units of A and B?

**1.25** As shown in Figure P1.25, a gas is contained in a piston–cylinder assembly. The piston mass and cross-sectional area are denoted  $m$  and  $A$ , respectively. The only force acting on the top of the piston is due to atmospheric pressure,  $p_{\text{atm}}$ . Assuming the piston moves smoothly in the cylinder and the local acceleration of gravity  $g$  is constant, show that the pressure of the gas acting on the bottom of the piston remains constant as gas volume varies. What would cause the gas volume to vary?

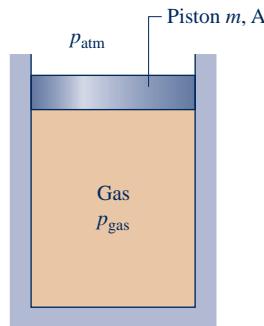


Fig. P1.25

**1.18** Using local acceleration of gravity data from the Internet, determine the weight, in N, of a person whose mass is 80 kg living in:

- (a) Mexico City, Mexico
- (b) Cape Town, South Africa
- (c) Tokyo, Japan
- (d) Chicago, IL
- (e) Copenhagen, Denmark

**1.19** A town has a 1-million-gallon storage capacity water tower. If the density of water is 62.4 lb/ft<sup>3</sup> and local acceleration of gravity is 32.1 ft/s<sup>2</sup>, what is the force, in lbf, the structural base must provide to support the water in the tower?

#### Using Specific Volume, Volume, and Pressure

**1.20** A closed system consists of 0.5 kmol of ammonia occupying a volume of 6 m<sup>3</sup>. Determine (a) the weight of the system, in N, and (b) the specific volume, in m<sup>3</sup>/kmol and m<sup>3</sup>/kg. Let  $g = 9.81 \text{ m/s}^2$ .

**1.21** A spherical balloon holding 35 lb of air has a diameter of 10 ft. For the air, determine (a) the specific volume, in ft<sup>3</sup>/lb and ft<sup>3</sup>/lbmol, and (b) the weight, in lbf. Let  $g = 31.0 \text{ ft/s}^2$ .

**1.22** A closed vessel having a volume of 1 liter holds  $2.5 \times 10^{22}$  molecules of ammonia vapor. For the ammonia, determine (a) the amount present, in kg and kmol, and (b) the specific volume, in m<sup>3</sup>/kg and m<sup>3</sup>/kmol.

**1.23** The specific volume of water vapor at 0.3 MPa, 160°C is 0.651 m<sup>3</sup>/kg. If the water vapor occupies a volume of 2 m<sup>3</sup>, determine (a) the amount present, in kg and kmol, and (b) the number of molecules.

**1.26** As shown in Fig. P1.26, a vertical piston–cylinder assembly containing a gas is placed on a hot plate. The piston initially rests on the stops. With the onset of heating, the gas pressure increases. At what pressure, in bar, does the piston start rising? The piston moves smoothly in the cylinder and  $g = 9.81 \text{ m/s}^2$ .

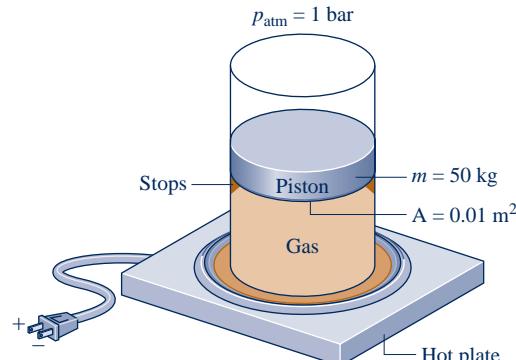


Fig. P1.26

**1.27** Three kg of gas in a piston–cylinder assembly undergo a process during which the relationship between pressure and specific volume is  $pV^{0.5} = \text{constant}$ . The process begins with  $p_1 = 250 \text{ kPa}$  and  $V_1 = 1.5 \text{ m}^3$  and ends with  $p_2 = 100 \text{ kPa}$ . Determine the final specific volume, in m<sup>3</sup>/kg. Plot the process on a graph of pressure versus specific volume.

**1.28** A closed system consisting of 2 lb of a gas undergoes a process during which the relation between pressure and volume is  $pV^n = \text{constant}$ . The process begins with  $p_1 = 20 \text{ lbf/in.}^2$ ,  $V_1 = 10 \text{ ft}^3$  and ends with  $p_2 = 100 \text{ lbf/in.}^2$ ,  $V_2 = 2.9 \text{ ft}^3$ . Determine (a) the value of  $n$  and (b) the specific volume at

states 1 and 2, each in  $\text{ft}^3/\text{lb}$ . (c) Sketch the process on pressure-volume coordinates.

- 1.29** A system consists of carbon monoxide (CO) in a piston-cylinder assembly, initially at  $p_1 = 200 \text{ lbf/in.}^2$ , and occupying a volume of  $2.0 \text{ m}^3$ . The carbon monoxide expands to  $p_2 = 40 \text{ lbf/in.}^2$  and a final volume of  $3.5 \text{ m}^3$ . During the process, the relationship between pressure and volume is linear. Determine the volume, in  $\text{ft}^3$ , at an intermediate state where the pressure is  $150 \text{ lbf/in.}^2$ , and sketch the process on a graph of pressure versus volume.

- 1.30** Figure P1.30 shows a gas contained in a vertical piston-cylinder assembly. A vertical shaft whose cross-sectional area is  $0.8 \text{ cm}^2$  is attached to the top of the piston. Determine the magnitude,  $F$ , of the force acting on the shaft, in N, required if the gas pressure is 3 bar. The masses of the piston and attached shaft are 24.5 kg and 0.5 kg, respectively. The piston diameter is 10 cm. The local atmospheric pressure is 1 bar. The piston moves smoothly in the cylinder and  $g = 9.81 \text{ m/s}^2$ .

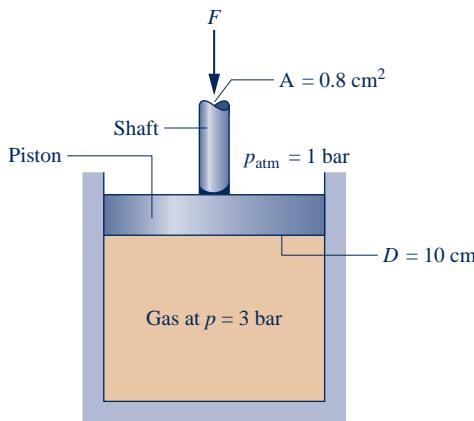


Fig. P1.30

- 1.31** A gas contained within a piston-cylinder assembly undergoes three processes in series:

**Process 1–2:** Compression with  $pV = \text{constant}$  from  $p_1 = 1 \text{ bar}$ ,  $V_1 = 1.0 \text{ m}^3$  to  $V_2 = 0.2 \text{ m}^3$

**Process 2–3:** Constant-pressure expansion to  $V_3 = 1.0 \text{ m}^3$

**Process 3–1:** Constant volume

Sketch the processes in series on a  $p$ - $V$  diagram labeled with pressure and volume values at each numbered state.

- 1.32** Referring to Fig. 1.7,

(a) if the pressure in the tank is 1.5 bar and atmospheric pressure is 1 bar, determine  $L$ , in m, for water with a density of  $997 \text{ kg/m}^3$  as the manometer liquid. Let  $g = 9.81 \text{ m/s}^2$ .

(b) determine  $L$ , in cm, if the manometer liquid is mercury with a density of  $13.59 \text{ g/cm}^3$  and the gas pressure is 1.3 bar. A barometer indicates the local atmospheric pressure is 750 mmHg. Let  $g = 9.81 \text{ m/s}^2$ .

- 1.33** Figure P1.33 shows a storage tank holding natural gas. In an adjacent instrument room, a U-tube mercury manometer in communication with the storage tank reads  $L = 1.0 \text{ m}$ . If the atmospheric pressure is 101 kPa, the density of the

mercury is  $13.59 \text{ g/cm}^3$ , and  $g = 9.81 \text{ m/s}^2$ , determine the pressure of the natural gas, in kPa.

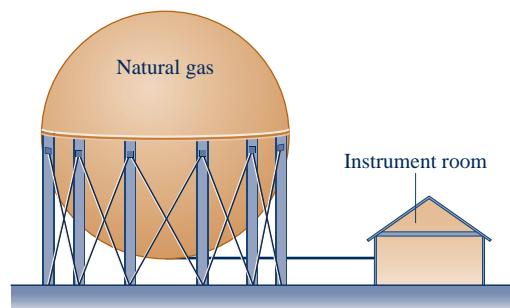


Fig. P1.33

- 1.34** As shown in Figure P1.34, the exit of a gas compressor empties into a receiver tank, maintaining the tank contents at a pressure of 200 kPa. If the local atmospheric pressure is 1 bar, what is the reading of the Bourdon gage mounted on the tank wall in kPa? Is this a *vacuum* pressure or a *gauge* pressure? Explain.

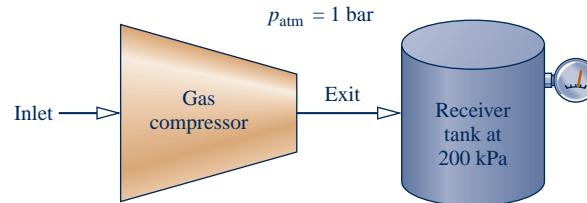


Fig. P1.34

- 1.35** The barometer shown in Fig. P1.35 contains mercury ( $\rho = 13.59 \text{ g/cm}^3$ ). If the local atmospheric pressure is 100 kPa and  $g = 9.81 \text{ m/s}^2$ , determine the height of the mercury column,  $L$ , in mmHg and inHg.

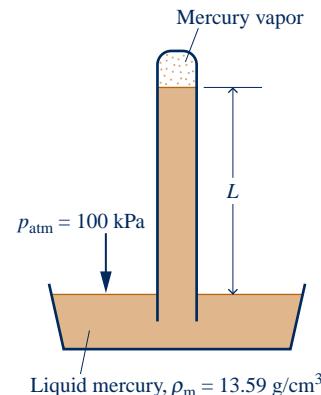
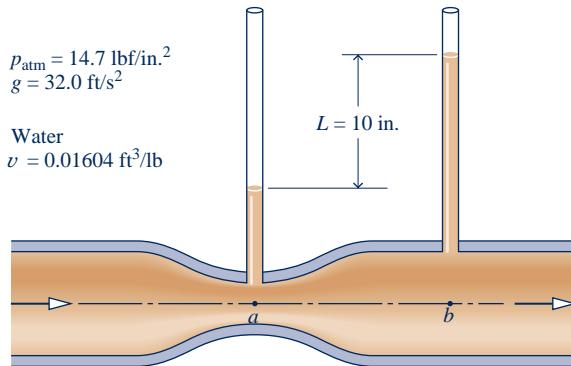


Fig. P1.35

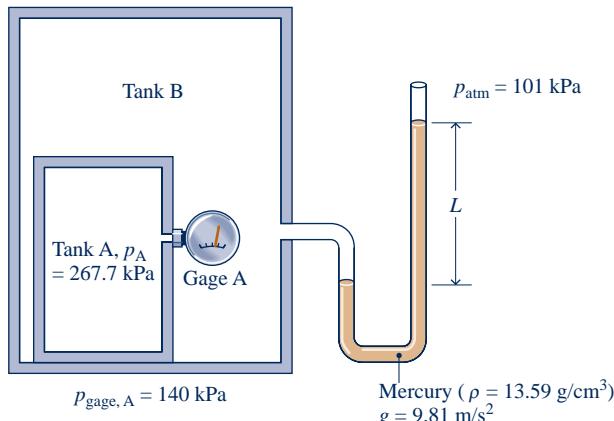
- 1.36** Water flows through a *Venturi meter*, as shown in Fig. P1.36. The pressure of the water in the pipe supports columns of water that differ in height by 10 in. Determine the difference in pressure between points a and b, in  $\text{lbf/in.}^2$ . Does the

pressure increase or decrease in the direction of flow? The atmospheric pressure is  $14.7 \text{ lbf/in.}^2$ , the specific volume of water is  $0.01604 \text{ ft}^3/\text{lb}$ , and the acceleration of gravity is  $g = 32.0 \text{ ft/s}^2$ .



**Fig. P1.36**

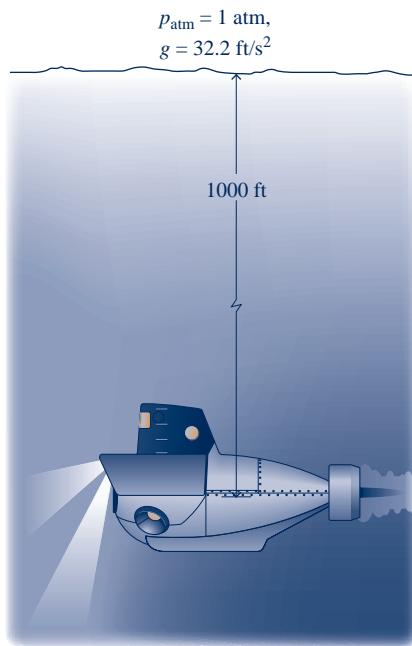
- 1.37** Figure P1.37 shows a tank within a tank, each containing air. The absolute pressure in tank A is  $267.7 \text{ kPa}$ . Pressure gage A is located inside tank B and reads  $140 \text{ kPa}$ . The U-tube manometer connected to tank B contains mercury. Using data on the diagram, determine the absolute pressure inside tank B, in kPa, and the column length  $L$ , in cm. The atmospheric pressure surrounding tank B is  $101 \text{ kPa}$ . The acceleration of gravity is  $g = 9.81 \text{ m/s}^2$ .



**Fig. P1.37**

- 1.38** As shown in Fig. P1.38, an underwater exploration vehicle submerges to a depth of  $1000 \text{ ft}$ . If the atmospheric pressure at the surface is  $1 \text{ atm}$ , the water density is  $62.4 \text{ lb/ft}^3$ , and  $g = 32.2 \text{ ft/s}^2$ , determine the pressure on the vehicle, in atm.

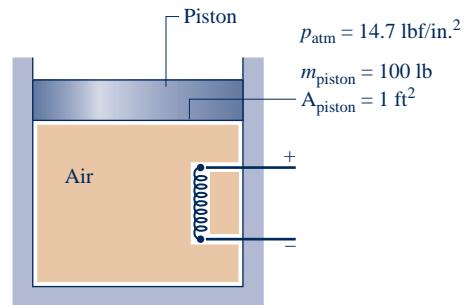
- 1.39** A vacuum gage indicates that the pressure of carbon dioxide in a closed tank is  $-10 \text{ kPa}$ . A mercury barometer gives the local atmospheric pressure as  $750 \text{ mmHg}$ . Determine the absolute pressure of the carbon dioxide, in kPa. The density of mercury is  $13.59 \text{ g/cm}^3$  and  $g = 9.81 \text{ m/s}^2$ .



**Fig. P1.38**

- 1.40** A gas enters a compressor that provides a pressure ratio (exit pressure to inlet pressure) equal to 8. If a gage indicates the gas pressure at the inlet is  $5.5 \text{ psig}$ , what is the absolute pressure, in psia, of the gas at the exit? Atmospheric pressure is  $14.5 \text{ lbf/in.}^2$ .

- 1.41** As shown in Fig. P1.41, air is contained in a vertical piston-cylinder assembly fitted with an electrical resistor. The atmosphere exerts a pressure of  $14.7 \text{ lbf/in.}^2$  on the top of the piston, which has a mass of  $100 \text{ lb}$  and face area of  $1 \text{ ft}^2$ . As electric current passes through the resistor, the volume of the air increases while the piston moves smoothly in the cylinder. The local acceleration of gravity is  $g = 32.0 \text{ ft/s}^2$ . Determine the pressure of the air in the piston-cylinder assembly, in  $\text{lbf/in.}^2$  and psig.



**Fig. P1.41**

- 1.42** Warm air is contained in a piston-cylinder assembly oriented horizontally as shown in Fig. P1.42. The air cools slowly from an initial volume of  $0.003 \text{ m}^3$  to a final volume of  $0.002 \text{ m}^3$ . During the process, the spring exerts a force that varies linearly from an initial value of  $900 \text{ N}$  to a final value of zero. The atmospheric pressure is  $100 \text{ kPa}$ , and the area of the piston face is  $0.018 \text{ m}^2$ . Friction between the piston and the cylinder wall can be neglected. For the air in the piston-cylinder assembly, determine the initial and final pressures, each in kPa and atm.

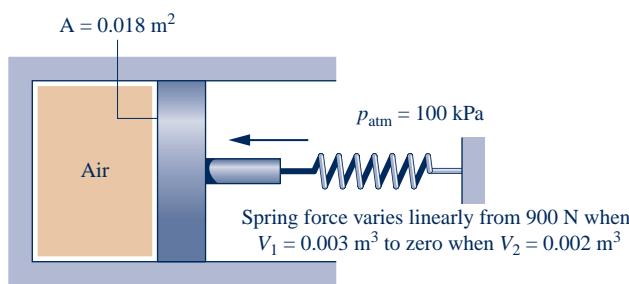


Fig. P1.42

**1.43** The pressure from water mains located at street level may be insufficient for delivering water to the upper floors of tall buildings. In such a case, water may be pumped up to a tank that feeds water to the building by gravity. For an open storage tank atop a 300-ft-tall building, determine the pressure, in lbf/in.<sup>2</sup>, at the bottom of the tank when filled to a depth of 20 ft. The density of water is 62.2 lb/ft<sup>3</sup>,  $g = 32.0 \text{ ft/s}^2$ , and the local atmospheric pressure is 14.7 lbf/in.<sup>2</sup>

**1.44** Figure P1.44 shows a tank used to collect rainwater having a diameter of 4 m. As shown in the figure, the depth of the tank varies linearly from 3.5 m at its center to 3 m along the perimeter. The local atmospheric pressure is 1 bar, the acceleration of gravity is  $9.8 \text{ m/s}^2$ , and the density of the water is  $987.1 \text{ kg/m}^3$ . When the tank is filled with water, determine

- (a) the pressure, in kPa, at the bottom center of the tank.
- (b) the total force, in kN, acting on the bottom of the tank.

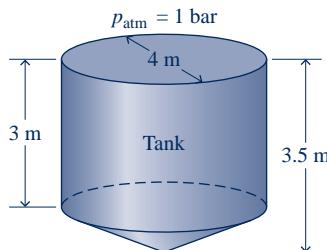


Fig. P1.44

**1.45** If the water pressure at the base of the water tower shown in Fig. P1.45 is 4.15 bar, determine the pressure of the air trapped above the water level, in bar. The density of the water is  $10^3 \text{ kg/m}^3$  and  $g = 9.81 \text{ m/s}^2$ .

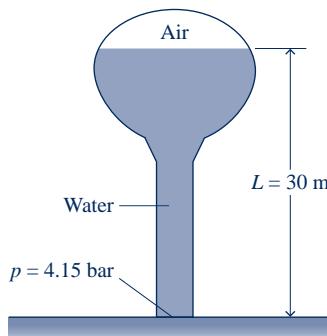


Fig. P1.45

**1.46** As shown in Figure P1.46, an *inclined* manometer is used to measure the pressure of the gas within the reservoir. (a) Using data on the figure, determine the gas pressure, in lbf/in.<sup>2</sup> (b) Express the pressure as a gage or a vacuum pressure, as appropriate, in lbf/in.<sup>2</sup> (c) What advantage does an inclined manometer have over the U-tube manometer shown in Figure 1.7?

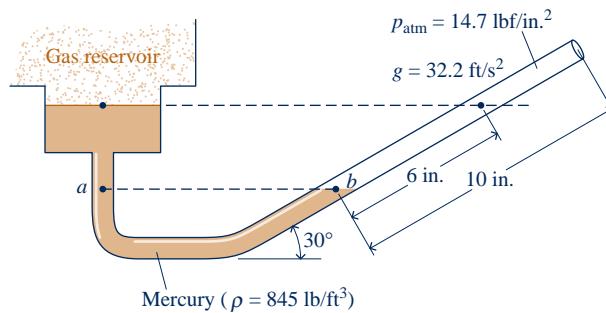


Fig. P1.46

**1.47** Figure P1.47 shows a spherical buoy, having a diameter of 1.5 m and weighing 8500 N, anchored to the floor of a lake by a cable. Determine the force exerted by the cable, in N. The density of the lake water is  $10^3 \text{ kg/m}^3$  and  $g = 9.81 \text{ m/s}^2$ .

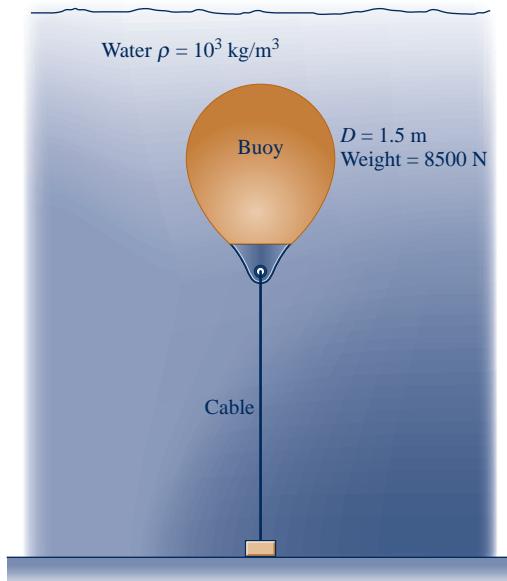


Fig. P1.47

**1.48** Because of a break in a buried oil storage tank, groundwater has leaked into the tank to the depth shown in Fig. P1.48. Determine the pressure at the oil–water interface and at the bottom of the tank, each in lbf/in.<sup>2</sup> (gage). The densities of the water and oil are, respectively, 62 and 55, each in lb/ft<sup>3</sup>. Let  $g = 32.2 \text{ ft/s}^2$ .

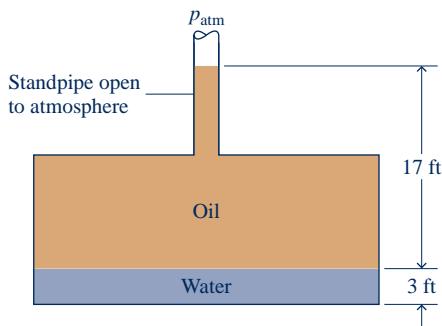


Fig. P1.48

- 1.49** Figure P1.49 shows a closed tank holding air and oil to which is connected a U-tube mercury manometer and a pressure gage. Determine the reading of the pressure gage, in  $\text{lbf/in}^2$  (gage). The densities of the oil and mercury are 55 and 845, respectively, each in  $\text{lb/ft}^3$ . Let  $g = 32.2 \text{ ft/s}^2$ .

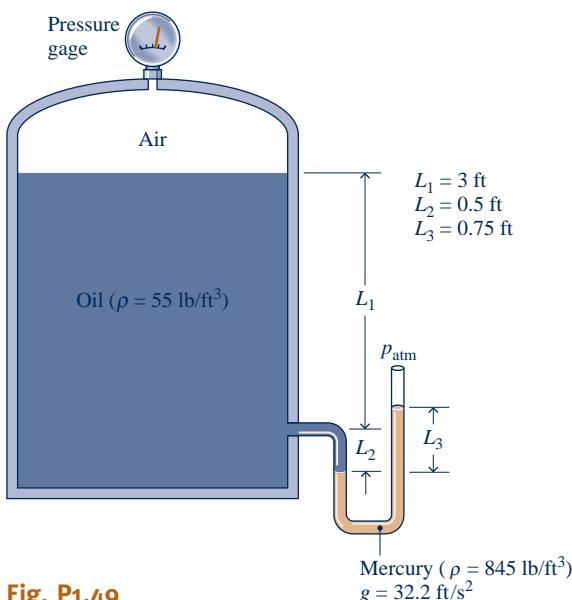


Fig. P1.49

### Exploring Temperature

- 1.50** The 30-year average temperature in Toronto, Canada, during summer is  $19.5^\circ\text{C}$  and during winter is  $-4.9^\circ\text{C}$ . What are the equivalent average summer and winter temperatures in  $^\circ\text{F}$  and  $^\circ\text{R}$ ?

- 1.51** Convert the following temperatures from  $^\circ\text{F}$  to  $^\circ\text{C}$ :  
 (a)  $86^\circ\text{F}$ , (b)  $-22^\circ\text{F}$ , (c)  $50^\circ\text{F}$ , (d)  $-40^\circ\text{F}$ , (e)  $32^\circ\text{F}$ , (f)  $-459.67^\circ\text{F}$ . Convert each temperature to K.

- 1.52** Natural gas is burned with air to produce gaseous products at  $1985^\circ\text{C}$ . Express this temperature in K,  $^\circ\text{R}$ , and  $^\circ\text{F}$ .

- 1.53** The temperature of a child ill with a fever is measured as  $40^\circ\text{C}$ . The child's normal temperature is  $37^\circ\text{C}$ . Express both temperatures in  $^\circ\text{F}$ .

- 1.54** Does the Rankine degree represent a larger or smaller temperature unit than the Kelvin degree? Explain.

- 1.55** Figure P1.55 shows a system consisting of a cylindrical copper rod insulated on its lateral surface while its ends are in contact with hot and cold walls at temperatures  $1000^\circ\text{R}$  and  $500^\circ\text{R}$ , respectively.

- (a) Sketch the variation of temperature with position through the rod,  $x$ .  
 (b) Is the rod in equilibrium? Explain.

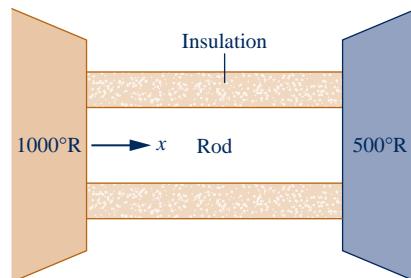


Fig. P1.55

- 1.56** What is (a) the lowest *naturally* occurring temperature recorded on Earth, (b) the lowest temperature recorded in a laboratory on Earth, (c) the lowest temperature recorded in the Earth's solar system, and (d) the temperature of deep space, each in K?

- 1.57** What is the maximum increase and maximum decrease in body temperature, each in  $^\circ\text{C}$ , from a normal body temperature of  $37^\circ\text{C}$  that humans can experience before serious medical complications result?

- 1.58** For liquid-in-glass thermometers, the *thermometric* property is the change in length of the thermometer liquid with temperature. However, other effects are present that can affect the temperature reading of such thermometers. What are some of these?

### Reviewing Concepts

- 1.59** Answer the following true or false. Explain.

- (a) A closed system always contains the same matter; there is no transfer of matter across its boundary.
- (b) The volume of a closed system can change.
- (c) One nanosecond equals  $10^9$  seconds.
- (d) When a closed system undergoes a process between two specified states, the change in temperature between the end states is independent of details of the process.
- (e) Body organs, such as the human heart, whose shapes change as they perform their normal functions can be studied as control volumes.
- (f) This book takes a *microscopic* approach to thermodynamics.

- 1.60** Answer the following true or false. Explain.

- (a) 1 N equals  $1 \text{ kg} \cdot \text{m/s}^2$  but 1 lbf does *not* equal  $1 \text{ lb} \cdot \text{ft/s}^2$ .
- (b) Specific volume, the volume per unit of mass, is an intensive property while volume and mass are extensive properties.
- (c) The kilogram for mass and the meter for length are examples of SI base units defined relative to fabricated objects.
- (d) If the value of *any* property of a system changes with time, that system cannot be at steady state.

- (e) The composition of a closed system cannot change.
- (f) According to Archimedes' principle, the magnitude of the buoyant force acting on a submerged body is equal to the weight of the body.

**1.61** Answer the following true or false. Explain.

- (a) A refrigerant at an absolute pressure of 0.8 atm is at a gage pressure of 0.2 atm.
- (b) Temperature is the property that is the same for each of two systems when they are in thermal equilibrium.

- (c) The Rankine degree is a smaller temperature unit than the Kelvin degree.
- (d) A vessel holding 0.5 kmol of oxygen ( $O_2$ ) contains 16 lb of  $O_2$ .
- (e) A control volume is a special type of closed system that does not interact in any way with its surroundings.
- (f) The pressure unit  $psia$  indicates an absolute pressure expressed in pounds force per square inch.

## ► DESIGN & OPEN ENDED PROBLEMS: EXPLORING ENGINEERING PRACTICE

**1.1D** In the United States today, nearly all of our electricity is produced by fossil-fuel power plants burning coal or natural gas, nuclear power plants, and hydroelectric power plants. Using the Internet, determine the percent contributions of these types of electricity generation to the U.S. total. For each of the four types, determine at least three significant environmental considerations associated with it and how such environmental aspects affect the respective plant design, operation, and cost. Write a report with at least three references.

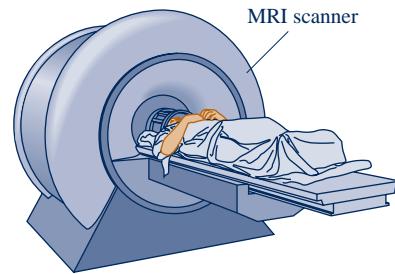
**1.2D** Mercury is recognized as a significant biohazard. This has led to the elimination of mercury-in-glass thermometers (see *Energy & Environment* in Sec. 1.7.1) and increasing regulation of coal-fired power plants, emissions from which are the major source of U.S. soil and water mercury contamination. Investigate medical complications of mercury exposure and their economic impact. Report your findings in a well-documented PowerPoint presentation.

**1.3D** *Ecological footprints* measure humankind's demands on nature. Using the Internet, estimate the amount of land and water needed annually to support your consumption of goods and services and to absorb your wastes. Prepare a memorandum reporting your estimates and listing at least three things you can do to reduce your footprint.

**1.4D** One type of prosthetic limb relies on suction to attach to an amputee's residual limb. The engineer must consider the required difference between atmospheric pressure and the pressure inside the socket of the prosthetic limb to develop suction sufficient to maintain attachment. What other considerations are important as engineers design this type of prosthetic device? Write a report of your findings including at least three references.

**1.5D** Design a low-cost, compact, light-weight, hand-held, human-powered air pump capable of directing a stream of air for cleaning computer keyboards, circuit boards, and hard-to-reach locations in electronic devices. The pump cannot use electricity, including batteries, nor employ any chemical propellants. All materials must be recyclable. Owing to existing patent protections, the pump must be a *distinct alternative* to the familiar tube and plunger bicycle pump and to existing products aimed at accomplishing the specified computer and electronic cleaning tasks.

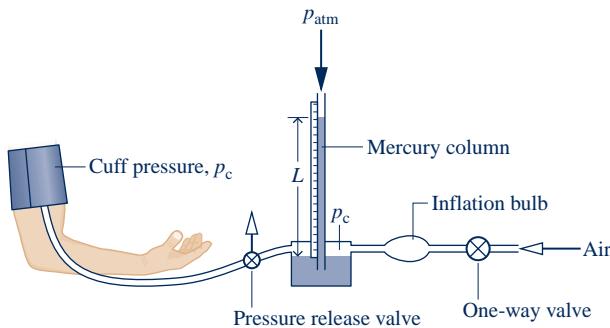
**1.6D** Magnetic resonance imaging (MRI) employs a strong magnetic field to produce detailed pictures of internal organs and tissues. As shown in Fig. P1.6D, the patient reclines on a table that slides into the cylindrical opening where the field is created. Considering a MRI scanner as a system, identify locations on the system boundary where the system interacts with its surroundings. Also describe significant occurrences within the system and the measures taken for patient comfort and safety. Write a report including at least three references.



**Fig. P1.6D**

**1.7D** A major barrier to wider deployment of solar power systems by homeowners and small businesses is the initial cost to purchase and install rooftop components. Today some U.S. municipalities and utilities are developing plans to assist property owners to acquire such components through loans and leasing arrangements. Investigate and critically evaluate these and other options for fostering deployment of solar power systems discovered through design-group *brainstorming* and use of the Internet. Report your findings in a poster presentation.

**1.8D** The *sphygmomanometer* commonly used to measure blood pressure is shown in Fig. P1.8D. During testing, the cuff is placed around the patient's arm and fully inflated by repeated squeezing of the inflation bulb. Then, as the cuff pressure is gradually reduced, arterial sounds known as *Korotkoff* sounds are monitored with a stethoscope. Using these sounds as cues, the *systolic* and *diastolic* pressures can be identified. These pressures are reported in terms of the mercury column length, in mmHg. Investigate the physical basis for the Korotkoff sounds, their role in identifying the systolic and diastolic pressures, and why these pressures are significant in medical practice. Write a report including at least three references.



**Fig. P1.8D**

**1.9D** Over the globe, unsafe levels of arsenic, which is a tasteless, odorless, and colorless poison, are present in underground wells providing drinking water to millions of people. The object of this project is to identify low-cost, easy-to-deploy, and easy-to-use treatment technologies for removing arsenic from drinking water. Technologies considered should include, but not be limited to, applications of *smart materials* and other nanotechnology approaches. Write a report critically evaluating existing and proposed technologies. List at least three references.

**1.10D** Conduct a term-length design project in the realm of bioengineering done on either an independent or a small-

group basis. The project might involve a device or technique for minimally invasive surgery, an implantable drug-delivery device, a biosensor, artificial blood, or something of special interest to you or your design group. Take several days to research your project idea and then prepare a brief written proposal, including several references, that provides a general statement of the core concept plus a list of objectives. During the project, observe good design practices such as discussed in Sec. 1.3 of *Thermal Design and Optimization*, John Wiley & Sons Inc., New York, 1996, by A. Bejan, G. Tsatsaronis, and M. J. Moran. Provide a well-documented final report, including several references.

**1.11D** Conduct a term-length design project involving the International Space Station pictured in Table 1.1 done on either an independent or a small-group basis. The project might involve an experiment that is best conducted in a low-gravity environment, a device for the comfort or use of the astronauts, or something of special interest to you or your design group. Take several days to research your project idea and then prepare a brief written proposal, including several references, that provides a general statement of the core concept plus a list of objectives. During the project, observe good design practices such as discussed in Sec. 1.3 of *Thermal Design and Optimization*, John Wiley & Sons Inc., New York, 1996, by A. Bejan, G. Tsatsaronis, and M. J. Moran. Provide a well-documented final report, including several references.



In Sec. 2.1, the relationship between *kinetic* and *gravitational potential energies* is considered.  
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**ENGINEERING CONTEXT** Energy is a fundamental concept of thermodynamics and one of the most significant aspects of engineering analysis. In this chapter we discuss energy and develop equations for applying the principle of conservation of energy. The current presentation is limited to closed systems. In Chap. 4 the discussion is extended to control volumes.

Energy is a familiar notion, and you already know a great deal about it. In the present chapter several important aspects of the energy concept are developed. Some of these you have encountered before. A basic idea is that energy can be *stored* within systems in various forms. Energy also can be *converted* from one form to another and *transferred* between systems. For closed systems, energy can be transferred by *work* and *heat transfer*. The total amount of energy is *conserved* in all conversions and transfers.

The **objective** of this chapter is to organize these ideas about energy into forms suitable for engineering analysis. The presentation begins with a review of energy concepts from mechanics. The thermodynamic concept of energy is then introduced as an extension of the concept of energy in mechanics.

# 2

# Energy and the First Law of Thermodynamics

## ► LEARNING OUTCOMES

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

- ▶ demonstrate understanding of key concepts related to energy and the first law of thermodynamics . . . including internal, kinetic, and potential energy, work and power, heat transfer and heat transfer modes, heat transfer rate, power cycle, refrigeration cycle, and heat pump cycle.
- ▶ apply closed system energy balances, appropriately modeling the case at hand, and correctly observing sign conventions for work and heat transfer.
- ▶ conduct energy analyses of systems undergoing thermodynamic cycles, evaluating as appropriate thermal efficiencies of power cycles and coefficients of performance of refrigeration and heat pump cycles.

## 2.1 Reviewing Mechanical Concepts of Energy

Building on the contributions of Galileo and others, Newton formulated a general description of the motions of objects under the influence of applied forces. Newton's laws of motion, which provide the basis for classical mechanics, led to the concepts of *work*, *kinetic energy*, and *potential energy*, and these led eventually to a broadened concept of energy. The present discussion begins with an application of Newton's second law of motion.

### 2.1.1 Work and Kinetic Energy

#### TAKE NOTE...

Boldface symbols denote vectors. Vector magnitudes are shown in lightface type.

The curved line in Fig. 2.1 represents the path of a body of mass  $m$  (a closed system) moving relative to the  $x$ - $y$  coordinate frame shown. The velocity of the center of mass of the body is denoted by  $\mathbf{V}$ . The body is acted on by a resultant force  $\mathbf{F}$ , which may vary in magnitude from location to location along the path. The resultant force is resolved into a component  $\mathbf{F}_s$  along the path and a component  $\mathbf{F}_n$  normal to the path. The effect of the component  $\mathbf{F}_s$  is to change the magnitude of the velocity, whereas the effect of the component  $\mathbf{F}_n$  is to change the direction of the velocity. As shown in Fig. 2.1,  $s$  is the instantaneous position of the body measured along the path from some fixed point denoted by 0. Since the magnitude of  $\mathbf{F}$  can vary from location to location along the path, the magnitudes of  $\mathbf{F}_s$  and  $\mathbf{F}_n$  are, in general, functions of  $s$ .

Let us consider the body as it moves from  $s = s_1$ , where the magnitude of its velocity is  $V_1$ , to  $s = s_2$ , where its velocity is  $V_2$ . Assume for the present discussion that the only interaction between the body and its surroundings involves the force  $\mathbf{F}$ . By Newton's second law of motion, the magnitude of the component  $\mathbf{F}_s$  is related to the change in the magnitude of  $\mathbf{V}$  by

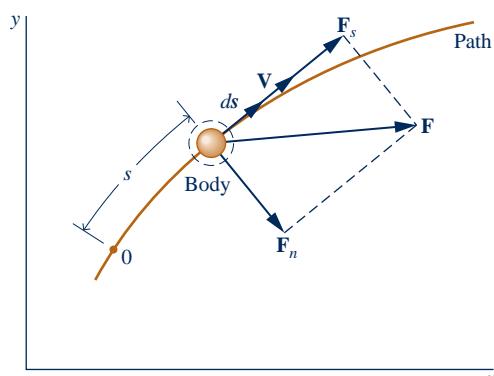
$$F_s = m \frac{d\mathbf{V}}{dt} \quad (2.1)$$

Using the chain rule, this can be written as

$$F_s = m \frac{d\mathbf{V}}{ds} \frac{ds}{dt} = m\mathbf{V} \frac{d\mathbf{V}}{ds} \quad (2.2)$$

where  $\mathbf{V} = ds/dt$ . Rearranging Eq. 2.2 and integrating from  $s_1$  to  $s_2$  gives

$$\int_{V_1}^{V_2} m\mathbf{V} d\mathbf{V} = \int_{s_1}^{s_2} F_s ds \quad (2.3)$$



**Fig. 2.1** Forces acting on a moving system.

The integral on the left of Eq. 2.3 is evaluated as follows

$$\int_{V_1}^{V_2} mV \, dV = \frac{1}{2} mV^2 \Big|_{V_1}^{V_2} = \frac{1}{2} m(V_2^2 - V_1^2) \quad (2.4)$$

The quantity  $\frac{1}{2}mV^2$  is the **kinetic energy**, KE, of the body. Kinetic energy is a scalar quantity. The *change* in kinetic energy,  $\Delta KE$ , of the body is

$$\Delta KE = KE_2 - KE_1 = \frac{1}{2}m(V_2^2 - V_1^2) \quad (2.5)$$

The integral on the right of Eq. 2.3 is the *work* of the force  $F_s$  as the body moves from  $s_1$  to  $s_2$  along the path. Work is also a scalar quantity.

With Eq. 2.4, Eq. 2.3 becomes

$$\frac{1}{2}m(V_2^2 - V_1^2) = \int_{s_1}^{s_2} \mathbf{F} \cdot d\mathbf{s} \quad (2.6)$$

where the expression for work has been written in terms of the scalar product (dot product) of the force vector  $\mathbf{F}$  and the displacement vector  $d\mathbf{s}$ . Equation 2.6 states that the work of the resultant force on the body equals the change in its kinetic energy. When the body is accelerated by the resultant force, the work done on the body can be considered a *transfer* of energy to the body, where it is *stored* as kinetic energy.

Kinetic energy can be assigned a value knowing only the mass of the body and the magnitude of its instantaneous velocity relative to a specified coordinate frame, without regard for how this velocity was attained. Hence, *kinetic energy is a property* of the body. Since kinetic energy is associated with the body as a whole, it is an *extensive* property.

### kinetic energy

#### TAKE NOTE...

The symbol  $\Delta$  always means “final value minus initial value.”



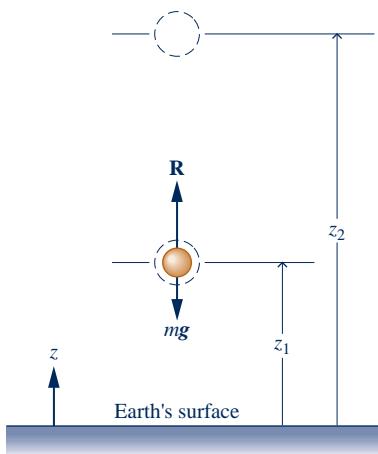
**ENERGY & ENVIRONMENT** Did you ever wonder what happens to the kinetic energy when you step on the brakes of your moving car? Automotive engineers have, and the result is the *hybrid vehicle* combining *regenerative* braking, batteries, an electric motor, and a conventional engine. When brakes are applied in a hybrid vehicle, some of the vehicle's kinetic energy is harvested and stored on board electrically for use when needed. Through regenerative braking and other innovative features, hybrids get much better mileage than comparably sized conventional vehicles.

Hybrid vehicle technology is quickly evolving. Today's hybrids use electricity to supplement conventional engine power, while future *plug-in* hybrids will use the power of a smaller engine to supplement electricity. The hybrids we now see on the road have enough battery power on board for acceleration to about 20 miles per hour and after that assist the engine when necessary. This improves fuel mileage, but the batteries are recharged by the engine—they are never *plugged in*.

Plug-in hybrids achieve even better fuel economy. Instead of relying on the engine to recharge batteries, most recharging will be received from an electrical outlet while the car is idle—overnight, for example. This will allow cars to get the energy they need mainly from the electrical grid, not the fuel pump. Widespread deployment of plug-ins awaits development of a new generation of batteries and ultra-capacitors (see Sec. 2.7).

Better fuel economy not only allows our society to be less reliant on oil to meet transportation needs but also reduces release of CO<sub>2</sub> into the atmosphere from vehicles. Each gallon of gasoline burned by a car's engine produces about 9 kg (20 lb) of CO<sub>2</sub>. A conventional vehicle produces several tons of CO<sub>2</sub> annually; fuel-thrifty hybrids produce much less. Still, since hybrids use electricity from the grid, we will have to make a greater effort to reduce power plant emissions by including more wind power, solar power, and other renewables in the national mix.

## 2.1.2 Potential Energy



**Fig. 2.2** Illustration used to introduce the potential energy concept.

Equation 2.6 is a principal result of the previous section. Derived from Newton's second law, the equation gives a relationship between two *defined* concepts: kinetic energy and work. In this section it is used as a point of departure to extend the concept of energy. To begin, refer to Fig. 2.2, which shows a body of mass  $m$  that moves vertically from an elevation  $z_1$  to an elevation  $z_2$  relative to the surface of the earth. Two forces are shown acting on the system: a downward force due to gravity with magnitude  $mg$  and a vertical force with magnitude  $R$  representing the resultant of all *other* forces acting on the system.

The work of each force acting on the body shown in Fig. 2.2 can be determined by using the definition previously given. The total work is the algebraic sum of these individual values. In accordance with Eq. 2.6, the total work equals the change in kinetic energy. That is

$$\frac{1}{2}m(V_2^2 - V_1^2) = \int_{z_1}^{z_2} R dz - \int_{z_1}^{z_2} mg dz \quad (2.7)$$

A minus sign is introduced before the second term on the right because the gravitational force is directed downward and  $z$  is taken as positive upward.

The first integral on the right of Eq. 2.7 represents the work done by the force  $\mathbf{R}$  on the body as it moves vertically from  $z_1$  to  $z_2$ . The second integral can be evaluated as follows:

$$\int_{z_1}^{z_2} mg dz = mg(z_2 - z_1) \quad (2.8)$$

where the acceleration of gravity has been assumed to be constant with elevation. By incorporating Eq. 2.8 into Eq. 2.7 and rearranging

$$\frac{1}{2}m(V_2^2 - V_1^2) + mg(z_2 - z_1) = \int_{z_1}^{z_2} R dz \quad (2.9)$$

### gravitational potential energy

The quantity  $mgz$  is the **gravitational potential energy**, PE. The *change* in gravitational potential energy,  $\Delta PE$ , is

$$\Delta PE = PE_2 - PE_1 = mg(z_2 - z_1) \quad (2.10)$$

Potential energy is associated with the force of gravity and is therefore an attribute of a system consisting of the body and the earth together. However, evaluating the force of gravity as  $mg$  enables the gravitational potential energy to be determined for a specified value of  $g$  knowing only the mass of the body and its elevation. With this view, potential energy is regarded as an *extensive property* of the body. Throughout this book it is assumed that elevation differences are small enough that the gravitational force can be considered constant. The concept of gravitational potential energy can be formulated to account for the variation of the gravitational force with elevation, however.

To assign a value to the kinetic energy or the potential energy of a system, it is necessary to assume a datum and specify a value for the quantity at the datum. Values of kinetic and potential energy are then determined relative to this arbitrary choice of datum and reference value. However, since only *changes* in kinetic and potential energy between two states are required, these arbitrary reference specifications cancel.

### 2.1.3 Units for Energy

Work has units of force times distance. The units of kinetic energy and potential energy are the same as for work. In SI, the energy unit is the newton-meter, N · m, called the joule, J. In this book it is convenient to use the kilojoule, kJ. Commonly used English units for work, kinetic energy, and potential energy are the foot-pound force, ft · lbf, and the British thermal unit, Btu.

When a system undergoes a process where there are changes in kinetic and potential energy, special care is required to obtain a consistent set of units.

► **FOR EXAMPLE** to illustrate the proper use of units in the calculation of such terms, consider a system having a mass of 1 kg whose velocity increases from 15 m/s to 30 m/s while its elevation decreases by 10 m at a location where  $g = 9.7 \text{ m/s}^2$ . Then

$$\begin{aligned}\Delta KE &= \frac{1}{2}m(V_2^2 - V_1^2) \\ &= \frac{1}{2}(1 \text{ kg})\left[\left(30 \frac{\text{m}}{\text{s}}\right)^2 - \left(15 \frac{\text{m}}{\text{s}}\right)^2\right] \left|\frac{1 \text{ N}}{1 \text{ kg} \cdot \text{m/s}^2}\right| \left|\frac{1 \text{ kJ}}{10^3 \text{ N} \cdot \text{m}}\right| \\ &= 0.34 \text{ kJ}\end{aligned}$$

$$\begin{aligned}\Delta PE &= mg(z_2 - z_1) \\ &= (1 \text{ kg})\left(9.7 \frac{\text{m}}{\text{s}^2}\right)(-10 \text{ m}) \left|\frac{1 \text{ N}}{1 \text{ kg} \cdot \text{m/s}^2}\right| \left|\frac{1 \text{ kJ}}{10^3 \text{ N} \cdot \text{m}}\right| \\ &= -0.10 \text{ kJ}\end{aligned}$$

For a system having a mass of 1 lb whose velocity increases from 50 ft/s to 100 ft/s while its elevation decreases by 40 ft at a location where  $g = 32.0 \text{ ft/s}^2$ , we have

$$\begin{aligned}\Delta KE &= \frac{1}{2}(1 \text{ lb})\left[\left(100 \frac{\text{ft}}{\text{s}}\right)^2 - \left(50 \frac{\text{ft}}{\text{s}}\right)^2\right] \left|\frac{1 \text{ lbf}}{32.2 \text{ lb} \cdot \text{ft/s}^2}\right| \left|\frac{1 \text{ Btu}}{778 \text{ ft} \cdot \text{lbf}}\right| \\ &= 0.15 \text{ Btu} \\ \Delta PE &= (1 \text{ lb})\left(32.0 \frac{\text{ft}}{\text{s}^2}\right)(-40 \text{ ft}) \left|\frac{1 \text{ lbf}}{32.2 \text{ lb} \cdot \text{ft/s}^2}\right| \left|\frac{1 \text{ Btu}}{778 \text{ ft} \cdot \text{lbf}}\right| \\ &= -0.05 \text{ Btu} \quad \blacktriangleleft \blacktriangleleft \blacktriangleleft \blacktriangleleft \blacktriangleleft\end{aligned}$$

### 2.1.4 Conservation of Energy in Mechanics

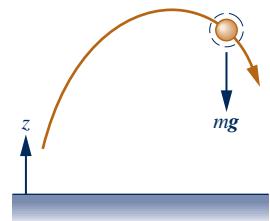
Equation 2.9 states that the total work of all forces acting on the body from the surroundings, with the exception of the gravitational force, equals the sum of the changes in the kinetic and potential energies of the body. When the resultant force causes the elevation to be increased, the body to be accelerated, or both, the work done by the force can be considered a *transfer* of energy to the body, where it is stored as gravitational potential energy and/or kinetic energy. The notion that *energy is conserved* underlies this interpretation.

The interpretation of Eq. 2.9 as an expression of the conservation of energy principle can be reinforced by considering the special case of a body on which the only force acting is that due to gravity, for then the right side of the equation vanishes and the equation reduces to

$$\frac{1}{2}m(V_2^2 - V_1^2) + mg(z_2 - z_1) = 0 \quad (2.11)$$

or

$$\frac{1}{2}mV_2^2 + mgz_2 = \frac{1}{2}mV_1^2 + mgz_1$$



Under these conditions, the *sum* of the kinetic and gravitational potential energies *remains constant*. Equation 2.11 also illustrates that energy can be *converted* from one form to another: For an object falling under the influence of gravity *only*, the potential energy would decrease as the kinetic energy increases by an equal amount.

### 2.1.5 • Closing Comment

The presentation thus far has centered on systems for which applied forces affect only their overall velocity and position. However, systems of engineering interest normally interact with their surroundings in more complicated ways, with changes in other properties as well. To analyze such systems, the concepts of kinetic and potential energy alone do not suffice, nor does the rudimentary conservation of energy principle introduced in this section. In thermodynamics the concept of energy is broadened to account for other observed changes, and the principle of *conservation of energy* is extended to include a wide variety of ways in which systems interact with their surroundings. The basis for such generalizations is experimental evidence. These extensions of the concept of energy are developed in the remainder of the chapter, beginning in the next section with a fuller discussion of work.

## 2.2 Broadening Our Understanding of Work

The work  $W$  done by, or on, a system evaluated in terms of macroscopically observable forces and displacements is

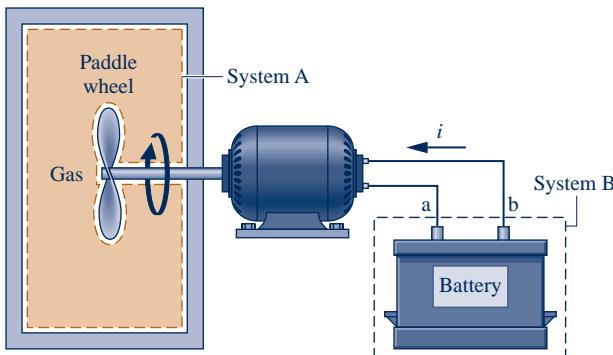
$$W = \int_{s_1}^{s_2} \mathbf{F} \cdot d\mathbf{s} \quad (2.12)$$

This relationship is important in thermodynamics, and is used later in the present section to evaluate the work done in the compression or expansion of gas (or liquid), the extension of a solid bar, and the stretching of a liquid film. However, thermodynamics also deals with phenomena not included within the scope of mechanics, so it is necessary to adopt a broader interpretation of work, as follows.

**thermodynamic definition of work**

A particular interaction is categorized as a work interaction if it satisfies the following criterion, which can be considered the **thermodynamic definition of work**: *Work is done by a system on its surroundings if the sole effect on everything external to the system could have been the raising of a weight*. Notice that the raising of a weight is, in effect, a force acting through a distance, so the concept of work in thermodynamics is a natural extension of the concept of work in mechanics. However, the test of whether a work interaction has taken place is not that the elevation of a weight has actually taken place, or that a force has actually acted through a distance, but that the sole effect *could have been* an increase in the elevation of a weight.

► **FOR EXAMPLE** consider Fig. 2.3 showing two systems labeled A and B. In system A, a gas is stirred by a paddle wheel: the paddle wheel does work on the gas. In principle, the work could be evaluated in terms of the forces and motions at the boundary between the paddle wheel and the gas. Such an evaluation of work is consistent with Eq. 2.12, where work is the product of force and displacement. By contrast, consider system B, which includes only the battery. At the boundary of system B, forces and motions are not evident. Rather, there is an electric current  $i$  driven by an electrical potential difference existing across the terminals a and b. That this type of interaction at the boundary can be classified as work follows from the thermodynamic

**Fig. 2.3** Two examples of work.

definition of work given previously: We can imagine the current is supplied to a *hypothetical* electric motor that lifts a weight in the surroundings. ◀◀◀◀◀

Work is a means for transferring energy. Accordingly, the term work does not refer to what is being transferred between systems or to what is stored within systems. Energy is transferred and stored when work is done.

### 2.2.1 • Sign Convention and Notation

Engineering thermodynamics is frequently concerned with devices such as internal combustion engines and turbines whose purpose is to do work. Hence, in contrast to the approach generally taken in mechanics, it is often convenient to consider such work as positive. That is,

$W > 0$ : work done *by* the system

$W < 0$ : work done *on* the system

This **sign convention** is used throughout the book. In certain instances, however, it is convenient to regard the work done *on* the system to be positive, as has been done in the discussion of Sec. 2.1. To reduce the possibility of misunderstanding in any such case, the direction of energy transfer is shown by an arrow on a sketch of the system, and work is regarded as positive in the direction of the arrow.

**sign convention for work**

To evaluate the integral in Eq. 2.12, it is necessary to know how the force varies with the displacement. This brings out an important idea about work: The value of  $W$  depends on the details of the interactions taking place between the system and surroundings during a process and not just the initial and final states of the system. It follows that **work is not a property** of the system or the surroundings. In addition, the limits on the integral of Eq. 2.12 mean “from state 1 to state 2” and cannot be interpreted as the *values* of work at these states. The notion of work at a state *has no meaning*, so the value of this integral should never be indicated as  $W_2 - W_1$ .

**work is not a property**



#### Nanoscale Machines on the Move.....

Engineers working in the field of nanotechnology, the engineering of molecular-sized devices, look forward to the time when practical nanoscale machines can be fabricated that are capable of movement, sensing and responding to stimuli such as light and sound, delivering medication within the body, performing computations, and numerous other functions that promote human well being. For inspiration, engineers study biological nanoscale *machines* in living things that perform functions

such as creating and repairing cells, circulating oxygen, and digesting food. These studies have yielded positive results. Molecules mimicking the function of mechanical devices have been fabricated, including gears, rotors, ratchets, brakes, switches, and abacus-like structures. A particular success is the development of molecular motors that convert light to rotary or linear motion. Although devices produced thus far are rudimentary, they do demonstrate the feasibility of constructing nanomachines, researchers say.

The differential of work,  $\delta W$ , is said to be *inexact* because, in general, the following integral cannot be evaluated without specifying the details of the process

$$\int_1^2 \delta W = W$$

On the other hand, the differential of a property is said to be *exact* because the change in a property between two particular states depends in no way on the details of the process linking the two states. For example, the change in volume between two states can be determined by integrating the differential  $dV$ , without regard for the details of the process, as follows

$$\int_{V_1}^{V_2} dV = V_2 - V_1$$

where  $V_1$  is the volume *at* state 1 and  $V_2$  is the volume *at* state 2. The differential of every property is exact. Exact differentials are written, as above, using the symbol  $d$ . To stress the difference between exact and inexact differentials, the differential of work is written as  $\delta W$ . The symbol  $\delta$  is also used to identify other inexact differentials encountered later.

## 2.2.2 Power

### power

Many thermodynamic analyses are concerned with the time rate at which energy transfer occurs. The rate of energy transfer by work is called **power** and is denoted by  $\dot{W}$ . When a work interaction involves a macroscopically observable force, the rate of energy transfer by work is equal to the product of the force and the velocity at the point of application of the force

$$\dot{W} = \mathbf{F} \cdot \mathbf{V} \quad (2.13)$$

A dot appearing over a symbol, as in  $\dot{W}$ , is used throughout this book to indicate a time rate. In principle, Eq. 2.13 can be integrated from time  $t_1$  to time  $t_s$  to get the total work done during the time interval

$$W = \int_{t_1}^{t_2} \dot{W} dt = \int_{t_1}^{t_2} \mathbf{F} \cdot \mathbf{V} dt \quad (2.14)$$

### units for power

The same sign convention applies for  $\dot{W}$  as for  $W$ . Since power is a time rate of doing work, it can be expressed in terms of any units for energy and time. In SI, the **unit for power** is J/s, called the watt. In this book the kilowatt, kW, is generally used. Commonly used English units for power are ft · lbf/s, Btu/h, and horsepower, hp.

**► FOR EXAMPLE** to illustrate the use of Eq. 2.13, let us evaluate the power required for a bicyclist traveling at 20 miles per hour to overcome the drag force imposed by the surrounding air. This *aerodynamic drag* force is given by

$$F_d = \frac{1}{2} C_d A \rho V^2$$

where  $C_d$  is a constant called the *drag coefficient*,  $A$  is the frontal area of the bicycle and rider, and  $\rho$  is the air density. By Eq. 2.13 the required power is  $\mathbf{F}_d \cdot \mathbf{V}$  or

$$\begin{aligned} \dot{W} &= (\frac{1}{2} C_d A \rho V^2) V \\ &= \frac{1}{2} C_d A \rho V^3 \end{aligned}$$



Using typical values:  $C_d = 0.88$ ,  $A = 3.9 \text{ ft}^2$ , and  $\rho = 0.075 \text{ lb}/\text{ft}^3$ , together with  $V = 20 \text{ mi/h} = 29.33 \text{ ft/s}$ , and also converting units to horsepower, the power required is

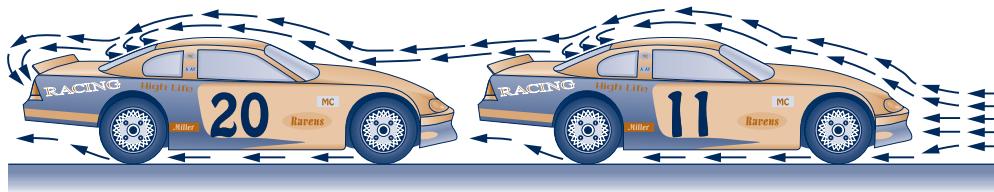
$$\dot{W} = \frac{1}{2}(0.88)(3.9 \text{ ft}^2) \left( 0.075 \frac{\text{lb}}{\text{ft}^3} \right) \left( 29.33 \frac{\text{ft}}{\text{s}} \right)^3 \left| \frac{1 \text{ lbf}}{32.2 \text{ lb} \cdot \text{ft/s}^2} \right| \left| \frac{1 \text{ hp}}{550 \text{ ft} \cdot \text{lbf/s}} \right| \\ = 0.183 \text{ hp} \quad \blacktriangleleft \quad \blacktriangleleft \quad \blacktriangleleft \quad \blacktriangleleft \quad \blacktriangleleft$$

Drag can be reduced by *streamlining* the shape of a moving object and using the strategy known as *drafting* (see box).

### Drafting

*Drafting* occurs when two or more moving vehicles or individuals align closely to reduce the overall effect of drag. Drafting is seen in competitive events such as auto racing, bicycle racing, speed-skating, and running.

Studies show that air flow over a single vehicle or individual in motion is characterized by a high-pressure region in front and a low-pressure region behind. The difference between these pressures creates a force, called drag, impeding motion. During drafting, as seen in the sketch below, a second vehicle or individual is closely aligned with another, and air flows over the pair nearly as if they were a single entity, thereby altering the pressure between them and reducing the drag each experiences. While race-car drivers use drafting to increase speed, non-motor sport competitors usually aim to reduce demands on their bodies while maintaining the same speed.



### 2.2.3 Modeling Expansion or Compression Work

There are many ways in which work can be done by or on a system. The remainder of this section is devoted to considering several examples, beginning with the important case of the work done when the volume of a quantity of a gas (or liquid) changes by expansion or compression.

Let us evaluate the work done by the closed system shown in Fig. 2.4 consisting of a gas (or liquid) contained in a piston–cylinder assembly as the gas expands. During the process the gas pressure exerts a normal force on the piston. Let  $p$  denote the pressure acting at the interface between the gas and the piston. The force exerted

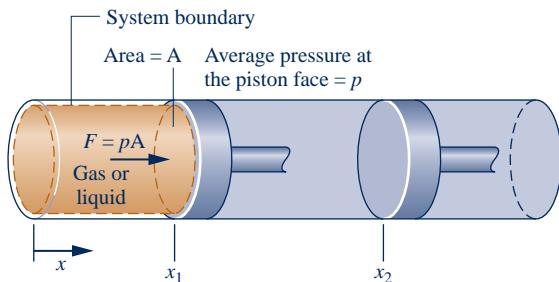


Fig. 2.4 Expansion or compression of a gas or liquid.

by the gas on the piston is simply the product  $pA$ , where  $A$  is the area of the piston face. The work done by the system as the piston is displaced a distance  $dx$  is

$$\delta W = pA dx \quad (2.15)$$

The product  $A dx$  in Eq. 2.15 equals the change in volume of the system,  $dV$ . Thus, the work expression can be written as

$$\delta W = p dV \quad (2.16)$$

Since  $dV$  is positive when volume increases, the work at the moving boundary is positive when the gas expands. For a compression,  $dV$  is negative, and so is work found from Eq. 2.16. These signs are in agreement with the previously stated sign convention for work.

For a change in volume from  $V_1$  to  $V_2$ , the work is obtained by integrating Eq. 2.16

$$W = \int_{V_1}^{V_2} p dV \quad (2.17)$$

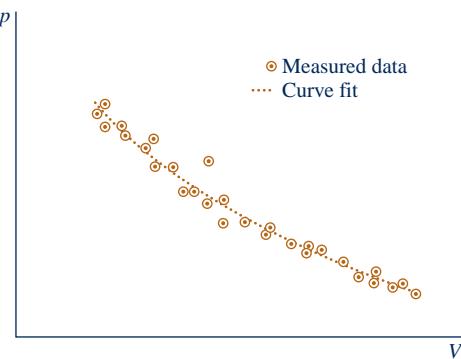
Although Eq. 2.17 is derived for the case of a gas (or liquid) in a piston–cylinder assembly, it is applicable to systems of *any* shape provided the pressure is uniform with position over the moving boundary.

## 2.2.4 Expansion or Compression Work in Actual Processes

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.

Typically, at a nonequilibrium state intensive properties vary with position at a given time. Also, at a specified position intensive properties may vary with time, sometimes chaotically. In certain cases, spatial and temporal variations in properties such as temperature, pressure, and velocity can be measured, or obtained by solving appropriate governing equations, which are generally differential equations.

To perform the integral of Eq. 2.17 requires a relationship between the gas pressure *at the moving boundary* and the system volume. However, due to nonequilibrium effects during an *actual* expansion or compression process, this relationship may be difficult, or even impossible, to obtain. In the cylinder of an automobile engine, for example, combustion and other nonequilibrium effects give rise to nonuniformities throughout the cylinder. Accordingly, if a pressure transducer were mounted on the cylinder head, the recorded output might provide only an approximation for the pressure at the piston face required by Eq. 2.17. Moreover, even when the measured pressure is essentially equal to that at the piston face, scatter might exist in the pressure–volume data, as illustrated in Fig. 2.5. Still, performing the integral of Eq. 2.17 based on a curve fitted to the data could give a *plausible estimate* of the work. We will see later that in some cases where lack of the required pressure–volume relationship keeps us from evaluating the work from Eq. 2.17, the work can be determined alternatively from an *energy balance* (Sec. 2.5).



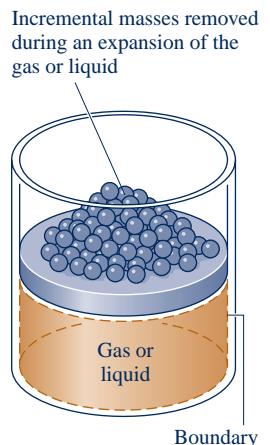
**Fig. 2.5** Pressure at the piston face versus cylinder volume.

## 2.2.5 Expansion or Compression Work in Quasiequilibrium Processes

Processes are sometime modeled as an idealized type of process called a **quasiequilibrium (or quasistatic) process**. A quasiequilibrium process is one in which the departure

from thermodynamic equilibrium is at most infinitesimal. All states through which the system passes in a quasiequilibrium process may be considered equilibrium states. Because nonequilibrium effects are inevitably present during actual processes, systems of engineering interest can at best approach, but never realize, a quasiequilibrium process. Still the quasiequilibrium process plays a role in our study of engineering thermodynamics. For details, see the box.

To consider how a gas (or liquid) might be expanded or compressed in a quasiequilibrium fashion, refer to Fig. 2.6, which shows a system consisting of a gas initially at an equilibrium state. As shown in the figure, the gas pressure is maintained uniform throughout by a number of small masses resting on the freely moving piston. Imagine that one of the masses is removed, allowing the piston to move upward as the gas expands slightly. During such an expansion the state of the gas would depart only slightly from equilibrium. The system would eventually come to a new equilibrium state, where the pressure and all other intensive properties would again be uniform in value. Moreover, were the mass replaced, the gas would be restored to its initial state, while again the departure from equilibrium would be slight. If several of the masses were removed one after another, the gas would pass through a sequence of equilibrium states without ever being far from equilibrium. In the limit as the increments of mass are made vanishingly small, the gas would undergo a quasiequilibrium expansion process. A quasiequilibrium compression can be visualized with similar considerations.



**Fig. 2.6** Illustration of a quasiequilibrium expansion or compression.

### Using the Quasiequilibrium Process Concept

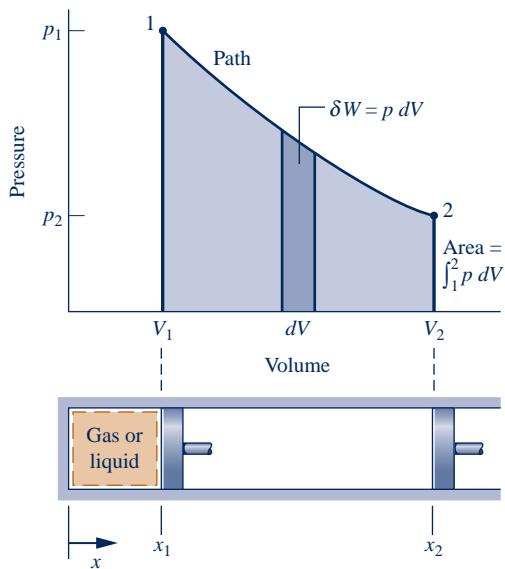
Our interest in the quasiequilibrium process concept stems mainly from two considerations:

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

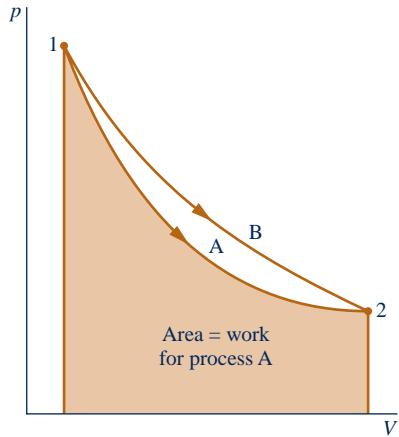
Equation 2.17 can be applied to evaluate the work in quasiequilibrium expansion or compression processes. For such idealized processes the pressure  $p$  in the equation is the pressure of the entire quantity of gas (or liquid) undergoing the process, and not just the pressure at the moving boundary. The relationship between the pressure and volume may be graphical or analytical. Let us first consider a graphical relationship.

A graphical relationship is shown in the pressure–volume diagram ( $p$ – $V$  diagram) of Fig. 2.7. Initially, the piston face is at position  $x_1$ , and the gas pressure is  $p_1$ ; at the conclusion of a quasiequilibrium expansion process the piston face is at position  $x_2$ , and the pressure is reduced to  $p_2$ . At each intervening piston position, the uniform pressure throughout the gas is shown as a point on the diagram. The curve, or *path*, connecting states 1 and 2 on the diagram represents the equilibrium states through which the system has passed during the process. The work done by the gas on the piston during the expansion is given by  $\int p dV$ , which can be interpreted as the area under the curve of pressure versus volume. Thus, the shaded area on Fig. 2.7 is equal to the work for the process. Had the gas been *compressed* from 2 to 1 along the same path on the  $p$ – $V$  diagram, the *magnitude* of the work would be the same, but the sign would be negative, indicating that for the compression the energy transfer was from the piston to the gas.

The area interpretation of work in a quasiequilibrium expansion or compression process allows a simple demonstration of the idea that work depends on the process.



**Fig. 2.7 Work of a quasiequilibrium expansion or compression process.**



**Fig. 2.8 Illustration that work depends on the process.**

**A**  
Comp\_Work  
A.4 – All Tabs

Exp\_Work  
A.5 – All Tabs

**polytropic process**

This can be brought out by referring to Fig. 2.8. Suppose the gas in a piston–cylinder assembly goes from an initial equilibrium state 1 to a final equilibrium state 2 along two different paths, labeled A and B on Fig. 2.8. Since the area beneath each path represents the work for that process, the work depends on the details of the process as defined by the particular curve and not just on the end states. Using the test for a property given in Sec. 1.3.3, we can conclude again (Sec. 2.2.1) that *work is not a property*. The value of work depends on the nature of the process between the end states.

The relation between pressure and volume, or pressure and specific volume, also can be described analytically. A quasiequilibrium process described by  $pV^n = \text{constant}$ , or  $pv^n = \text{constant}$ , where  $n$  is a constant, is called a **polytropic process**. Additional analytical forms for the pressure–volume relationship also may be considered.

The example to follow illustrates the application of Eq. 2.17 when the relationship between pressure and volume during an expansion process is described analytically as  $pV^n = \text{constant}$ .

## EXAMPLE 2.1 ►

### Evaluating Expansion Work

A gas in a piston–cylinder assembly undergoes an expansion process for which the relationship between pressure and volume is given by

$$pV^n = \text{constant}$$

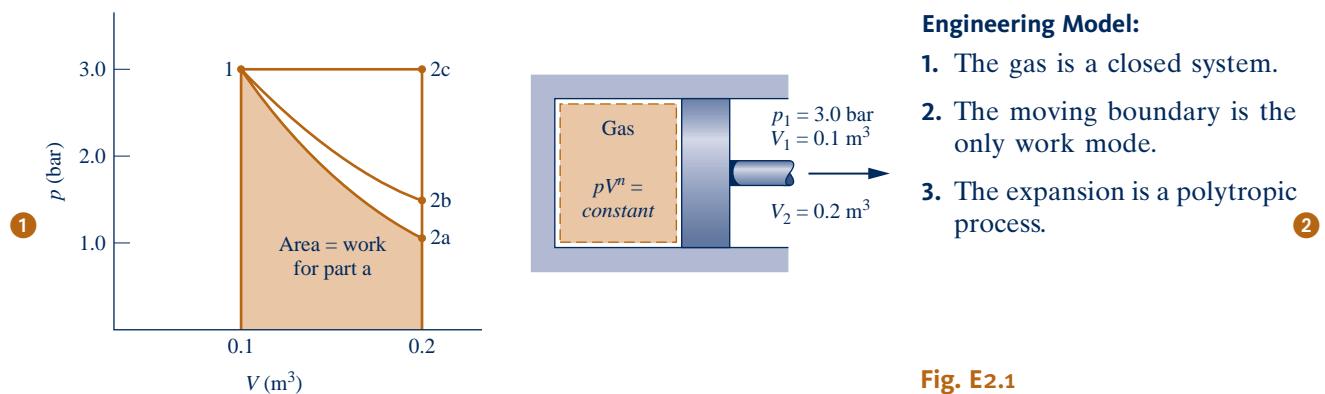
The initial pressure is 3 bar, the initial volume is  $0.1 \text{ m}^3$ , and the final volume is  $0.2 \text{ m}^3$ . Determine the work for the process, in kJ, if (a)  $n = 1.5$ , (b)  $n = 1.0$ , and (c)  $n = 0$ .

#### SOLUTION

**Known:** A gas in a piston–cylinder assembly undergoes an expansion for which  $pV^n = \text{constant}$ .

**Find:** Evaluate the work if (a)  $n = 1.5$ , (b)  $n = 1.0$ , (c)  $n = 0$ .

**Schematic and Given Data:** The given  $p$ - $V$  relationship and the given data for pressure and volume can be used to construct the accompanying pressure–volume diagram of the process.



### Engineering Model:

1. The gas is a closed system.
2. The moving boundary is the only work mode.
3. The expansion is a polytropic process.

Fig. E2.1

**Analysis:** The required values for the work are obtained by integration of Eq. 2.17 using the given pressure–volume relation.

(a) Introducing the relationship  $p = \text{constant}/V^n$  into Eq. 2.17 and performing the integration

$$\begin{aligned} W &= \int_{V_1}^{V_2} p \, dV = \int_{V_1}^{V_2} \frac{\text{constant}}{V^n} \, dV \\ &= \frac{(\text{constant})V_2^{1-n} - (\text{constant})V_1^{1-n}}{1-n} \end{aligned}$$

The constant in this expression can be evaluated at either end state:  $\text{constant} = p_1 V_1^n = p_2 V_2^n$ . The work expression then becomes

$$W = \frac{(p_2 V_2^n) V_2^{1-n} - (p_1 V_1^n) V_1^{1-n}}{1-n} = \frac{p_2 V_2 - p_1 V_1}{1-n} \quad (\text{a})$$

This expression is valid for all values of  $n$  except  $n = 1.0$ . The case  $n = 1.0$  is taken up in part (b).

To evaluate  $W$ , the pressure at state 2 is required. This can be found by using  $p_1 V_1^n = p_2 V_2^n$ , which on rearrangement yields

$$p_2 = p_1 \left( \frac{V_1}{V_2} \right)^n = (3 \text{ bar}) \left( \frac{0.1}{0.2} \right)^{1.5} = 1.06 \text{ bar}$$

Accordingly,

$$\begin{aligned} W &= \left( \frac{(1.06 \text{ bar})(0.2 \text{ m}^3) - (3)(0.1)}{1 - 1.5} \right) \left| \frac{10^5 \text{ N/m}^2}{1 \text{ bar}} \right| \left| \frac{1 \text{ kJ}}{10^3 \text{ N} \cdot \text{m}} \right| \\ &= +17.6 \text{ kJ} \end{aligned}$$

(b) For  $n = 1.0$ , the pressure–volume relationship is  $pV = \text{constant}$  or  $p = \text{constant}/V$ . The work is

$$W = \text{constant} \int_{V_1}^{V_2} \frac{dV}{V} = (\text{constant}) \ln \frac{V_2}{V_1} = (p_1 V_1) \ln \frac{V_2}{V_1} \quad (\text{b})$$

Substituting values

$$W = (3 \text{ bar})(0.1 \text{ m}^3) \left| \frac{10^5 \text{ N/m}^2}{1 \text{ bar}} \right| \left| \frac{1 \text{ kJ}}{10^3 \text{ N} \cdot \text{m}} \right| \ln \left( \frac{0.2}{0.1} \right) = +20.79 \text{ kJ}$$

(c) For  $n = 0$ , the pressure–volume relation reduces to  $p = \text{constant}$ , and the integral becomes  $W = p(V_2 - V_1)$ , which is a special case of the expression found in part (a). Substituting values and converting units as above,  $W = +30 \text{ kJ}$ .

4

- 1 In each case, the work for the process can be interpreted as the area under the curve representing the process on the accompanying  $p$ - $V$  diagram. Note that the relative areas are in agreement with the numerical results.
- 2 The assumption of a polytropic process is significant. If the given pressure–volume relationship were obtained as a fit to experimental pressure–volume data, the value of  $\int p \, dV$  would provide a plausible estimate of the work only when the measured pressure is essentially equal to that exerted at the piston face.
- 3 Observe the use of unit conversion factors here and in part (b).
- 4 In each of the cases considered, it is not necessary to identify the gas (or liquid) contained within the piston–cylinder assembly. The calculated values for  $W$  are determined by the process path and the end states. However, if it is desired to evaluate a property such as temperature, both the nature and amount of the substance must be provided because appropriate relations among the properties of the particular substance would then be required.



### Skills Developed

*Ability to...*

- apply the problem-solving methodology.
- define a closed system and identify interactions on its boundary.
- evaluate work using Eq. 2.17.
- apply the pressure–volume relation  $pV^n = \text{constant}$ .

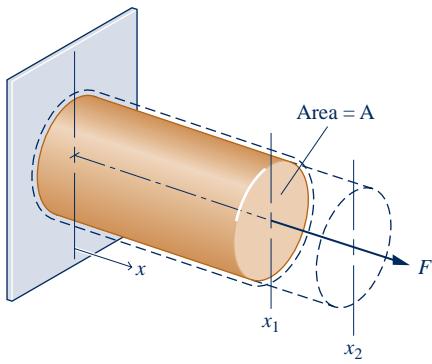
### QuickQUIZ

Evaluate the work, in kJ, for a two-step process consisting of an expansion with  $n = 1.0$  from  $p_1 = 3$  bar,  $V_1 = 0.1 \text{ m}^3$  to  $V = 0.15 \text{ m}^3$ , followed by an expansion with  $n = 0$  from  $V = 0.15 \text{ m}^3$  to  $V_2 = 0.2 \text{ m}^3$ .

**Ans.** 22.16 kJ.

## 2.2.6 • Further Examples of Work

To broaden our understanding of the work concept, we now briefly consider several other examples of work.



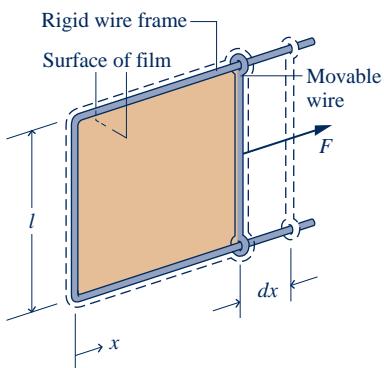
**Fig. 2.9** Elongation of a solid bar.

### Extension of a Solid Bar

Consider a system consisting of a solid bar under tension, as shown in Fig. 2.9. The bar is fixed at  $x = 0$ , and a force  $F$  is applied at the other end. Let the force be represented as  $F = \sigma A$ , where  $A$  is the cross-sectional area of the bar and  $\sigma$  the *normal stress acting at the end* of the bar. The work done as the end of the bar moves a distance  $dx$  is given by  $\delta W = -\sigma A \, dx$ . The minus sign is required because work is done *on* the bar when  $dx$  is positive. The work for a change in length from  $x_1$  to  $x_2$  is found by integration

$$W = - \int_{x_1}^{x_2} \sigma A \, dx \quad (2.18)$$

Equation 2.18 for a solid is the counterpart of Eq. 2.17 for a gas undergoing an expansion or compression.



**Fig. 2.10** Stretching of a liquid film.

### Stretching of a Liquid Film

Figure 2.10 shows a system consisting of a liquid film suspended on a wire frame. The two surfaces of the film support the thin liquid layer inside by the effect of *surface tension*, owing to microscopic forces between molecules near the liquid–air interfaces. These forces give rise to a macroscopically measurable force perpendicular to any line in the surface. The force per unit length across such a line is the surface tension. Denoting the surface tension *acting at the movable wire* by  $\tau$ , the force  $F$  indicated on the figure can be expressed as  $F = 2l\tau$ , where the factor 2 is introduced because two film surfaces act at the wire. If the movable wire is displaced by  $dx$ , the work is given by  $\delta W = -2l\tau \, dx$ . The minus sign is required because work is done *on* the system when  $dx$  is positive. Corresponding to a displacement  $dx$  is a change in the total area of the surfaces in contact with

the wire of  $dA = 2l dx$ , so the expression for work can be written alternatively as  $\delta W = -\tau dA$ . The work for an increase in surface area from  $A_1$  to  $A_2$  is found by integrating this expression

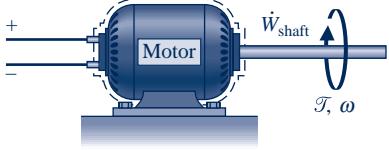
$$W = - \int_{A_1}^{A_2} \tau dA \quad (2.19)$$

### Power Transmitted by a Shaft

A rotating shaft is a commonly encountered machine element. Consider a shaft rotating with angular velocity  $\omega$  and exerting a torque  $\mathcal{T}$  on its surroundings. Let the torque be expressed in terms of a tangential force  $F_t$  and radius  $R$ :  $\mathcal{T} = F_t R$ . The velocity at the point of application of the force is  $V = R\omega$ , where  $\omega$  is in radians per unit time. Using these relations with Eq. 2.13, we obtain an expression for the power transmitted from the shaft to the surroundings

$$\dot{W} = F_t V = (\mathcal{T}/R)(R\omega) = \mathcal{T}\omega \quad (2.20)$$

A related case involving a gas stirred by a paddle wheel is considered in the discussion of Fig. 2.3.



### Electric Power

Shown in Fig. 2.11 is a system consisting of an electrolytic cell. The cell is connected to an external circuit through which an electric current,  $i$ , is flowing. The current is driven by the electrical potential difference  $\mathcal{E}$  existing across the terminals labeled a and b. That this type of interaction can be classed as work is considered in the discussion of Fig. 2.3.

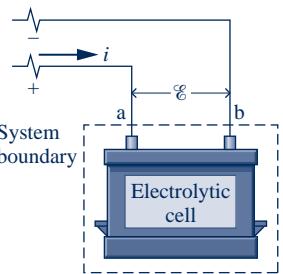
The rate of energy transfer by work, or the power, is

$$\dot{W} = -\mathcal{E}i \quad (2.21)$$

Since the current  $i$  equals  $dZ/dt$ , the work can be expressed in differential form as

$$\delta W = -\mathcal{E}dZ \quad (2.22)$$

where  $dZ$  is the amount of electrical charge that flows into the system. The minus signs appearing in Eqs. 2.21 and 2.22 are required to be in accord with our previously stated sign convention for work.



**Fig. 2.11** Electrolytic cell used to discuss electric power.

### Work Due to Polarization or Magnetization

Let us next refer briefly to the types of work that can be done on systems residing in electric or magnetic fields, known as the work of polarization and magnetization, respectively. From the microscopic viewpoint, electrical dipoles within dielectrics resist turning, so work is done when they are aligned by an electric field. Similarly, magnetic dipoles resist turning, so work is done on certain other materials when their magnetization is changed. Polarization and magnetization give rise to *macroscopically* detectable changes in the total dipole moment as the particles making up the material are given new alignments. In these cases the work is associated with forces imposed on the overall system by fields in the surroundings. Forces acting on the material in the system interior are called *body forces*. For such forces the appropriate displacement in evaluating work is the displacement of the matter on which the body force acts.

#### TAKE NOTE...

When power is evaluated in terms of the watt, and the unit of current is the ampere (an SI base unit), the unit of electric potential is the volt, defined as 1 watt per ampere.

### 2.2.7 Further Examples of Work in Quasiequilibrium Processes

Systems other than a gas or liquid in a piston–cylinder assembly also can be envisioned as undergoing processes in a quasiequilibrium fashion. To apply the quasiequilibrium process concept in any such case, it is necessary to conceive of an *ideal situation* in

**TAKE NOTE...**

Some readers may elect to defer Secs. 2.2.7 and 2.2.8 and proceed directly to Sec. 2.3 where the energy concept is broadened.

which the external forces acting on the system can be varied so slightly that the resulting imbalance is infinitesimal. As a consequence, the system undergoes a process without ever departing significantly from thermodynamic equilibrium.

The extension of a solid bar and the stretching of a liquid surface can readily be envisioned to occur in a quasiequilibrium manner by direct analogy to the piston–cylinder case. For the bar in Fig. 2.9 the external force can be applied in such a way that it differs only slightly from the opposing force within. The normal stress is then essentially uniform throughout and can be determined as a function of the instantaneous length:  $\sigma = \sigma(x)$ . Similarly, for the liquid film shown in Fig. 2.10 the external force can be applied to the movable wire in such a way that the force differs only slightly from the opposing force within the film. During such a process, the surface tension is essentially uniform throughout the film and is functionally related to the instantaneous area:  $\tau = \tau(A)$ . In each of these cases, once the required functional relationship is known, the work can be evaluated using Eq. 2.18 or 2.19, respectively, in terms of properties of the system as a whole as it passes through equilibrium states.

Other systems also can be imagined as undergoing quasiequilibrium processes. For example, it is possible to envision an electrolytic cell being charged or discharged in a quasiequilibrium manner by adjusting the potential difference across the terminals to be slightly greater, or slightly less, than an ideal potential called the cell *electromotive force* (emf). The energy transfer by work for passage of a differential quantity of charge *to* the cell,  $dZ$ , is given by the relation

$$\delta W = -\mathcal{E} dZ \quad (2.23)$$

In this equation  $\mathcal{E}$  denotes the cell emf, an intensive property of the cell, and not just the potential difference across the terminals as in Eq. 2.22.

Consider next a dielectric material residing in a *uniform electric field*. The energy transferred by work from the field when the polarization is increased slightly is

$$\delta W = -\mathbf{E} \cdot d(\mathbf{VP}) \quad (2.24)$$

where the vector  $\mathbf{E}$  is the electric field strength within the system, the vector  $\mathbf{P}$  is the electric dipole moment per unit volume, and  $V$  is the volume of the system. A similar equation for energy transfer by work from a *uniform magnetic field* when the magnetization is increased slightly is

$$\delta W = -\mu_0 \mathbf{H} \cdot d(\mathbf{VM}) \quad (2.25)$$

where the vector  $\mathbf{H}$  is the magnetic field strength within the system, the vector  $\mathbf{M}$  is the magnetic dipole moment per unit volume, and  $\mu_0$  is a constant, the permeability of free space. The minus signs appearing in the last three equations are in accord with our previously stated sign convention for work:  $W$  takes on a negative value when the energy transfer is *into* the system.

## 2.2.8 Generalized Forces and Displacements

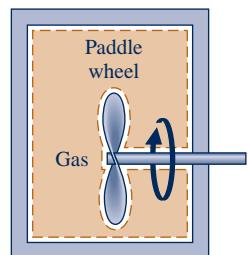
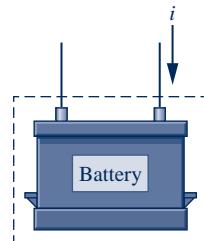
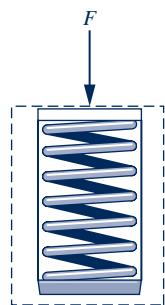
The similarity between the expressions for work in the quasiequilibrium processes considered thus far should be noted. In each case, the work expression is written in the form of an intensive property and the differential of an extensive property. This is brought out by the following expression, which allows for one or more of these work modes to be involved in a process

$$\delta W = p dV - \sigma d(Ax) - \tau dA - \mathcal{E} dZ - \mathbf{E} \cdot d(\mathbf{VP}) - \mu_0 \mathbf{H} \cdot d(\mathbf{VM}) + \dots \quad (2.26)$$

where the last three dots represent other products of an intensive property and the differential of a related extensive property that account for work. Because of the notion of work being a product of force and displacement, the intensive property in these relations is sometimes referred to as a “generalized” force and the extensive

property as a “generalized” displacement, even though the quantities making up the work expressions may not bring to mind actual forces and displacements.

Owing to the underlying quasiequilibrium restriction, Eq. 2.26 does not represent every type of work of practical interest. An example is provided by a paddle wheel that stirs a gas or liquid taken as the system. Whenever any shearing action takes place, the system necessarily passes through nonequilibrium states. To appreciate more fully the implications of the quasiequilibrium process concept requires consideration of the second law of thermodynamics, so this concept is discussed again in Chap. 5 after the second law has been introduced.



## 2.3 Broadening Our Understanding of Energy

The objective in this section is to use our deeper understanding of work developed in Sec. 2.2 to broaden our understanding of the energy of a system. In particular, we consider the *total* energy of a system, which includes kinetic energy, gravitational potential energy, and other forms of energy. The examples to follow illustrate some of these forms of energy. Many other examples could be provided that enlarge on the same idea.

When work is done to compress a spring, energy is stored within the spring. When a battery is charged, the energy stored within it is increased. And when a gas (or liquid) initially at an equilibrium state in a closed, insulated vessel is stirred vigorously and allowed to come to a final equilibrium state, the energy of the gas is increased in the process. In keeping with the discussion of work in Sec. 2.2, we can also think of other ways in which work done on systems increases energy stored within those systems—work related to magnetization, for example. In each of these examples the change in system energy cannot be attributed to changes in the system’s *overall* kinetic or gravitational potential energy as given by Eqs. 2.5 and 2.10, respectively. The change in energy can be accounted for in terms of *internal energy*, as considered next.

In engineering thermodynamics the change in the total energy of a system is considered to be made up of three *macroscopic* contributions. One is the change in kinetic energy, associated with the motion of the system *as a whole* relative to an external coordinate frame. Another is the change in gravitational potential energy, associated with the position of the system *as a whole* in the earth’s gravitational field. All other energy changes are lumped together in the **internal energy** of the system. Like kinetic energy and gravitational potential energy, *internal energy is an extensive property* of the system, as is the total energy.

**internal energy**

Internal energy is represented by the symbol  $U$ , and the change in internal energy in a process is  $U_2 - U_1$ . The specific internal energy is symbolized by  $u$  or  $\bar{u}$ , respectively, depending on whether it is expressed on a unit mass or per mole basis.

The change in the total energy of a system is

$$E_2 - E_1 = (U_2 - U_1) + (\text{KE}_2 - \text{KE}_1) + (\text{PE}_2 - \text{PE}_1) \quad (2.27\text{a})$$

or

$$\Delta E = \Delta U + \Delta \text{KE} + \Delta \text{PE} \quad (2.27\text{b})$$

**Total Energy**  
A.6 – Tab a



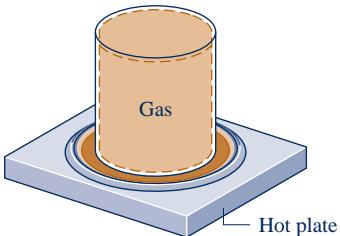
All quantities in Eq. 2.27 are expressed in terms of the energy units previously introduced.

The identification of internal energy as a macroscopic form of energy is a significant step in the present development, for it sets the concept of energy in thermodynamics apart from that of mechanics. In Chap. 3 we will learn how to evaluate changes

### microscopic interpretation of internal energy for a gas

in internal energy for practically important cases involving gases, liquids, and solids by using empirical data.

To further our understanding of internal energy, consider a system we will often encounter in subsequent sections of the book, a system consisting of a gas contained in a tank. Let us develop a **microscopic interpretation of internal energy** by thinking of the energy attributed to the motions and configurations of the individual molecules, atoms, and subatomic particles making up the matter in the system. Gas molecules move about, encountering other molecules or the walls of the container. Part of the internal energy of the gas is the *translational* kinetic energy of the molecules. Other contributions to the internal energy include the kinetic energy due to *rotation* of the molecules relative to their centers of mass and the kinetic energy associated with *vibrational* motions within the molecules. In addition, energy is stored in the chemical bonds between the atoms that make up the molecules. Energy storage on the atomic level includes energy associated with electron orbital states, nuclear spin, and binding forces in the nucleus. In dense gases, liquids, and solids, intermolecular forces play an important role in affecting the internal energy.



**energy transfer by heat**

### sign convention for heat transfer

The symbol  $Q$  denotes an amount of energy transferred across the boundary of a system in a heat interaction with the system's surroundings. Heat transfer *into* a system is taken to be *positive*, and heat transfer *from* a system is taken as *negative*.

$Q > 0$ : heat transfer *to* the system

$Q < 0$ : heat transfer *from* the system

This **sign convention** is used throughout the book. However, as was indicated for work, it is sometimes convenient to show the direction of energy transfer by an arrow on a sketch of the system. Then the heat transfer is regarded as positive in the direction of the arrow.

The sign convention for heat transfer is just the *reverse* of the one adopted for work, where a positive value for  $W$  signifies an energy transfer *from* the system to the surroundings. These signs for heat and work are a legacy from engineers and scientists who were concerned mainly with steam engines and other devices that develop a work output from an energy input by heat transfer. For such applications, it was convenient to regard both the work developed and the energy input by heat transfer as positive quantities.

The value of a heat transfer depends on the details of a process and not just the end states. Thus, like work, **heat is not a property**, and its differential is written as  $\delta Q$ . The amount of energy transfer by heat for a process is given by the integral

$$Q = \int_1^2 \delta Q \quad (2.28)$$

where the limits mean “from state 1 to state 2” and do not refer to the values of heat at those states. As for work, the notion of “heat” at a state has no meaning, and the integral should *never* be evaluated as  $Q_2 - Q_1$ .

The net **rate of heat transfer** is denoted by  $\dot{Q}$ . In principle, the amount of energy transfer by heat during a period of time can be found by integrating from time  $t_1$  to time  $t_2$

$$Q = \int_{t_1}^{t_2} \dot{Q} dt \quad (2.29)$$

To perform the integration, it is necessary to know how the rate of heat transfer varies with time.

In some cases it is convenient to use the *heat flux*,  $\dot{q}$ , which is the heat transfer rate per unit of system surface area. The net rate of heat transfer,  $\dot{Q}$ , is related to the heat flux  $\dot{q}$  by the integral

$$\dot{Q} = \int_A \dot{q} dA \quad (2.30)$$

where A represents the area on the boundary of the system where heat transfer occurs.

The units for heat transfer  $Q$  and heat transfer rate  $\dot{Q}$  are the same as those introduced previously for  $W$  and  $\dot{W}$ , respectively. The units for the heat flux are those of the heat transfer rate per unit area:  $\text{kW/m}^2$  or  $\text{Btu/h} \cdot \text{ft}^2$ .

The word **adiabatic** means *without heat transfer*. Thus, if a system undergoes a process involving no heat transfer with its surroundings, that process is called an *adiabatic process*.

**heat is not a property**

**rate of heat transfer**

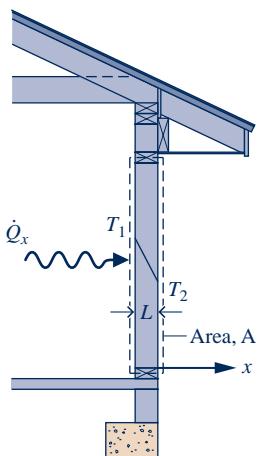
**adiabatic**



**BIO CONNECTIONS** Medical researchers have found that by gradually increasing the temperature of cancerous tissue to 41–45°C the effectiveness of chemotherapy and radiation therapy is enhanced for some patients. Different approaches can be used, including raising the temperature of the entire body with heating devices and, more selectively, by beaming microwaves or ultrasound onto the tumor or affected organ. Speculation about why a temperature increase may be beneficial varies. Some say it helps chemotherapy penetrate certain tumors more readily by dilating blood vessels. Others think it helps radiation therapy by increasing the amount of oxygen in tumor cells, making them more receptive to radiation. Researchers report that further study is needed before the efficacy of this approach is established and the mechanisms whereby it achieves positive results are known.

## 2.4.2 • Heat Transfer Modes

Methods based on experiment are available for evaluating energy transfer by heat. These methods recognize two basic transfer mechanisms: *conduction* and *thermal radiation*. In addition, empirical relationships are available for evaluating energy transfer involving a *combined* mode called *convection*. A brief description of each of these is given next. A detailed consideration is left to a course in engineering heat transfer, where these topics are studied in depth.



**Fig. 2.12** Illustration of Fourier's conduction law.

### Fourier's law

### Conduction

Energy transfer by *conduction* can take place in solids, liquids, and gases. Conduction can be thought of as the transfer of energy from the more energetic particles of a substance to adjacent particles that are less energetic due to interactions between particles. The time rate of energy transfer by conduction is quantified macroscopically by *Fourier's law*. As an elementary application, consider Fig. 2.12 showing a plane wall of thickness  $L$  at steady state, where the temperature  $T(x)$  varies linearly with position  $x$ . By **Fourier's law**, the rate of heat transfer across any plane normal to the  $x$  direction,  $\dot{Q}_x$ , is proportional to the wall area,  $A$ , and the temperature gradient in the  $x$  direction,  $dT/dx$ :

$$\dot{Q}_x = -\kappa A \frac{dT}{dx} \quad (2.31)$$

where the proportionality constant  $\kappa$  is a property called the *thermal conductivity*. The minus sign is a consequence of energy transfer in the direction of *decreasing* temperature.

► **FOR EXAMPLE** in the case of Fig. 2.12 the temperature varies linearly; thus, the temperature gradient is

$$\frac{dT}{dx} = \frac{T_2 - T_1}{L} (< 0)$$

and the rate of heat transfer in the  $x$  direction is then

$$\dot{Q}_x = -\kappa A \left[ \frac{T_2 - T_1}{L} \right] \quad \blacktriangleleft \blacktriangleleft \blacktriangleleft \blacktriangleleft \blacktriangleleft$$

Values of thermal conductivity are given in Table A-19 for common materials. Substances with large values of thermal conductivity such as copper are good conductors, and those with small conductivities (cork and polystyrene foam) are good insulators.



**HT Modes**  
A.7 – Tab b

### Stefan–Boltzmann law

### Radiation

*Thermal radiation* is emitted by matter as a result of changes in the electronic configurations of the atoms or molecules within it. The energy is transported by electromagnetic waves (or photons). Unlike conduction, thermal radiation requires no intervening medium to propagate and can even take place in a vacuum. Solid surfaces, gases, and liquids all emit, absorb, and transmit thermal radiation to varying degrees. The rate at which energy is emitted,  $\dot{Q}_e$ , from a surface of area  $A$  is quantified macroscopically by a modified form of the **Stefan–Boltzmann law**

$$\dot{Q}_e = \varepsilon \sigma A T_b^4 \quad (2.32)$$

which shows that thermal radiation is associated with the fourth power of the absolute temperature of the surface,  $T_b$ . The emissivity,  $\varepsilon$ , is a property of the surface that indicates how effectively the surface radiates ( $0 \leq \varepsilon \leq 1.0$ ), and  $\sigma$  is the Stefan–Boltzmann constant:

$$\sigma = 5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4 = 0.1714 \times 10^{-8} \text{ Btu/h} \cdot \text{ft}^2 \cdot {}^\circ\text{R}^4$$

In general, the *net* rate of energy transfer by thermal radiation between two surfaces involves relationships among the properties of the surfaces, their orientations with respect to each other, the extent to which the intervening medium scatters, emits, and absorbs thermal radiation, and other factors. A special case that occurs frequently is radiation exchange between a surface at temperature  $T_b$  and a much larger surrounding surface at  $T_s$ , as shown in Fig. 2.13. The *net* rate of radiant exchange between the smaller surface, whose area is  $A$  and emissivity is  $\varepsilon$ , and the larger surroundings is

$$\dot{Q}_e = \varepsilon \sigma A [T_b^4 - T_s^4] \quad (2.33)$$



**HT Modes**  
A.7 – Tab d

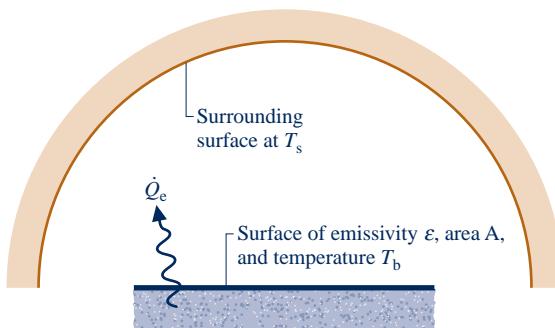


Fig. 2.13 Net radiation exchange.

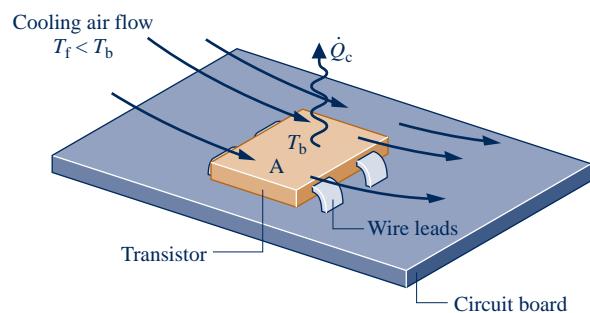


Fig. 2.14 Illustration of Newton's law of cooling.

### Convection

Energy transfer between a solid surface at a temperature  $T_b$  and an adjacent gas or liquid at another temperature  $T_f$  plays a prominent role in the performance of many devices of practical interest. This is commonly referred to as *convection*. As an illustration, consider Fig. 2.14, where  $T_b > T_f$ . In this case, energy is transferred *in the direction indicated by the arrow* due to the *combined effects of conduction within the air and the bulk motion of the air*. The rate of energy transfer *from* the surface *to* the air can be quantified by the following *empirical* expression:

$$\dot{Q}_c = hA(T_b - T_f) \quad (2.34)$$

known as **Newton's law of cooling**. In Eq. 2.34,  $A$  is the surface area and the proportionality factor  $h$  is called the *heat transfer coefficient*. In subsequent applications of Eq. 2.34, a minus sign may be introduced on the right side to conform to the sign convention for heat transfer introduced in Sec. 2.4.1.

#### Newton's law of cooling

The heat transfer coefficient is *not* a thermodynamic property. It is an empirical parameter that incorporates into the heat transfer relationship the nature of the flow pattern near the surface, the fluid properties, and the geometry. When fans or pumps cause the fluid to move, the value of the heat transfer coefficient is generally greater than when relatively slow buoyancy-induced motions occur. These two general categories are called *forced* and *free* (or natural) convection, respectively. Table 2.1 provides typical values of the convection heat transfer coefficient for forced and free convection.

**HT Modes**  
A.7 – Tab c



### 2.4.3 • Closing Comments

The first step in a thermodynamic analysis is to define the system. It is only after the system boundary has been specified that possible heat interactions with the surroundings are considered, for these are *always* evaluated at the system boundary.

TABLE 2.1

#### Typical Values of the Convection Heat Transfer Coefficient

Applications	$h$ (W/m <sup>2</sup> · K)	$h$ (Btu/h · ft <sup>2</sup> · °R)
<b>Free convection</b>		
Gases	2–25	0.35–4.4
Liquids	50–1000	8.8–180
<b>Forced convection</b>		
Gases	25–250	4.4–44
Liquids	50–20,000	8.8–3500

In ordinary conversation, the term *heat* is often used when the word *energy* would be more correct thermodynamically. For example, one might hear, “Please close the door or ‘heat’ will be lost.” In *thermodynamics*, heat refers only to a particular means whereby energy is transferred. It does not refer to what is being transferred between systems or to what is stored within systems. Energy is transferred and stored, not heat.

Sometimes the heat transfer of energy to, or from, a system can be neglected. This might occur for several reasons related to the mechanisms for heat transfer discussed above. One might be that the materials surrounding the system are good insulators, or heat transfer might not be significant because there is a small temperature difference between the system and its surroundings. A third reason is that there might not be enough surface area to allow significant heat transfer to occur. When heat transfer is neglected, it is because one or more of these considerations apply.

In the discussions to follow, the value of  $Q$  is provided or it is an unknown in the analysis. When  $Q$  is provided, it can be assumed that the value has been determined by the methods introduced above. When  $Q$  is the unknown, its value is usually found by using the *energy balance*, discussed next.

## 2.5 Energy Accounting: Energy Balance for Closed Systems

### first law of thermodynamics

As our previous discussions indicate, the *only ways* the energy of a closed system can be changed are through transfer of energy by work or by heat. Further, based on the experiments of Joule and others, a fundamental aspect of the energy concept is that *energy is conserved*; we call this the **first law of thermodynamics**. For further discussion of the first law, see the box.

#### Joule's Experiments and the First Law

In classic experiments conducted in the early part of the nineteenth century, Joule studied processes by which a closed system can be taken from one equilibrium state to another. In particular, he considered processes that involve work interactions but no heat interactions between the system and its surroundings. Any such process is an *adiabatic process*, in keeping with the discussion of Sec. 2.4.1.

Based on his experiments Joule deduced that the value of the net work is the same for *all* adiabatic processes between two equilibrium states. In other words, the value of the net work done by or on a closed system undergoing an adiabatic process between two given states *depends solely on the end states* and not on the details of the adiabatic process.

If the net work is the same for all adiabatic processes of a closed system between a given pair of end states, it follows from the definition of property (Sec. 1.3) that the net work for such a process is the change in some property of the system. This property is called *energy*.

Following Joule's reasoning, the *change in energy* between the two states is *defined by*

$$E_2 - E_1 = -W_{ad} \quad (\text{a})$$

where the symbol  $E$  denotes the energy of a system and  $W_{ad}$  represents the net work for any adiabatic process between the two states. The minus sign before the work term is in

accord with the previously stated sign convention for work. Finally, note that since any arbitrary value  $E_1$  can be assigned to the energy of a system at a given state 1, no particular significance can be attached to the value of the energy at state 1 or at *any* other state. Only *changes* in the energy of a system have significance.

The foregoing discussion is based on experimental evidence beginning with the experiments of Joule. Because of inevitable experimental uncertainties, it is not possible to prove by measurements that the net work is *exactly* the same for *all* adiabatic processes between the same end states. However, the preponderance of experimental findings supports this conclusion, so it is adopted as a fundamental principle that the work actually is the same. This principle is an alternative formulation of the *first law*, and has been used by subsequent scientists and engineers as a springboard for developing the *conservation of energy* concept and the *energy balance* as we know them today.

### Summarizing Energy Concepts

All energy aspects introduced in this book thus far are summarized in words as follows:

$$\left[ \begin{array}{l} \text{change in the amount} \\ \text{of energy contained} \\ \text{within a system} \\ \text{during some time} \\ \text{interval} \end{array} \right] = \left[ \begin{array}{l} \text{net amount of energy} \\ \text{transferred } in \text{ across} \\ \text{the system boundary by} \\ \text{heat transfer during} \\ \text{the time interval} \end{array} \right] - \left[ \begin{array}{l} \text{net amount of energy} \\ \text{transferred } out \text{ across} \\ \text{the system boundary} \\ \text{by work during the} \\ \text{time interval} \end{array} \right]$$

This word statement is just an accounting balance for energy, an energy balance. It requires that in any process of a closed system the energy of the system increases or decreases by an amount equal to the net amount of energy transferred across its boundary.

The phrase *net amount* used in the word statement of the energy balance must be carefully interpreted, for there may be heat or work transfers of energy at many different places on the boundary of a system. At some locations the energy transfers may be into the system, whereas at others they are out of the system. The two terms on the right side account for the *net* results of all the energy transfers by heat and work, respectively, taking place during the time interval under consideration.

The **energy balance** can be expressed in symbols as

$$E_2 - E_1 = Q - W \quad (2.35a)$$

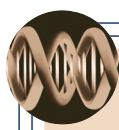
Introducing Eq. 2.27 an alternative form is

**energy balance**

$$\Delta KE + \Delta PE + \Delta U = Q - W \quad (2.35b)$$

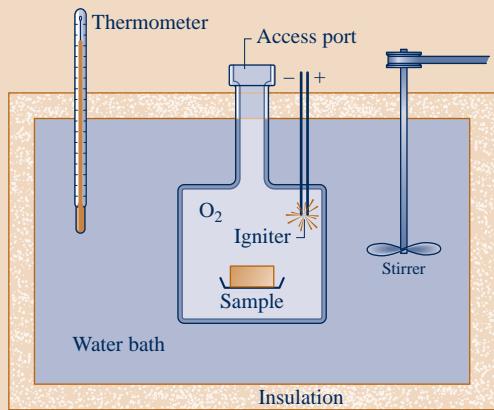
which shows that an energy transfer across the system boundary results in a change in one or more of the macroscopic energy forms: kinetic energy, gravitational potential energy, and internal energy. All previous references to energy as a conserved quantity are included as special cases of Eqs. 2.35.

Note that the algebraic signs before the heat and work terms of Eqs. 2.35 are different. This follows from the sign conventions previously adopted. A minus sign appears before  $W$  because energy transfer by work *from* the system *to* the surroundings is taken to be positive. A plus sign appears before  $Q$  because it is regarded to be positive when the heat transfer of energy is *into* the system *from* the surroundings.



**BIO CONNECTIONS** The energy required by animals to sustain life is derived from oxidation of ingested food. We often speak of food being *burned* in the body.

This is an appropriate expression because experiments show that when food is burned with oxygen, approximately the same energy is released as when the food is oxidized in the body. Such an experimental device is the well-insulated, constant-volume *calorimeter* shown in Fig. 2.15.



**Fig. 2.15 Constant-volume calorimeter.**

A carefully weighed food sample is placed in the chamber of the calorimeter together with oxygen ( $O_2$ ). The entire chamber is submerged in the calorimeter's water bath. The chamber contents are then electrically ignited, fully oxidizing the food sample. The energy released during the reaction within the chamber results in an increase in calorimeter temperature. Using the measured temperature rise, the energy released can be calculated from an energy balance for the calorimeter as the system. This is reported as the calorie value of the food sample, usually in terms of kilocalorie (kcal), which is the "Calorie" seen on food labels.

### 2.5.1 • Important Aspects of the Energy Balance

Various special forms of the energy balance can be written. For example, the energy balance in differential form is

$$dE = \delta Q - \delta W \quad (2.36)$$

where  $dE$  is the differential of energy, a property. Since  $Q$  and  $W$  are not properties, their differentials are written as  $\delta Q$  and  $\delta W$ , respectively.

The instantaneous **time rate form of the energy balance** is

**time rate form of the energy balance**

$$\frac{dE}{dt} = \dot{Q} - \dot{W} \quad (2.37)$$

The rate form of the energy balance expressed in words is

$$\left[ \begin{array}{l} \text{time rate of change} \\ \text{of the energy} \\ \text{contained within} \\ \text{the system at} \\ \text{time } t \end{array} \right] = \left[ \begin{array}{l} \text{net rate at which} \\ \text{energy is being} \\ \text{transferred in} \\ \text{by heat transfer} \\ \text{at time } t \end{array} \right] - \left[ \begin{array}{l} \text{net rate at which} \\ \text{energy is being} \\ \text{transferred out} \\ \text{by work at} \\ \text{time } t \end{array} \right]$$

Since the time rate of change of energy is given by

$$\frac{dE}{dt} = \frac{d\text{KE}}{dt} + \frac{d\text{PE}}{dt} + \frac{dU}{dt}$$

Equation 2.37 can be expressed alternatively as

$$\frac{d\text{KE}}{dt} + \frac{d\text{PE}}{dt} + \frac{dU}{dt} = \dot{Q} - \dot{W} \quad (2.38)$$

Equations 2.35 through 2.38 provide alternative forms of the energy balance that are convenient starting points when applying the principle of conservation of energy to closed systems. In Chap. 4 the conservation of energy principle is expressed in forms suitable for the analysis of control volumes. When applying the energy balance in *any* of its forms, it is important to be careful about signs and units and to distinguish carefully between rates and amounts. In addition, it is important to recognize that the location of the system boundary can be relevant in determining whether a particular energy transfer is regarded as heat or work.

**► FOR EXAMPLE** consider Fig. 2.16, in which three alternative systems are shown that include a quantity of a gas (or liquid) in a rigid, well-insulated container. In Fig. 2.16a, the gas itself is the system. As current flows through the copper plate, there is an energy transfer from the copper plate to the gas. Since this energy transfer occurs as a result of the temperature difference between the plate and the gas, it is classified as a heat transfer. Next, refer to Fig. 2.16b, where the boundary is drawn to include the copper plate. It follows from the thermodynamic definition of work that the energy transfer that occurs as current crosses the boundary of this system must be regarded as work. Finally, in Fig. 2.16c, the boundary is located so that no energy is transferred across it by heat or work. ▲ ▲ ▲ ▲ ▲

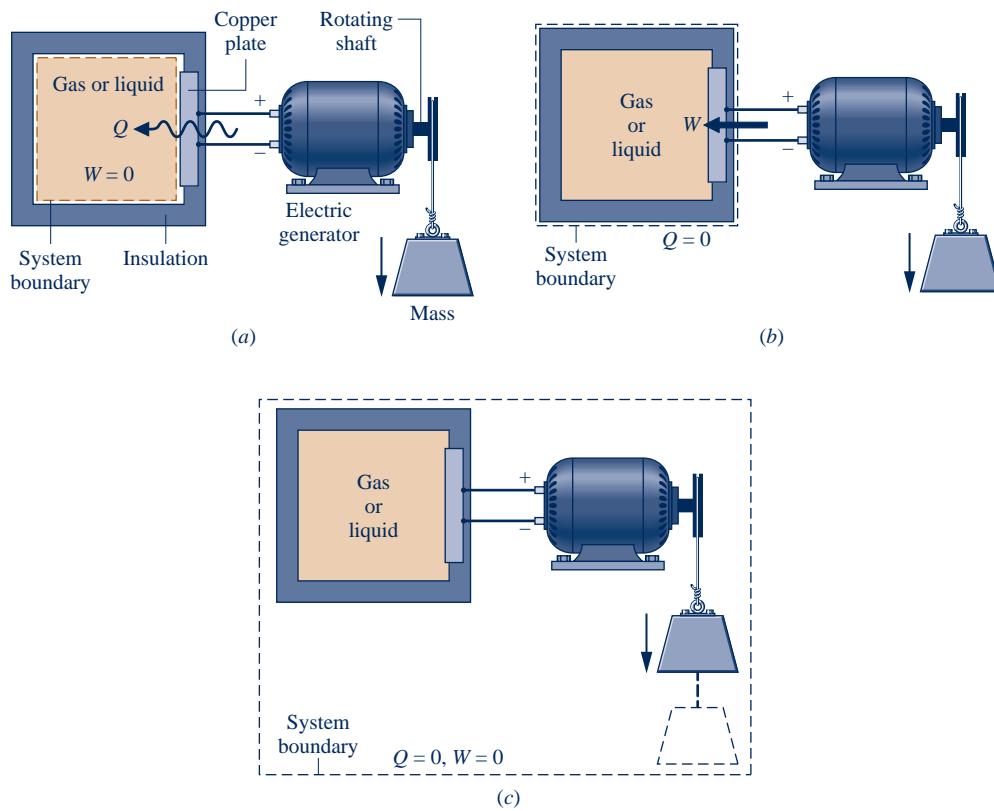


Fig. 2.16 Alternative choices for system boundaries.

### Closing Comments

Thus far, we have been careful to emphasize that the quantities symbolized by  $W$  and  $Q$  in the foregoing equations account for transfers of *energy* and not transfers of work and heat, respectively. The terms work and heat denote different *means* whereby energy is transferred and not *what* is transferred. However, to achieve economy of expression in subsequent discussions,  $W$  and  $Q$  are often referred to simply as work and heat transfer, respectively. This less formal manner of speaking is commonly used in engineering practice.

The five solved examples provided in Secs. 2.5.2–2.5.4 bring out important ideas about energy and the energy balance. They should be studied carefully, and similar approaches should be used when solving the end-of-chapter problems. In this text, most applications of the energy balance will not involve significant kinetic or potential energy changes. Thus, to expedite the solutions of many subsequent examples and end-of-chapter problems, we indicate in the problem statement that such changes can be neglected. If this is not made explicit in a problem statement, you should decide on the basis of the problem at hand how best to handle the kinetic and potential energy terms of the energy balance.

## 2.5.2 • Using the Energy Balance: Processes of Closed Systems

The next two examples illustrate the use of the energy balance for processes of closed systems. In these examples, internal energy data are provided. In Chap. 3, we learn how to obtain internal energy and other thermodynamic property data using tables, graphs, equations, and computer software.

### EXAMPLE 2.2

#### Cooling a Gas in a Piston–Cylinder

Four-tenths kilogram of a certain gas is contained within a piston–cylinder assembly. The gas undergoes a process for which the pressure–volume relationship is

$$pV^{1.5} = \text{constant}$$

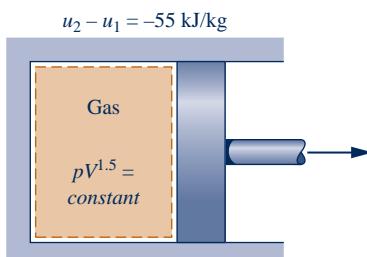
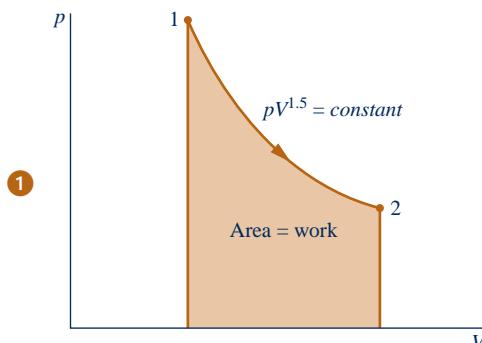
The initial pressure is 3 bar, the initial volume is  $0.1 \text{ m}^3$ , and the final volume is  $0.2 \text{ m}^3$ . The change in specific internal energy of the gas in the process is  $u_2 - u_1 = -55 \text{ kJ/kg}$ . There are no significant changes in kinetic or potential energy. Determine the net heat transfer for the process, in kJ.

#### SOLUTION

**Known:** A gas within a piston–cylinder assembly undergoes an expansion process for which the pressure–volume relation and the change in specific internal energy are specified.

**Find:** Determine the net heat transfer for the process.

#### Schematic and Given Data:



#### Engineering Model:

1. The gas is a closed system.
2. The process is described by  $pV^{1.5} = \text{constant}$ .
3. There is no change in the kinetic or potential energy of the system.

Fig. E2.2

**Analysis:** An energy balance for the closed system takes the form

$$\Delta KE^0 + \Delta PE^0 + \Delta U = Q - W$$

where the kinetic and potential energy terms drop out by assumption 3. Then, writing  $\Delta U$  in terms of specific internal energies, the energy balance becomes

$$m(u_2 - u_1) = Q - W$$

where  $m$  is the system mass. Solving for  $Q$

$$Q = m(u_2 - u_1) + W$$

The value of the work for this process is determined in the solution to part (a) of Example 2.1:  $W = +17.6$  kJ. The change in internal energy is obtained using given data as

$$m(u_2 - u_1) = 0.4 \text{ kg} \left( -55 \frac{\text{kJ}}{\text{kg}} \right) = -22 \text{ kJ}$$

Substituting values

②

$$Q = -22 + 17.6 = -4.4 \text{ kJ}$$

- ① The given relationship between pressure and volume allows the process to be represented by the path shown on the accompanying diagram. The area under the curve represents the work. Since they are not properties, the values of the work and heat transfer depend on the details of the process and cannot be determined from the end states only.
- ② The minus sign for the value of  $Q$  means that a net amount of energy has been transferred from the system to its surroundings by heat transfer.

### QuickQUIZ

If the gas undergoes a process for which  $pV = \text{constant}$  and  $\Delta u = 0$ , determine the heat transfer, in kJ, keeping the initial pressure and given volumes fixed. **Ans.** 20.79 kJ.

### Skills Developed

**Ability to...**

- define a closed system and identify interactions on its boundary.
- apply the closed-system energy balance.

In the next example, we follow up the discussion of Fig. 2.16 by considering two alternative systems. This example highlights the need to account correctly for the heat and work interactions occurring on the boundary as well as the energy change.

## EXAMPLE 2.3

### Considering Alternative Systems

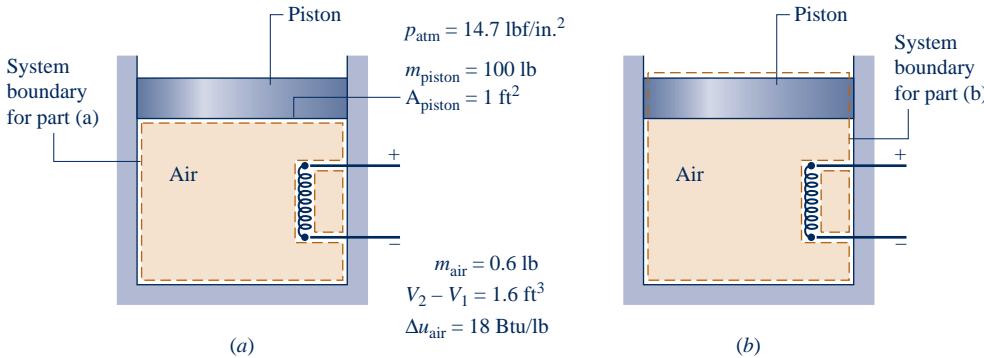
Air is contained in a vertical piston–cylinder assembly fitted with an electrical resistor. The atmosphere exerts a pressure of  $14.7 \text{ lbf/in}^2$  on the top of the piston, which has a mass of 100 lb and a face area of  $1 \text{ ft}^2$ . Electric current passes through the resistor, and the volume of the air slowly increases by  $1.6 \text{ ft}^3$  while its pressure remains constant. The mass of the air is 0.6 lb, and its specific internal energy increases by 18 Btu/lb. The air and piston are at rest initially and finally. The piston–cylinder material is a ceramic composite and thus a good insulator. Friction between the piston and cylinder wall can be ignored, and the local acceleration of gravity is  $g = 32.0 \text{ ft/s}^2$ . Determine the heat transfer from the resistor to the air, in Btu, for a system consisting of (a) the air alone, (b) the air and the piston.

### SOLUTION

**Known:** Data are provided for air contained in a vertical piston–cylinder fitted with an electrical resistor.

**Find:** Considering each of two alternative systems, determine the heat transfer from the resistor to the air.

**Schematic and Given Data:**

**Fig. E2.3**

**Engineering Model:**

1. Two closed systems are under consideration, as shown in the schematic.
2. The only significant heat transfer is from the resistor to the air, during which the air expands slowly and its pressure remains constant.
3. There is no net change in kinetic energy; the change in potential energy of the air is negligible; and since the piston material is a good insulator, the internal energy of the piston is not affected by the heat transfer.
4. Friction between the piston and cylinder wall is negligible.
5. The acceleration of gravity is constant;  $g = 32.0 \text{ ft/s}^2$ .

**Analysis:** (a) Taking the air as the system, the energy balance, Eq. 2.35, reduces with assumption 3 to

$$(\Delta KE^0 + \Delta PE^0 + \Delta U)_{\text{air}} = Q - W$$

Or, solving for  $Q$

$$Q = W + \Delta U_{\text{air}}$$

For this system, work is done by the force of the pressure  $p$  acting on the *bottom* of the piston as the air expands. With Eq. 2.17 and the assumption of constant pressure

$$W = \int_{V_1}^{V_2} p dV = p(V_2 - V_1)$$

To determine the pressure  $p$ , we use a force balance on the slowly moving, frictionless piston. The upward force exerted by the air on the *bottom* of the piston equals the weight of the piston plus the downward force of the atmosphere acting on the *top* of the piston. In symbols

$$pA_{\text{piston}} = m_{\text{piston}} g + p_{\text{atm}}A_{\text{piston}}$$

Solving for  $p$  and inserting values

$$\begin{aligned} p &= \frac{m_{\text{piston}} g}{A_{\text{piston}}} + p_{\text{atm}} \\ &= \frac{(100 \text{ lb})(32.0 \text{ ft/s}^2)}{1 \text{ ft}^2} \left| \frac{1 \text{ lbf}}{32.2 \text{ lb} \cdot \text{ft/s}^2} \right| \left| \frac{1 \text{ ft}^2}{144 \text{ in.}^2} \right| + 14.7 \frac{\text{lbf}}{\text{in.}^2} = 15.4 \frac{\text{lbf}}{\text{in.}^2} \end{aligned}$$

Thus, the work is

$$\begin{aligned} W &= p(V_2 - V_1) \\ &= \left( 15.4 \frac{\text{lbf}}{\text{in.}^2} \right)(1.6 \text{ ft}^3) \left| \frac{144 \text{ in.}^2}{1 \text{ ft}^2} \right| \left| \frac{1 \text{ Btu}}{778 \text{ ft} \cdot \text{lbf}} \right| = 4.56 \text{ Btu} \end{aligned}$$

With  $\Delta U_{\text{air}} = m_{\text{air}}(\Delta u_{\text{air}})$ , the heat transfer is

$$\begin{aligned} Q &= W + m_{\text{air}}(\Delta u_{\text{air}}) \\ &= 4.56 \text{ Btu} + (0.6 \text{ lb}) \left( 18 \frac{\text{Btu}}{\text{lb}} \right) = 15.36 \text{ Btu} \end{aligned}$$

- (b) Consider next a system consisting of the air and the piston. The energy change of the overall system is the sum of the energy changes of the air and the piston. Thus, the energy balance, Eq. 2.35, reads

$$(\Delta KE^0 + \Delta PE^0 + \Delta U)_{\text{air}} + (\Delta KE^0 + \Delta PE + \Delta U^0)_{\text{piston}} = Q - W$$

where the indicated terms drop out by assumption 3. Solving for  $Q$

$$Q = W + (\Delta PE)_{\text{piston}} + (\Delta U)_{\text{air}}$$

For this system, work is done at the *top* of the piston as it pushes aside the surrounding atmosphere. Applying Eq. 2.17

$$\begin{aligned} W &= \int_{V_1}^{V_2} p \, dV = p_{\text{atm}}(V_2 - V_1) \\ &= \left( 14.7 \frac{\text{lbf}}{\text{in.}^2} \right) (1.6 \text{ ft}^3) \left| \frac{144 \text{ in.}^2}{1 \text{ ft}^2} \right| \left| \frac{1 \text{ Btu}}{778 \text{ ft} \cdot \text{lbf}} \right| = 4.35 \text{ Btu} \end{aligned}$$

The elevation change,  $\Delta z$ , required to evaluate the potential energy change of the piston can be found from the volume change of the air and the area of the piston face as

$$\Delta z = \frac{V_2 - V_1}{A_{\text{piston}}} = \frac{1.6 \text{ ft}^3}{1 \text{ ft}^2} = 1.6 \text{ ft}$$

Thus, the potential energy change of the piston is

$$\begin{aligned} (\Delta PE)_{\text{piston}} &= m_{\text{piston}} g \Delta z \\ &= (100 \text{ lb}) \left( 32.0 \frac{\text{ft}}{\text{s}^2} \right) (1.6 \text{ ft}) \left| \frac{1 \text{ lbf}}{32.2 \text{ lb} \cdot \text{ft/s}^2} \right| \left| \frac{1 \text{ Btu}}{778 \text{ ft} \cdot \text{lbf}} \right| = 0.2 \text{ Btu} \end{aligned}$$

Finally,

$$\begin{aligned} Q &= W + (\Delta PE)_{\text{piston}} + m_{\text{air}} \Delta u_{\text{air}} \\ &= 4.35 \text{ Btu} + 0.2 \text{ Btu} + (0.6 \text{ lb}) \left( 18 \frac{\text{Btu}}{\text{lb}} \right) = 15.35 \text{ Btu} \end{aligned}$$

- ① ② To within round-off, this answer agrees with the result of part (a).

- ① Although the value of  $Q$  is the same for each system, observe that the values for  $W$  differ. Also, observe that the energy changes differ, depending on whether the air alone or the air and the piston is the system.
- ② For the system of part (b), the following *energy balance sheet* gives a full accounting of the heat transfer of energy to the system:

#### Energy In by Heat Transfer

15.35 Btu

#### Disposition of the Energy In

• Energy stored	
Internal energy of the air	10.8 Btu (70.4%)
Potential energy of the piston	0.2 Btu ( 1.3%)
• Energy out by work	<u>4.35 Btu (28.3%)</u>
	15.35 Btu (100%)



#### Skills Developed

Ability to...

- define alternative closed systems and identify interactions on their boundaries.
- evaluate work using Eq. 2.17.
- apply the closed-system energy balance.
- develop an energy balance sheet.

#### QuickQUIZ

What is the change in potential energy of the air, in Btu?

Ans.  $\approx 10^{-3}$  Btu.

### 2.5.3 Using the Energy Rate Balance: Steady-State Operation

A system is at steady state if none of its properties change with time (Sec. 1.3). Many devices operate at steady state or nearly at steady state, meaning that property variations with time are small enough to ignore. The two examples to follow illustrate the application of the energy rate equation to closed systems at steady state.

#### EXAMPLE 2.4

### Evaluating Energy Transfer Rates of a Gearbox at Steady State

During steady-state operation, a gearbox receives 60 kW through the input shaft and delivers power through the output shaft. For the gearbox as the system, the rate of energy transfer by convection is

$$\dot{Q} = -hA(T_b - T_f)$$

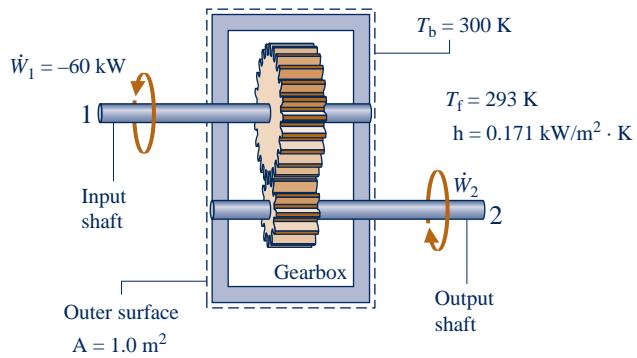
where  $h = 0.171 \text{ kW/m}^2 \cdot \text{K}$  is the heat transfer coefficient,  $A = 1.0 \text{ m}^2$  is the outer surface area of the gearbox,  $T_b = 300 \text{ K}$  ( $27^\circ\text{C}$ ) is the temperature at the outer surface, and  $T_f = 293 \text{ K}$  ( $20^\circ\text{C}$ ) is the temperature of the surrounding air away from the immediate vicinity of the gearbox. For the gearbox, evaluate the heat transfer rate and the power delivered through the output shaft, each in kW.

#### SOLUTION

**Known:** A gearbox operates at steady state with a known power input. An expression for the heat transfer rate from the outer surface is also known.

**Find:** Determine the heat transfer rate and the power delivered through the output shaft, each in kW.

#### Schematic and Given Data:



#### Engineering Model:

- The gearbox is a closed system at steady state.
- For the gearbox, convection is the dominant heat transfer mode.

Fig. E2.4

**Analysis:** Using the given expression for  $\dot{Q}$  together with known data, the rate of energy transfer by heat is

$$\begin{aligned} ① \quad \dot{Q} &= -hA(T_b - T_f) \\ &= -\left(0.171 \frac{\text{kW}}{\text{m}^2 \cdot \text{K}}\right)(1.0 \text{ m}^2)(300 - 293) \text{ K} \\ &= -1.2 \text{ kW} \end{aligned}$$

The minus sign for  $\dot{Q}$  signals that energy is carried *out* of the gearbox by heat transfer.

The energy rate balance, Eq. 2.37, reduces at steady state to

$$② \quad \frac{dE^0}{dt} = \dot{Q} - \dot{W} \quad \text{or} \quad \dot{W} = \dot{Q}$$

The symbol  $\dot{W}$  represents the *net* power from the system. The net power is the sum of  $\dot{W}_1$  and the output power  $\dot{W}_2$

$$\dot{W} = \dot{W}_1 + \dot{W}_2$$

With this expression for  $\dot{W}$ , the energy rate balance becomes

$$\dot{W}_1 + \dot{W}_2 = \dot{Q}$$

Solving for  $\dot{W}_2$ , inserting  $\dot{Q} = -1.2 \text{ kW}$ , and  $\dot{W}_1 = -60 \text{ kW}$ , where the minus sign is required because the input shaft brings energy *into* the system, we have

③

$$\begin{aligned}\dot{W}_2 &= \dot{Q} - \dot{W}_1 \\ &= (-1.2 \text{ kW}) - (-60 \text{ kW}) \\ &= +58.8 \text{ kW}\end{aligned}$$

- ④ The positive sign for  $\dot{W}_2$  indicates that energy is transferred from the system through the output shaft, as expected.

- ① In accord with the sign convention for the heat transfer rate in the energy rate balance (Eq. 2.37), Eq. 2.34 is written with a minus sign:  $\dot{Q}$  is negative since  $T_b$  is greater than  $T_f$ .
- ② Properties of a system at steady state do not change with time. Energy  $E$  is a property, but heat transfer and work are not properties.
- ③ For this system, energy transfer by work occurs at two different locations, and the signs associated with their values differ.
- ④ At steady state, the rate of heat transfer from the gear box accounts for the difference between the input and output power. This can be summarized by the following energy rate “balance sheet” in terms of *magnitudes*:

Input	Output
60 kW (input shaft)	58.8 kW (output shaft)
	1.2 kW (heat transfer)
Total: 60 kW	60 kW



### Skills Developed

#### Ability to...

- define a closed system and identify interactions on its boundary.
- evaluate the rate of energy transfer by convection.
- apply the energy rate balance for steady-state operation.
- develop an energy rate balance sheet.

### QuickQUIZ

For an emissivity of 0.8 and taking  $T_s = T_f$ , use Eq. 2.33 to determine the net rate at which energy is radiated from the outer surface of the gearbox, in kW. **Ans.** 0.03 kW

### EXAMPLE 2.5

#### Determining Surface Temperature of a Silicon Chip at Steady State

A silicon chip measuring 5 mm on a side and 1 mm in thickness is embedded in a ceramic substrate. At steady state, the chip has an electrical power input of 0.225 W. The top surface of the chip is exposed to a coolant whose temperature is 20°C. The heat transfer coefficient for convection between the chip and the coolant is 150 W/m<sup>2</sup> · K. If heat transfer by conduction between the chip and the substrate is negligible, determine the surface temperature of the chip, in °C.

#### SOLUTION

**Known:** A silicon chip of known dimensions is exposed on its top surface to a coolant. The electrical power input and convective heat transfer coefficient are known.

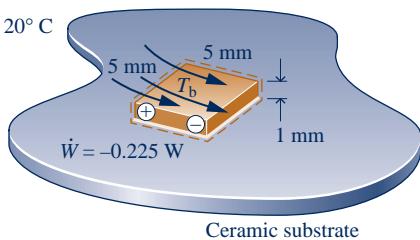
**Find:** Determine the surface temperature of the chip at steady state.

**Schematic and Given Data:**

Coolant

$$h = 150 \text{ W/m}^2 \cdot \text{K}$$

$$T_f = 20^\circ \text{C}$$



**Engineering Model:**

1. The chip is a closed system at steady state.
2. There is no heat transfer between the chip and the substrate.

**Fig. E2.5**

**Analysis:** The surface temperature of the chip,  $T_b$ , can be determined using the energy rate balance, Eq. 2.37, which at steady state reduces as follows

1

$$\frac{dE}{dt}^0 = \dot{Q} - \dot{W}$$

With assumption 2, the only heat transfer is by convection to the coolant. In this application, Newton's law of cooling, Eq. 2.34, takes the form

2

$$\dot{Q} = -hA(T_b - T_f)$$

Collecting results

$$0 = -hA(T_b - T_f) - \dot{W}$$

Solving for  $T_b$

$$T_b = \frac{-\dot{W}}{hA} + T_f$$

In this expression,  $\dot{W} = -0.225 \text{ W}$ ,  $A = 25 \times 10^{-6} \text{ m}^2$ ,  $h = 150 \text{ W/m}^2 \cdot \text{K}$ , and  $T_f = 293 \text{ K}$ , giving

$$\begin{aligned} T_b &= \frac{-(-0.225 \text{ W})}{(150 \text{ W/m}^2 \cdot \text{K})(25 \times 10^{-6} \text{ m}^2)} + 293 \text{ K} \\ &= 353 \text{ K (80°C)} \end{aligned}$$

- 1 Properties of a system at steady state do not change with time. Energy  $E$  is a property, but heat transfer and work are not properties.
- 2 In accord with the sign convention for heat transfer in the energy rate balance (Eq. 2.37), Eq. 2.34 is written with a minus sign:  $\dot{Q}$  is negative since  $T_b$  is greater than  $T_f$ .

**Skills Developed**

Ability to...

- define a closed system and identify interactions on its boundary.
- evaluate the rate of energy transfer by convection.
- apply the energy rate balance for steady-state operation.

**QuickQUIZ**

If the surface temperature of the chip must be no greater than  $60^\circ \text{C}$ , what is the corresponding range of values required for the convective heat transfer coefficient, assuming all other quantities remain unchanged? **Ans.**  $h \geq 225 \text{ W/m}^2 \cdot \text{K}$ .

### 2.5.4 Using the Energy Rate Balance: Transient Operation

Many devices undergo periods of transient operation where the state changes with time. This is observed during startup and shutdown periods. The next example illustrates the application of the energy rate balance to an electric motor during startup. The example also involves both electrical work and power transmitted by a shaft.

**EXAMPLE 2.6 ▶****Investigating Transient Operation of a Motor**

The rate of heat transfer between a certain electric motor and its surroundings varies with time as

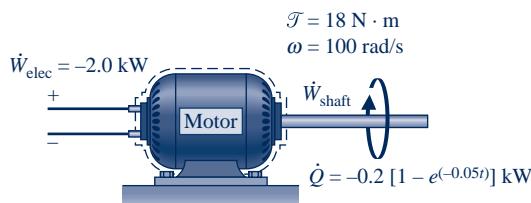
$$\dot{Q} = -0.2[1 - e^{(-0.05t)}]$$

where  $t$  is in seconds and  $\dot{Q}$  is in kW. The shaft of the motor rotates at a constant speed of  $\omega = 100 \text{ rad/s}$  (about 955 revolutions per minute, or RPM) and applies a constant torque of  $\mathcal{T} = 18 \text{ N} \cdot \text{m}$  to an external load. The motor draws a constant electric power input equal to 2.0 kW. For the motor, plot  $\dot{Q}$  and  $\dot{W}$ , each in kW, and the change in energy  $\Delta E$ , in kJ, as functions of time from  $t = 0$  to  $t = 120 \text{ s}$ . Discuss.

**SOLUTION**

**Known:** A motor operates with constant electric power input, shaft speed, and applied torque. The time-varying rate of heat transfer between the motor and its surroundings is given.

**Find:** Plot  $\dot{Q}$ ,  $\dot{W}$ , and  $\Delta E$  versus time. Discuss.

**Schematic and Given Data:**

**Engineering Model:** The system shown in the accompanying sketch is a closed system.

**Fig. E2.6a**

**Analysis:** The time rate of change of system energy is

$$\frac{dE}{dt} = \dot{Q} - \dot{W}$$

$\dot{W}$  represents the *net power from* the system: the sum of the power associated with the rotating shaft,  $\dot{W}_{\text{shaft}}$ , and the power associated with the electricity flow,  $\dot{W}_{\text{elec}}$ :

$$\dot{W} = \dot{W}_{\text{shaft}} + \dot{W}_{\text{elec}}$$

The rate  $\dot{W}_{\text{elec}}$  is known from the problem statement:  $\dot{W}_{\text{elec}} = -2.0 \text{ kW}$ , where the negative sign is required because energy is carried into the system by electrical work. The term  $\dot{W}_{\text{shaft}}$  can be evaluated with Eq. 2.20 as

$$\dot{W}_{\text{shaft}} = \mathcal{T}\omega = (18 \text{ N} \cdot \text{m})(100 \text{ rad/s}) = 1800 \text{ W} = +1.8 \text{ kW}$$

Because energy exits the system along the rotating shaft, this energy transfer rate is positive.

In summary,

$$\dot{W} = \dot{W}_{\text{elec}} + \dot{W}_{\text{shaft}} = (-2.0 \text{ kW}) + (+1.8 \text{ kW}) = -0.2 \text{ kW}$$

where the minus sign means that the electrical power input is greater than the power transferred out along the shaft.

With the foregoing result for  $\dot{W}$  and the given expression for  $\dot{Q}$ , the energy rate balance becomes

$$\frac{dE}{dt} = -0.2[1 - e^{(-0.05t)}] - (-0.2) = 0.2e^{(-0.05t)}$$

Integrating

$$\begin{aligned} \Delta E &= \int_0^t 0.2e^{(-0.05t)} dt \\ &= \frac{0.2}{(-0.05)} e^{(-0.05t)} \Big|_0^t = 4[1 - e^{(-0.05t)}] \end{aligned}$$

- ① The accompanying plots, Figs. E2.6b and c, are developed using the given expression for  $\dot{Q}$  and the expressions for  $\dot{W}$  and  $\Delta E$  obtained in the analysis. Because of our sign conventions for heat and work, the values of  $\dot{Q}$

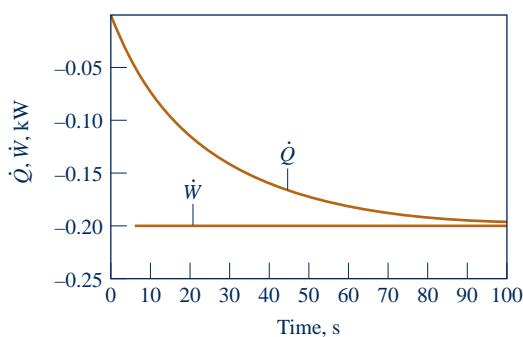
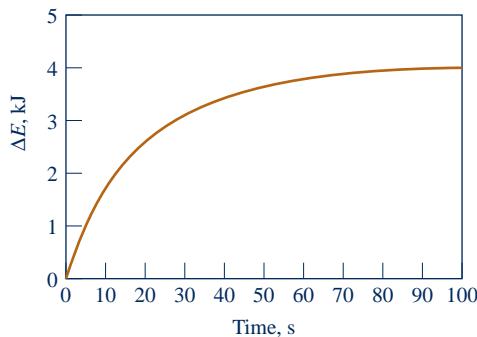


Fig. E2.6b and c

and  $\dot{W}$  are negative. In the first few seconds, the *net* rate that energy is carried in by work greatly exceeds the rate that energy is carried out by heat transfer. Consequently, the energy stored in the motor increases rapidly as the motor “warms up.” As time elapses, the value of  $\dot{Q}$  approaches  $\dot{W}$ , and the rate of energy storage diminishes. After about 100 s, this *transient* operating mode is nearly over, and there is little further change in the amount of energy stored, or in any other property. We may say that the motor

② is then at steady state.

- Figures E.2.6b and c can be developed using appropriate software or can be drawn by hand.
- At steady state, the value of  $\dot{Q}$  is constant at  $-0.2 \text{ kW}$ . This constant value for the heat transfer rate can be thought of as the portion of the electrical power input that is not obtained as a mechanical power output because of effects within the motor such as electrical resistance and friction.

### Skills Developed

Ability to...

- define a closed system and identify interactions on its boundary.
- apply the energy rate balance for transient operation.
- develop and interpret graphical data.

#### QuickQUIZ

If the dominant mode of heat transfer from the outer surface of the motor is convection, determine *at steady state* the temperature  $T_b$  on the outer surface, in K, for  $h = 0.17 \text{ kW/m}^2 \cdot \text{K}$ ,  $A = 0.3 \text{ m}^2$ , and  $T_f = 293 \text{ K}$ .

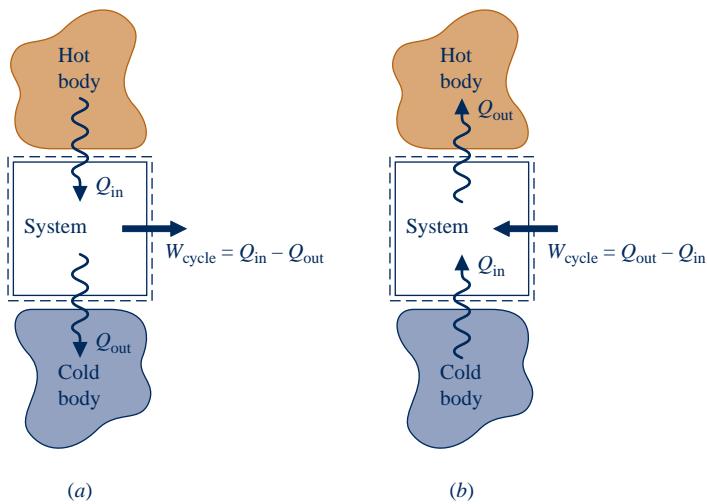
Ans. 297 K.

## 2.6 Energy Analysis of Cycles

### thermodynamic cycle

In this section the energy concepts developed thus far are illustrated further by application to systems undergoing thermodynamic cycles. A **thermodynamic cycle** is a sequence of processes that begins and ends at the same state. At the conclusion of a cycle all properties have the same values they had at the beginning. Consequently, over the cycle the system experiences no *net* change of state. Cycles that are repeated periodically play prominent roles in many areas of application. For example, steam circulating through an electrical power plant executes a cycle.

The study of systems undergoing cycles has played an important role in the development of the subject of engineering thermodynamics. Both the first and second laws of thermodynamics have roots in the study of cycles. Additionally, there are many important practical applications involving power generation, vehicle propulsion, and refrigeration for which an understanding of thermodynamic cycles is essential. In this section, cycles are considered from the perspective of the conservation of energy principle. Cycles are studied in greater detail in subsequent chapters, using both the conservation of energy principle and the second law of thermodynamics.



**Fig. 2.17** Schematic diagrams of two important classes of cycles. (a) Power cycles. (b) Refrigeration and heat pump cycles.

## 2.6.1 Cycle Energy Balance

The energy balance for any system undergoing a thermodynamic cycle takes the form

$$\Delta E_{\text{cycle}} = Q_{\text{cycle}} - W_{\text{cycle}} \quad (2.39)$$

where  $Q_{\text{cycle}}$  and  $W_{\text{cycle}}$  represent *net* amounts of energy transfer by heat and work, respectively, for the cycle. Since the system is returned to its initial state after the cycle, there is no *net* change in its energy. Therefore, the left side of Eq. 2.39 equals zero, and the equation reduces to

$$W_{\text{cycle}} = Q_{\text{cycle}} \quad (2.40)$$

Equation 2.40 is an expression of the conservation of energy principle that must be satisfied by *every* thermodynamic cycle, regardless of the sequence of processes followed by the system undergoing the cycle or the nature of the substances making up the system.

Figure 2.17 provides simplified schematics of two general classes of cycles considered in this book: power cycles and refrigeration and heat pump cycles. In each case pictured, a system undergoes a cycle while communicating thermally with two bodies, one hot and the other cold. These bodies are systems located in the surroundings of the system undergoing the cycle. During each cycle there is also a net amount of energy exchanged with the surroundings by work. Carefully observe that in using the symbols  $Q_{in}$  and  $Q_{out}$  on Fig. 2.17 we have departed from the previously stated sign convention for heat transfer. In this section it is advantageous to regard  $Q_{in}$  and  $Q_{out}$  as transfers of energy in the *directions indicated by the arrows*. The direction of the net work of the cycle,  $W_{cycle}$ , is also indicated by an arrow. Finally, note that the directions of the energy transfers shown in Fig. 2.17b are opposite to those of Fig. 2.17a.

## 2.6.2 • Power Cycles

Systems undergoing cycles of the type shown in Fig. 2.17a deliver a net work transfer of energy to their surroundings during each cycle. Any such cycle is called a **power cycle**. From Eq. 2.40, the net work output equals the net heat transfer to the cycle, or

$$W_{\text{cycle}} = Q_{\text{in}} - Q_{\text{out}} \quad (\text{power cycle}) \quad (2.41)$$

where  $Q_{\text{in}}$  represents the heat transfer of energy *into* the system from the hot body, and  $Q_{\text{out}}$  represents heat transfer *out of* the system to the cold body. From Eq. 2.41 it is clear

**TAKE NOTE...**

When analyzing cycles, we normally take energy transfers as positive in the directions of arrows on a sketch of the system and write the energy balance accordingly.

that  $Q_{in}$  must be greater than  $Q_{out}$  for a *power cycle*. The energy supplied by heat transfer to a system undergoing a power cycle is normally derived from the combustion of fuel or a moderated nuclear reaction; it can also be obtained from solar radiation. The energy  $Q_{out}$  is generally discharged to the surrounding atmosphere or a nearby body of water.

The performance of a system undergoing a *power cycle* can be described in terms of the extent to which the energy added by heat,  $Q_{in}$ , is *converted* to a net work output,  $W_{cycle}$ . The extent of the energy conversion from heat to work is expressed by the following ratio, commonly called the **thermal efficiency**

### thermal efficiency

$$\eta = \frac{W_{cycle}}{Q_{in}} \quad (\text{power cycle}) \quad (2.42)$$

Introducing Eq. 2.41, an alternative form is obtained as

$$\eta = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} \quad (\text{power cycle}) \quad (2.43)$$

Since energy is conserved, it follows that the thermal efficiency can never be greater than unity (100%). However, experience with *actual* power cycles shows that the value of thermal efficiency is invariably *less* than unity. That is, not all the energy added to the system by heat transfer is converted to work; a portion is discharged to the cold body by heat transfer. Using the second law of thermodynamics, we will show in Chap. 5 that the conversion from heat to work cannot be fully accomplished by any power cycle. The thermal efficiency of *every* power cycle must be less than unity:  $\eta < 1$  (100%).

### A Power Cycle A.9 – Tabs a & b



**ENERGY & ENVIRONMENT** Today fossil-fueled power plants can have thermal efficiencies of 40%, or more. This means that up to 60% of the energy added by heat transfer during the power plant cycle is discharged from the plant other than by work, principally by heat transfer. One way power plant cooling is achieved is to use water drawn from a nearby river or lake. The water is eventually returned to the river or lake but at a higher temperature, which is a practice having several possible environmental consequences.

The return of large quantities of warm water to a river or lake can affect its ability to hold dissolved gases, including the oxygen required for aquatic life. If the return water temperature is greater than about 35°C (95°F), the dissolved oxygen may be too low to support some species of fish. If the return water temperature is too great, some species also can be stressed. As rivers and lakes become warmer, non-native species that thrive in the warmth can take over. Warmer water also fosters bacterial populations and algae growth.

Regulatory agencies have acted to limit warm water discharges from power plants, which has made cooling towers (Sec. 12.9) adjacent to power plants a common sight.

### 2.6.3 Refrigeration and Heat Pump Cycles

### refrigeration and heat pump cycles

Next, consider the **refrigeration and heat pump cycles** shown in Fig. 2.17b. For cycles of this type,  $Q_{in}$  is the energy transferred by heat *into* the system undergoing the cycle *from* the cold body, and  $Q_{out}$  is the energy discharged by heat transfer *from* the system *to* the hot body. To accomplish these energy transfers requires a net work *input*,  $W_{cycle}$ . The quantities  $Q_{in}$ ,  $Q_{out}$ , and  $W_{cycle}$  are related by the energy balance, which for refrigeration and heat pump cycles takes the form

$$W_{cycle} = Q_{out} - Q_{in} \quad (\text{refrigeration and heat pump cycles}) \quad (2.44)$$

Since  $W_{cycle}$  is positive in this equation, it follows that  $Q_{out}$  is greater than  $Q_{in}$ .

Although we have treated them as the same to this point, refrigeration and heat pump cycles actually have different objectives. The objective of a refrigeration cycle is to cool a refrigerated space or to maintain the temperature within a dwelling or other building *below* that of the surroundings. The objective of a heat pump is to maintain the temperature within a dwelling or other building *above* that of the surroundings or to provide heating for certain industrial processes that occur at elevated temperatures.

Since refrigeration and heat pump cycles have different objectives, their performance parameters, called *coefficients of performance*, are defined differently. These coefficients of performance are considered next.

### Refrigeration Cycles

The performance of *refrigeration cycles* can be described as the ratio of the amount of energy received by the system undergoing the cycle from the cold body,  $Q_{in}$ , to the net work into the system to accomplish this effect,  $W_{cycle}$ . Thus, the **coefficient of performance**,  $\beta$ , is

$$\beta = \frac{Q_{in}}{W_{cycle}} \quad (\text{refrigeration cycle}) \quad (2.45)$$

**coefficient of performance:  
refrigeration**

Introducing Eq. 2.44, an alternative expression for  $\beta$  is obtained as

$$\beta = \frac{Q_{in}}{Q_{out} - Q_{in}} \quad (\text{refrigeration cycles}) \quad (2.46)$$

For a household refrigerator,  $Q_{out}$  is discharged to the space in which the refrigerator is located.  $W_{cycle}$  is usually provided in the form of electricity to run the motor that drives the refrigerator.

**► FOR EXAMPLE** in a refrigerator the inside compartment acts as the cold body and the ambient air surrounding the refrigerator is the hot body. Energy  $Q_{in}$  passes to the circulating refrigerant *from* the food and other contents of the inside compartment. For this heat transfer to occur, the refrigerant temperature is necessarily below that of the refrigerator contents. Energy  $Q_{out}$  passes *to* the surrounding air. For this heat transfer to occur, the temperature of the circulating refrigerant must necessarily be above that of the surrounding air. To achieve these effects, a work *input* is required. For a refrigerator,  $W_{cycle}$  is provided in the form of electricity. ▲ ▲ ▲ ▲ ▲

### Heat Pump Cycles

The performance of *heat pumps* can be described as the ratio of the amount of energy discharged from the system undergoing the cycle to the hot body,  $Q_{out}$ , to the net work into the system to accomplish this effect,  $W_{cycle}$ . Thus, the **coefficient of performance**,  $\gamma$ , is

$$\gamma = \frac{Q_{out}}{W_{cycle}} \quad (\text{heat pump cycle}) \quad (2.47)$$

**coefficient of performance:  
heat pump**

Introducing Eq. 2.44, an alternative expression for this coefficient of performance is obtained as

$$\gamma = \frac{Q_{out}}{Q_{out} - Q_{in}} \quad (\text{heat pump cycle}) \quad (2.48)$$

From this equation it can be seen that the value of  $\gamma$  is never less than unity. For residential heat pumps, the energy quantity  $Q_{in}$  is normally drawn from the surrounding atmosphere, the ground, or a nearby body of water.  $W_{cycle}$  is usually provided by electricity.

The coefficients of performance  $\beta$  and  $\gamma$  are defined as ratios of the desired heat transfer effect to the cost in terms of work to accomplish that effect. Based on the definitions, it is desirable thermodynamically that these coefficients have values that are as large as possible. However, as discussed in Chap. 5, coefficients of performance must satisfy restrictions imposed by the second law of thermodynamics.

## 2.7 Energy Storage

In this section we consider energy storage, which is deemed a critical national need today and likely will continue to be so in years ahead. The need is widespread, including use with conventional fossil- and nuclear-fueled power plants, power plants using renewable sources like solar and wind, and countless applications in transportation, industry, business, and the home.

### 2.7.1 Overview

While aspects of the present discussion of energy storage are broadly relevant, we are mainly concerned here with storage and recapture of electricity. Electricity can be stored as internal energy, kinetic energy, and gravitational potential energy and converted back to electricity when needed. Owing to thermodynamic limitations associated with such conversions, the effects of friction and electrical resistance for instance, an overall input-to-output *loss* of electricity is *always* observed, however.

Among technically feasible storage options, economics usually determines if, when, and how, storage is implemented. For power companies, consumer demand for electricity is a key issue in storage decisions. Consumer demand varies over the day and typically is greatest in the 8 a.m. to 8 p.m. period, with demand *spikes* during that interval. Demand is least in nighttime hours, on weekends, and on major holidays. Accordingly, power companies must decide which option makes the greatest economic sense: marketing electricity as generated, storing it for later use, or a combination—and if stored, how to store it.

### 2.7.2 Storage Technologies

The focus in this section is on five storage technologies: batteries, ultra-capacitors, superconducting magnets, flywheels, and hydrogen production. Thermal storage is considered in Sec. 3.8. Pumped-hydro and compressed-air storage are considered in Sec. 4.8.3.

Batteries are a widely deployed means of electricity storage appearing in cell phones, laptop computers, automobiles, power-generating systems, and numerous other applications. Yet battery makers struggle to keep up with demands for lighter-weight, greater-capacity, longer-lasting, and more quickly recharged units. For years batteries have been the subject of vigorous research and development programs. Through these efforts, batteries have been developed providing significant improvements over the *lead-acid* batteries used for decades. These include utility-scale *sodium-sulfur* batteries and the *lithium-ion* and *nickel-metal hydride* types seen in consumer products and hybrid vehicles. Novel nanotechnology-based batteries promise even better performance: greater capacity, longer service life, and a quicker recharge time, all of which are essential for use in hybrid vehicles.

Ultra-capacitors are energy storage devices that work like large versions of common electrical capacitors. When an ultra-capacitor is charged electrically, energy is stored as a charge on the surface of a material. In contrast to batteries, ultra-capacitors require no chemical reactions and consequently enjoy a much longer service life. This

storage type is also capable of very rapid charging and discharging. Applications today include starting railroad locomotives and diesel trucks. Ultra-capacitors are also used in hybrid vehicles, where they work in tandem with batteries. In hybrids, ultra-capacitors are best suited for performing short-duration tasks, such as storing electricity from regenerative braking and delivering power for acceleration during start-stop driving, while batteries provide energy needed for sustained vehicle motion, all with less total mass and longer service life than with batteries alone.

Superconducting magnetic systems store an electrical input in the magnetic field created by flow of electric current in a coil of cryogenically cooled, superconducting material. This storage type provides power nearly instantaneously, and with very low input-to-output loss of electricity. Superconducting magnetic systems are used by high-speed magnetic-levitation trains, by utilities for power-quality control, and by industry for special applications such as microchip fabrication.

Flywheels provide another way to store an electrical input—as kinetic energy. When electricity is required, kinetic energy is drained from the spinning flywheel and provided to a generator. Flywheels typically exhibit low input-to-output loss of electricity. Flywheel storage is used, for instance, by Internet providers to protect equipment from power outages.

Hydrogen has also been proposed as an energy storage medium for electricity. With this approach, electricity is used to *dissociate* water to hydrogen via the *electrolysis* reaction,  $\text{H}_2\text{O} \rightarrow \text{H}_2 + \frac{1}{2} \text{O}_2$ . Hydrogen produced this way can be stored to meet various needs, including generating electricity by fuel cells via the *inverse* reaction:  $\text{H}_2 + \frac{1}{2} \text{O}_2 \rightarrow \text{H}_2\text{O}$ . A shortcoming of this type of storage is its characteristically significant input-to-output loss of electricity. For discussion of hydrogen production for use in fuel cell vehicles, see *Horizons* in Sec. 5.3.3.

## ► CHAPTER SUMMARY AND STUDY GUIDE

In this chapter, we have considered the concept of energy from an engineering perspective and have introduced energy balances for applying the conservation of energy principle to closed systems. A basic idea is that energy can be stored within systems in three macroscopic forms: internal energy, kinetic energy, and gravitational potential energy. Energy also can be transferred to and from systems.

Energy can be transferred to and from closed systems by two means only: work and heat transfer. Work and heat transfer are identified at the system boundary and are not properties. In mechanics, work is energy transfer associated with macroscopic forces and displacements. The thermodynamic definition of work introduced in this chapter extends the notion of work from mechanics to include other types of work. Energy transfer by heat to or from a system is due to a temperature difference between the system and its surroundings, and occurs in the direction of decreasing temperature. Heat transfer modes include conduction, radiation, and convection. These sign conventions are used for work and heat transfer:

- ▶  $W, \dot{W}$  {  $> 0$ : work done by the system  
   $< 0$ : work done on the system }
- ▶  $Q, \dot{Q}$  {  $> 0$ : heat transfer to the system  
   $< 0$ : heat transfer from the system }

Energy is an extensive property of a system. Only changes in the energy of a system have significance. Energy changes are

accounted for by the energy balance. The energy balance for a process of a closed system is Eq. 2.35 and an accompanying time rate form is Eq. 2.37. Equation 2.40 is a special form of the energy balance for a system undergoing a thermodynamic cycle.

The following checklist provides a study guide for this chapter. When your study of the text and end-of-chapter exercises has been completed, you should be able to

- ▶ write out the meanings of the terms listed in the margins throughout the chapter and understand each of the related concepts. The subset of key concepts listed below is particularly important in subsequent chapters.
- ▶ evaluate these energy quantities  
—kinetic and potential energy changes using Eqs. 2.5 and 2.10, respectively.  
—work and power using Eqs. 2.12 and 2.13, respectively.  
—expansion or compression work using Eq. 2.17
- ▶ apply closed system energy balances in each of several alternative forms, appropriately modeling the case at hand, correctly observing sign conventions for work and heat transfer, and carefully applying SI and English units.
- ▶ conduct energy analyses for systems undergoing thermodynamic cycles using Eq. 2.40, and evaluating, as appropriate, the thermal efficiencies of power cycles and coefficients of performance of refrigeration and heat pump cycles.

## ► KEY ENGINEERING CONCEPTS

kinetic energy, p. 39  
 gravitational potential energy, p. 40  
 work, p. 42  
 sign convention for work, p. 43  
 power, p. 44  
 internal energy, p. 53

heat transfer, p. 54  
 sign convention for heat transfer, p. 54  
 adiabatic, p. 55  
 first law of thermodynamics, p. 58  
 energy balance, p. 59

thermodynamic cycle, p. 70  
 power cycle, p. 71  
 refrigeration cycle, p. 72  
 heat pump cycle, p. 72

## ► KEY EQUATIONS

$\Delta E = \Delta U + \Delta KE + \Delta PE$	(2.27) p. 53	Change in total energy of a system.
$\Delta KE = KE_2 - KE_1 = \frac{1}{2}m(V_2^2 - V_1^2)$	(2.5) p. 39	Change in kinetic energy of a mass $m$ .
$\Delta PE = PE_2 - PE_1 = mg(z_2 - z_1)$	(2.10) p. 40	Change in gravitational potential energy of a mass $m$ at constant $g$ .
$E_2 - E_1 = Q - W$	(2.35a) p. 59	Energy balance for closed systems.
$\frac{dE}{dt} = \dot{Q} - \dot{W}$	(2.37) p. 60	Energy rate balance for closed systems.
$W = \int_{s_1}^{s_2} \mathbf{F} \cdot d\mathbf{s}$	(2.12) p. 42	Work due to action of a force $\mathbf{F}$ .
$\dot{W} = \mathbf{F} \cdot \mathbf{V}$	(2.13) p. 44	Power due to action of a force $\mathbf{F}$ .
$W = \int_{V_1}^{V_2} p \, dV$	(2.17) p. 46	Expansion or compression work related to fluid pressure. See Fig. 2.4.

### Thermodynamic Cycles

$W_{cycle} = Q_{in} - Q_{out}$	(2.41) p. 71	Energy balance for a <i>power cycle</i> . As in Fig. 2.17a, all quantities are regarded as positive.
$\eta = \frac{W_{cycle}}{Q_{in}}$	(2.42) p. 72	Thermal efficiency of a power cycle.
$W_{cycle} = Q_{out} - Q_{in}$	(2.44) p. 72	Energy balance for a <i>refrigeration</i> or <i>heat pump cycle</i> . As in Fig. 2.17b, all quantities are regarded as positive.
$\beta = \frac{Q_{in}}{W_{cycle}}$	(2.45) p. 73	Coefficient of performance of a refrigeration cycle.
$\gamma = \frac{Q_{out}}{W_{cycle}}$	(2.47) p. 73	Coefficient of performance of a heat pump cycle.

## ► EXERCISES: THINGS ENGINEERS THINK ABOUT

1. Why are aerodynamic drag coefficients of Formula One race cars typically much greater than for ordinary automobiles?
2. What are several things you as an individual can do to reduce energy use in your home? While meeting your transportation needs?

3. How is it possible for the temperature of air trapped in a balloon to increase? To decrease?
4. Why is it incorrect to say that a system *contains* heat?
5. What examples of heat transfer by conduction, radiation, and convection do you encounter when using a charcoal grill?
6. After running 5 miles on a treadmill at her campus rec center, Ashley observes that the treadmill belt is warm to the touch. Why is the belt warm?
7. When microwaves are beamed onto a tumor during cancer therapy to increase the tumor's temperature, this interaction is considered work and not heat transfer. Why?
8. For good acceleration, what is more important for an automobile engine, horsepower or torque?
9. Experimental molecular motors are reported to exhibit movement upon the absorption of light, thereby achieving a conversion of electromagnetic radiation into motion. Should the incident light be considered work or heat transfer?
10. Referring to Fig. 2.8, which process, A or B, has the greater heat transfer?
11. In the *differential* form of the closed system energy balance,  $dE = \delta Q - \delta W$ , why is  $d$  and not  $\delta$  used for the differential on the left?
12. When two amusement park bumper cars collide head-on and come to a stop, how do you account for the kinetic energy the pair had just before the collision?
13. What form does the energy balance take for an *isolated* system?
14. What forms of energy and energy transfer are present in the life cycle of a thunderstorm?
15. How would you define an *efficiency* for the motor of Example 2.6?
16. How much kinetic energy per unit of mass does a human sneeze develop?
17. How many tons of CO<sub>2</sub> are produced annually by a conventional automobile?

## ► PROBLEMS: DEVELOPING ENGINEERING SKILLS

### Exploring Energy Concepts

- 2.1** A baseball has a mass of 0.3 lb. What is the kinetic energy relative to home plate of a 94 mile per hour fastball, in Btu?

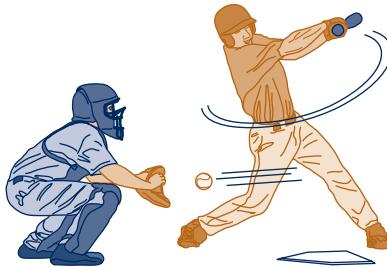


Fig. P2.1

- 2.2** An object whose mass is 400 kg is located at an elevation of 25 m above the surface of the earth. For  $g = 9.78 \text{ m/s}^2$ , determine the gravitational potential energy of the object, in kJ, relative to the surface of the earth.

- 2.3** An object whose weight is 100 lbf experiences a decrease in kinetic energy of 500 ft · lbf and an increase in potential energy of 1500 ft · lbf. The initial velocity and elevation of the object, each relative to the surface of the earth, are 40 ft/s and 30 ft, respectively. If  $g = 32.2 \text{ ft/s}^2$ , determine

- the final velocity, in ft/s.
- the final elevation, in ft.

- 2.4** A  $2.5 \times 3.5 \times 6$  in. brick whose density is 120 lb/ft<sup>3</sup> slips off the top of a building under construction and falls 69 ft. For  $g = 32.0 \text{ ft/s}^2$ , determine the change in gravitational potential energy of the brick, in ft · lbf.

- 2.5** What is the overall change in potential energy, in ft · lbf and Btu, of an automobile weighing 2500 lbf in a drive from San Diego, CA to Santa Fe, NM? Take  $g$  constant.

- 2.6** An object of mass 1000 kg, initially having a velocity of 100 m/s, decelerates to a final velocity of 20 m/s. What is the change in kinetic energy of the object, in kJ?

- 2.7** A 30-seat turboprop airliner whose mass is 14,000 kg takes off from an airport and eventually achieves its cruising speed of 620 km/h at an altitude of 10,000 m. For  $g = 9.78 \text{ m/s}^2$ , determine the change in kinetic energy and the change in gravitational potential energy of the airliner, each in kJ.

- 2.8** An automobile having a mass of 900 kg initially moves along a level highway at 100 km/h relative to the highway. It then climbs a hill whose crest is 50 m above the level highway and parks at a rest area located there. For the automobile, determine its changes in kinetic and potential energy, each in kJ. For each quantity, kinetic energy and potential energy, specify your choice of datum and reference value at that datum. Let  $g = 9.81 \text{ m/s}^2$ .

- 2.9** Vehicle crumple zones are designed to absorb energy during an impact by deforming to reduce transfer of energy to occupants. How much kinetic energy, in Btu, must a crumple zone absorb to fully protect occupants in a 3000-lb vehicle that suddenly decelerates from 10 mph to 0 mph?

- 2.10** An object whose mass is 300 lb experiences changes in its kinetic and potential energies owing to the action of a resultant force  $\mathbf{R}$ . The work done on the object by the resultant force is 140 Btu. There are no other interactions between the object and its surroundings. If the object's elevation increases by 100 ft and its final velocity is 200 ft/s, what is its initial velocity, in ft/s? Let  $g = 32.2 \text{ ft/s}^2$ .

**2.11** A disk-shaped flywheel, of uniform density  $\rho$ , outer radius  $R$ , and thickness  $w$ , rotates with an angular velocity  $\omega$ , in rad/s.

(a) Show that the moment of inertia,  $I = \int_{\text{vol}} \rho r^2 dV$ , can be expressed as  $I = \pi \rho w R^4 / 2$  and the kinetic energy can be expressed as  $\text{KE} = I\omega^2 / 2$ .

(b) For a steel flywheel rotating at 3000 RPM, determine the kinetic energy, in N · m, and the mass, in kg, if  $R = 0.38$  m and  $w = 0.025$  m.

(c) Determine the radius, in m, and the mass, in kg, of an aluminum flywheel having the same width, angular velocity, and kinetic energy as in part (b).

**2.12** Using  $\text{KE} = I\omega^2 / 2$  from Problem 2.11a, how fast would a flywheel whose moment of inertia is 200 lb · ft<sup>2</sup> have to spin, in RPM, to store an amount of kinetic energy equivalent to the potential energy of a 100 lb mass raised to an elevation of 30 ft above the surface of the earth? Let  $g = 32.2$  ft/s<sup>2</sup>.

**2.13** Two objects having different masses fall freely under the influence of gravity from rest and the same initial elevation. Ignoring the effect of air resistance, show that the magnitudes of the velocities of the objects are equal at the moment just before they strike the earth.

**2.14** An object whose mass is 50 lb is projected upward from the surface of the earth with an initial velocity of 200 ft/s. The only force acting on the object is the force of gravity. Plot the velocity of the object versus elevation. Determine the elevation of the object, in ft, when its velocity reaches zero. The acceleration of gravity is  $g = 31.5$  ft/s<sup>2</sup>.

**2.15** During the packaging process, a can of soda of mass 0.4 kg moves down a surface inclined 20° relative to the horizontal, as shown in Fig. P2.15. The can is acted upon by a constant force  $\mathbf{R}$  parallel to the incline and by the force of gravity. The magnitude of the constant force  $\mathbf{R}$  is 0.05 N. Ignoring friction between the can and the inclined surface, determine the can's change in kinetic energy, in J, and whether it is *increasing* or *decreasing*. If friction between the can and the inclined surface were significant, what effect would that have on the value of the change in kinetic energy? Let  $g = 9.8$  m/s<sup>2</sup>.

**2.16** Beginning from rest, an object of mass 200 kg slides down a 10-m-long ramp. The ramp is inclined at an angle of 40° from the horizontal. If air resistance and friction between the object and the ramp are negligible, determine the velocity of the object, in m/s, at the bottom of the ramp. Let  $g = 9.81$  m/s<sup>2</sup>.

**2.17** Jack, who weighs 150 lbf, runs 5 miles in 43 minutes on a treadmill set at a one-degree incline. The treadmill display shows he has *burned* 620 kcal. For Jack to break even calorie-wise, how much vanilla ice cream, in cups, may he have after his workout?



Fig. P2.17

### Evaluating Work

**2.18** A system with a mass of 8 kg, initially moving horizontally with a velocity of 30 m/s, experiences a constant horizontal deceleration of 3 m/s<sup>2</sup> due to the action of a resultant force. As a result, the system comes to rest. Determine the magnitude of the resultant force, in N, the amount of energy transfer by work, in kJ, and the total distance, in m, that the system travels.

**2.19** An object initially at rest experiences a constant horizontal acceleration due to the action of a resultant force applied for 10 s. The work of the resultant force is 10 Btu. The mass of the object is 55 lb. Determine the constant horizontal acceleration in ft/s<sup>2</sup>.

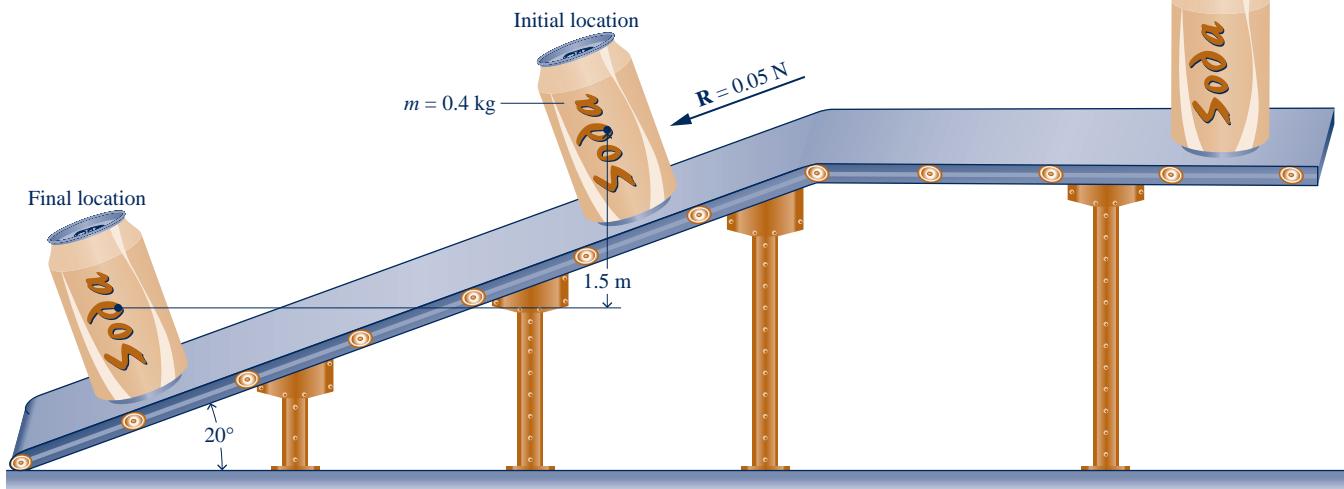


Fig. P2.15

**2.20** The drag force,  $F_d$ , imposed by the surrounding air on a vehicle moving with velocity  $V$  is given by

$$F_d = C_d A \frac{1}{2} \rho V^2$$

where  $C_d$  is a constant called the drag coefficient,  $A$  is the projected frontal area of the vehicle, and  $\rho$  is the air density. Determine the power, in hp, required to overcome aerodynamic drag for an automobile moving at (a) 25 miles per hour, (b) 70 miles per hour. Assume  $C_d = 0.28$ ,  $A = 25 \text{ ft}^2$ , and  $\rho = 0.075 \text{ lb/ft}^2$ .

**2.21** A major force opposing the motion of a vehicle is the rolling resistance of the tires,  $F_r$ , given by

$$F_r = f W$$

where  $f$  is a constant called the rolling resistance coefficient and  $W$  is the vehicle weight. Determine the power, in kW, required to overcome rolling resistance for a truck weighing 322.5 kN that is moving at 110 km/h. Let  $f = 0.0069$ .

**2.22** The two major forces opposing the motion of a vehicle moving on a level road are the rolling resistance of the tires,  $F_r$ , and the aerodynamic drag force of the air flowing around the vehicle,  $F_d$ , given respectively by

$$F_r = f W, \quad F_d = C_d A \frac{1}{2} \rho V^2$$

where  $f$  and  $C_d$  are constants known as the rolling resistance coefficient and drag coefficient, respectively,  $W$  and  $A$  are the vehicle weight and projected frontal area, respectively,  $V$  is the vehicle velocity, and  $\rho$  is the air density. For a passenger car with  $W = 3550 \text{ lbf}$ ,  $A = 23.3 \text{ ft}^2$ , and  $C_d = 0.34$ , and when  $f = 0.02$  and  $\rho = 0.08 \text{ lb/ft}^3$

- (a) determine the power required, in hp, to overcome rolling resistance and aerodynamic drag when  $V$  is 55 mi/h.
- (b) plot versus vehicle velocity ranging from 0 to 75 mi/h
- (i) the power to overcome rolling resistance, (ii) the power to overcome aerodynamic drag, and (iii) the total power, all in hp.

What implication for vehicle fuel economy can be deduced from the results of part (b)?



**2.23** Measured data for pressure versus volume during the compression of a refrigerant within the cylinder of a refrigeration compressor are given in the table below. Using data from the table, complete the following:

- (a) Determine a value of  $n$  such that the data are fit by an equation of the form  $pV^n = \text{constant}$ .
- (b) Evaluate analytically the work done on the refrigerant, in Btu, using Eq. 2.17 along with the result of part (a).
- (c) Using graphical or numerical integration of the data, evaluate the work done on the refrigerant, in Btu.
- (d) Compare the different methods for estimating the work used in parts (b) and (c). Why are they estimates?

Data Point	$p (\text{lbf/in.}^2)$	$V (\text{in.}^3)$
1	112	13.0
2	131	11.0
3	157	9.0
4	197	7.0
5	270	5.0
6	424	3.0

**2.24** Measured data for pressure versus volume during the expansion of gases within the cylinder of an internal combustion engine are given in the table below. Using data from the table, complete the following:

- (a) Determine a value of  $n$  such that the data are fit by an equation of the form,  $pV^n = \text{constant}$ .
- (b) Evaluate analytically the work done by the gases, in kJ, using Eq. 2.17 along with the result of part (a).
- (c) Using graphical or numerical integration of the data, evaluate the work done by the gases, in kJ.
- (d) Compare the different methods for estimating the work used in parts (b) and (c). Why are they estimates?

Data Point	$p (\text{bar})$	$V (\text{cm}^3)$
1	15	300
2	12	361
3	9	459
4	6	644
5	4	903
6	2	1608

**2.25** A gas in a piston–cylinder assembly undergoes a process for which the relationship between pressure and volume is  $pV^2 = \text{constant}$ . The initial pressure is 1 bar, the initial volume is  $0.1 \text{ m}^3$ , and the final pressure is 9 bar. Determine (a) the final volume, in  $\text{m}^3$ , and (b) the work for the process, in kJ.

**2.26** Carbon dioxide ( $\text{CO}_2$ ) gas within a piston–cylinder assembly undergoes an expansion from a state where  $p_1 = 20 \text{ lbf/in.}^2$ ,  $V_1 = 0.5 \text{ ft}^3$  to a state where  $p_2 = 5 \text{ lbf/in.}^2$ ,  $V_2 = 2.5 \text{ ft}^3$ . The relationship between pressure and volume during the process is  $p = A + BV$ , where  $A$  and  $B$  are constants. (a) For the  $\text{CO}_2$ , evaluate the work, in  $\text{ft} \cdot \text{lbf}$  and Btu. (b) Evaluate  $A$ , in  $\text{lbf/in.}^2$ , and  $B$ , in  $(\text{lbf/in.}^2)/\text{ft}^3$ .

**2.27** A gas in a piston–cylinder assembly undergoes a compression process for which the relation between pressure and volume is given by  $pV^n = \text{constant}$ . The initial volume is  $0.1 \text{ m}^3$ , the final volume is  $0.04 \text{ m}^3$ , and the final pressure is 2 bar. Determine the initial pressure, in bar, and the work for the process, in kJ, if (a)  $n = 0$ , (b)  $n = 1$ , (c)  $n = 1.3$ .

**2.28** Nitrogen ( $\text{N}_2$ ) gas within a piston–cylinder assembly undergoes a compression from  $p_1 = 0.2 \text{ MPa}$ ,  $V_1 = 2.75 \text{ m}^3$  to a state where  $p_2 = 2 \text{ MPa}$ . The relationship between pressure and volume during the process is  $pV^{1.35} = \text{constant}$ . For the  $\text{N}_2$ , determine (a) the volume at state 2, in  $\text{m}^3$ , and (b) the work, in kJ.

**2.29** Oxygen ( $\text{O}_2$ ) gas within a piston–cylinder assembly undergoes an expansion from a volume  $V_1 = 0.01 \text{ m}^3$  to a volume  $V_2 = 0.03 \text{ m}^3$ . The relationship between pressure and volume during the process is  $p = AV^{-1} + B$ , where  $A = 0.06 \text{ bar} \cdot \text{m}^3$  and  $B = 3.0 \text{ bar}$ . For the  $\text{O}_2$ , determine (a) the initial and final pressures, each in bar, and (b) the work, in kJ.

**2.30** A closed system consisting of 14.5 lb of air undergoes a polytropic process from  $p_1 = 80 \text{ lbf/in.}^2$ ,  $v_1 = 4 \text{ ft}^3/\text{lb}$  to a final state where  $p_2 = 20 \text{ lbf/in.}^2$ ,  $v_2 = 11 \text{ ft}^3/\text{lb}$ . Determine the amount of energy transfer by work, in Btu, for the process.

**2.31** Air contained within a piston–cylinder assembly is slowly heated. As shown in Fig. P2.31, during this process the pressure first varies linearly with volume and then remains constant. Determine the total work, in kJ.

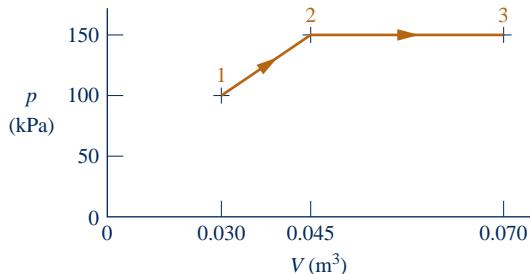


Fig. P2.31

**2.32** A gas contained within a piston–cylinder assembly undergoes three processes in series:

**Process 1–2:** Constant volume from  $p_1 = 1 \text{ bar}$ ,  $V_1 = 4 \text{ m}^3$  to state 2, where  $p_2 = 2 \text{ bar}$ .

**Process 2–3:** Compression to  $V_3 = 2 \text{ m}^3$ , during which the pressure–volume relationship is  $pV = \text{constant}$ .

**Process 3–4:** Constant pressure to state 4, where  $V_4 = 1 \text{ m}^3$ .

Sketch the processes in series on  $p$ – $V$  coordinates and evaluate the work for each process, in kJ.

**2.33** Carbon monoxide gas (CO) contained within a piston–cylinder assembly undergoes three processes in series:

**Process 1–2:** Expansion from  $p_1 = 5 \text{ bar}$ ,  $V_1 = 0.2 \text{ m}^3$  to  $V_2 = 1 \text{ m}^3$ , during which the pressure–volume relationship is  $pV = \text{constant}$ .

**Process 2–3:** Constant-volume heating from state 2 to state 3, where  $p_3 = 5 \text{ bar}$ .

**Process 3–1:** Constant-pressure compression to the initial state.

Sketch the processes in series on  $p$ – $V$  coordinates and evaluate the work for each process, in kJ.

**2.34** Air contained within a piston–cylinder assembly undergoes three processes in series:

**Process 1–2:** Compression at constant pressure from  $p_1 = 10 \text{ lbf/in.}^2$ ,  $V_1 = 4 \text{ ft}^3$  to state 2.

**Process 2–3:** Constant-volume heating to state 3, where  $p_3 = 50 \text{ lbf/in.}^2$ .

**Process 3–1:** Expansion to the initial state, during which the pressure–volume relationship is  $pV = \text{constant}$ .

Sketch the processes in series on  $p$ – $V$  coordinates. Evaluate (a) the volume at state 2, in  $\text{ft}^3$ , and (b) the work for each process, in Btu.

**2.35** The belt sander shown in Fig. P2.35 has a belt speed of 1500 ft/min. The coefficient of friction between the sander and a plywood surface being finished is 0.2. If the downward (normal) force on the sander is 15 lbf, determine (a) the

power transmitted by the belt, in Btu/s and hp, and (b) the work done in one minute of sanding, in Btu.

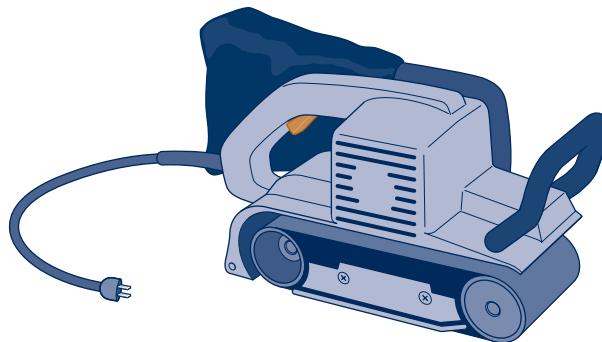


Fig. P2.35

**2.36** A 0.15-m-diameter pulley turns a belt rotating the driveshaft of a power plant pump. The torque applied by the belt on the pulley is 200 N · m, and the power transmitted is 7 kW. Determine the net force applied by the belt on the pulley, in kN, and the rotational speed of the driveshaft, in RPM.

**2.37** A 10-V battery supplies a constant current of 0.5 amp to a resistance for 30 min. (a) Determine the resistance, in ohms. (b) For the battery, determine the amount of energy transfer by work, in kJ.

**2.38** A car magazine article states that the power  $\dot{W}$  delivered by an automobile engine, in hp, is calculated by multiplying the torque  $\mathcal{T}$ , in ft · lbf, by the rotational speed of the driveshaft  $\omega$ , in RPM, and dividing by a constant:

$$\dot{W} = \frac{\mathcal{T}\omega}{C}$$

What is the value and units of the constant  $C$ ?

**2.39** The pistons of a V-6 automobile engine develop 226 hp. If the engine driveshaft rotational speed is 4700 RPM and the torque is 248 ft · lbf, what percentage of the developed power is transferred to the driveshaft? What accounts for the difference in power? Does an engine this size meet your transportation needs? Comment.

**2.40** As shown in Fig. P2.40, a steel wire suspended vertically having a cross-section area  $A$  and an initial length  $x_0$  is

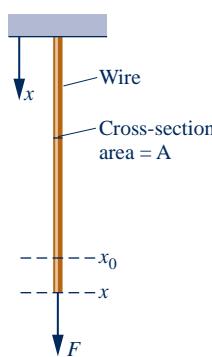


Fig. P2.40

stretched by a downward force  $F$  applied to the end of the wire. The normal stress in the wire varies linearly according to  $\sigma = C\varepsilon$ , where  $\varepsilon$  is the strain, given by  $\varepsilon = (x - x_0)/x_0$ , and  $x$  is the stretched length of the wire.  $C$  is a material constant (Young's modulus). Assuming the cross-sectional area remains constant,

- obtain an expression for the work done on the wire.
- evaluate the work done on the wire, in  $\text{ft} \cdot \text{lbf}$ , and the magnitude of the downward force, in  $\text{lbf}$ , if  $x_0 = 10 \text{ ft}$ ,  $x = 10.01 \text{ ft}$ ,  $A = 0.1 \text{ in.}^2$ , and  $C = 2.5 \times 10^7 \text{ lbf/in.}^2$ .

**2.41** A soap film is suspended on a wire frame, as shown in Fig. 2.10. The movable wire is displaced by an applied force  $F$ . If the surface tension remains constant,

- obtain an expression for the work done in stretching the film in terms of the surface tension  $\tau$ , length  $\ell$ , and a finite displacement  $\Delta x$ .
- evaluate the work done, in  $\text{J}$ , if  $\ell = 5 \text{ cm}$ ,  $\Delta x = 0.5 \text{ cm}$ , and  $\tau = 25 \times 10^{-5} \text{ N/cm}$ .

**2.42** As shown in Fig. P2.42, a spring having an initial unstretched length of  $\ell_0$  is stretched by a force  $F$  applied at its end. The stretched length is  $\ell$ . By *Hooke's law*, the force is linearly related to the spring extension by  $F = k(\ell - \ell_0)$  where  $k$  is the *stiffness*. If stiffness is constant,

- obtain an expression for the work done in changing the spring's length from  $\ell_1$  to  $\ell_2$ .
- evaluate the work done, in  $\text{J}$ , if  $\ell_0 = 3 \text{ cm}$ ,  $\ell_1 = 6 \text{ cm}$ ,  $\ell_2 = 10 \text{ cm}$ , and the stiffness is  $k = 10^4 \text{ N/m}$ .

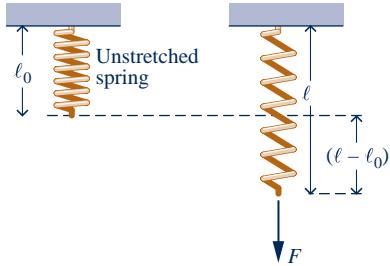


Fig. P2.42

### Evaluating Heat Transfer

**2.43** A fan forces air over a computer circuit board with surface area of  $70 \text{ cm}^2$  to avoid overheating. The air temperature is  $300 \text{ K}$  while the circuit board surface temperature is  $340 \text{ K}$ . Using data from Table 2.1, determine the largest and smallest heat transfer rates, in  $\text{W}$ , that might be encountered for this forced convection.

**2.44** As shown in Fig. P2.44, the 6-in.-thick exterior wall of a building has an average thermal conductivity of  $0.32 \text{ Btu/h} \cdot \text{ft} \cdot {}^\circ\text{R}$ . At steady state, the temperature of the wall decreases linearly from  $T_1 = 70^\circ\text{F}$  on the inner surface to  $T_2$  on the outer surface. The outside ambient air temperature is  $T_0 = 25^\circ\text{F}$  and the convective heat transfer coefficient is  $5.1 \text{ Btu/h} \cdot \text{ft}^2 \cdot {}^\circ\text{R}$ . Determine (a) the temperature  $T_2$  in  ${}^\circ\text{F}$ , and (b) the rate of heat transfer through the wall, in  $\text{Btu/h per ft}^2$  of surface area.

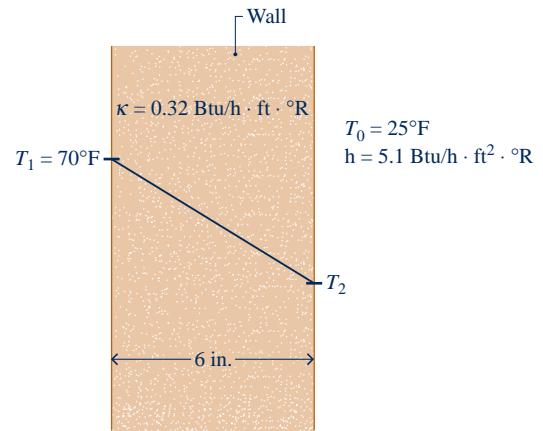


Fig. P2.44

**2.45** As shown in Fig. P2.45, an oven wall consists of a 0.25-in.-thick layer of steel ( $\kappa_s = 8.7 \text{ Btu/h} \cdot \text{ft} \cdot {}^\circ\text{R}$ ) and a layer of brick ( $\kappa_b = 0.42 \text{ Btu/h} \cdot \text{ft} \cdot {}^\circ\text{R}$ ). At steady state, a temperature decrease of  $1.2^\circ\text{F}$  occurs over the steel layer. The inner temperature of the steel layer is  $540^\circ\text{F}$ . If the temperature of the outer surface of the brick must be no greater than  $105^\circ\text{F}$  determine the minimum thickness of brick, in in., that ensures this limit is met.

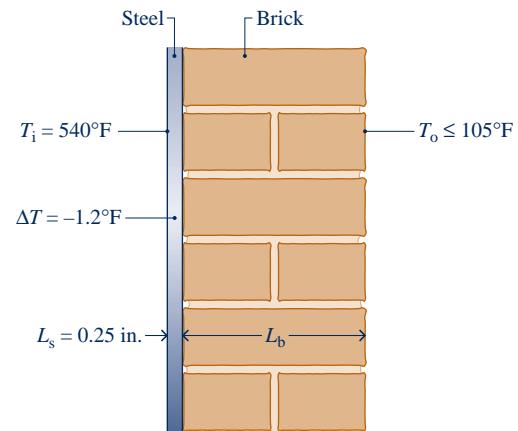


Fig. P2.45

**2.46** A composite plane wall consists of a 12-in.-thick layer of insulating concrete block ( $\kappa_c = 0.27 \text{ Btu/h} \cdot \text{ft} \cdot {}^\circ\text{R}$ ) and a 0.625-in.-thick layer of gypsum board ( $\kappa_b = 1.11 \text{ Btu/h} \cdot \text{ft} \cdot {}^\circ\text{R}$ ). The outer surface temperature of the concrete block and gypsum board are  $460^\circ\text{R}$  and  $560^\circ\text{R}$ , respectively, and there is perfect contact at the interface between the two layers. Determine at steady state the instantaneous rate of heat transfer, in  $\text{Btu/h per ft}^2$  of surface area, and the temperature, in  ${}^\circ\text{R}$ , at the interface between the concrete block and gypsum board.

**2.47** A composite plane wall consists of a 75-mm-thick layer of insulation ( $\kappa_i = 0.05 \text{ W/m} \cdot \text{K}$ ) and a 25-mm-thick layer of siding ( $\kappa = 0.10 \text{ W/m} \cdot \text{K}$ ). The inner temperature of the insulation is  $20^\circ\text{C}$ . The outer temperature of the siding is  $-13^\circ\text{C}$ . Determine at steady state (a) the temperature at the

interface of the two layers, in °C, and (b) the rate of heat transfer through the wall, in W per m<sup>2</sup> of surface area.

**2.48** An insulated frame wall of a house has an average thermal conductivity of 0.04 Btu/h · ft · °R. The thickness of the wall is 6 in. The inside air temperature is 70°F, and the heat transfer coefficient for convection between the inside air and the wall is 2 Btu/h · ft<sup>2</sup> · °R. On the outside, the ambient air temperature is 32°F and the heat transfer coefficient for convection between the wall and the outside air is 5 Btu/h · ft<sup>2</sup> · °R. Determine at steady state the rate of heat transfer through the wall, in Btu/h per ft<sup>2</sup> of surface area.

**2.49** Complete the following exercise using heat transfer relations:

(a) Referring to Fig. 2.13, determine the net rate of radiant exchange, in W, for  $\varepsilon = 0.8$ ,  $A = 0.125 \text{ m}^2$ ,  $T_b = 475 \text{ K}$ ,  $T_s = 298 \text{ K}$ .

(b) Referring to Fig. 2.14, determine the rate of convection heat transfer from the surface to the air, in W, for  $h = 10 \text{ W/m}^2 \cdot \text{K}$ ,  $A = 0.125 \text{ m}^2$ ,  $T_b = 305 \text{ K}$ ,  $T_f = 298 \text{ K}$ .

**2.50** At steady state, a spherical interplanetary electronics-laden probe having a diameter of 0.5 m transfers energy by radiation from its outer surface at a rate of 150 W. If the probe does not receive radiation from the sun or deep space, what is the surface temperature, in K? Let  $\varepsilon = 0.8$ .

**2.51** A body whose surface area is 0.5 m<sup>2</sup>, emissivity is 0.8, and temperature is 150°C is placed in a large, evacuated chamber whose walls are at 25°C. What is the rate at which radiation is emitted by the surface, in W? What is the net rate at which radiation is exchanged between the surface and the chamber walls, in W?

**2.52** The outer surface of the grill hood shown in Fig. P2.52 is at 47°C and the emissivity is 0.93. The heat transfer coefficient for convection between the hood and the surroundings at 27°C is 10 W/m<sup>2</sup> · K. Determine the net rate of heat transfer between the grill hood and the surroundings by convection and radiation, in kW per m<sup>2</sup> of surface area.

$$T_0 = 27^\circ\text{C}$$

$$h = 10 \text{ W/m}^2 \cdot \text{K}$$

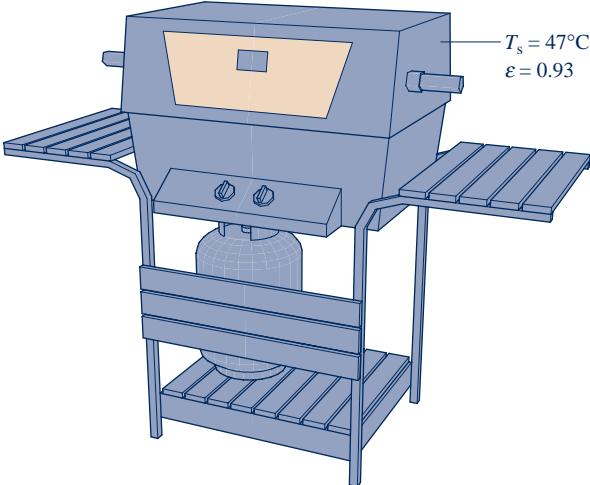


Fig. P2.52

### Using the Energy Balance

**2.53** Each line of the following table gives data for a process of a closed system. Each entry has the same energy units. Determine the missing entries.

Process	Q	W	E <sub>1</sub>	E <sub>2</sub>	ΔE
a		-20		+50	+70
b	+50		+20	+50	
c		-60		+60	+20
d		-90		+50	0
e	+50	+150	+20		

**2.54** Each line of the following table gives data, in Btu, for a process of a closed system. Determine the missing table entries, in Btu.

Process	Q	W	E <sub>1</sub>	E <sub>2</sub>	ΔE
a	+40		+15		+15
b		+5	+7	+22	
c	-4	+10		-8	
d	-10		-10		+20
e	+3	-3	+8		

**2.55** A mass of 10 kg undergoes a process during which there is heat transfer from the mass at a rate of 5 kJ per kg, an elevation decrease of 50 m, and an increase in velocity from 15 m/s to 30 m/s. The specific internal energy decreases by 5 kJ/kg and the acceleration of gravity is constant at 9.7 m/s<sup>2</sup>. Determine the work for the process, in kJ.

**2.56** As shown in Fig. P2.56, a gas contained within a piston–cylinder assembly, initially at a volume of 0.1 m<sup>3</sup>, undergoes a constant-pressure expansion at 2 bar to a final volume of 0.12 m<sup>3</sup>, while being slowly heated through the base. The change in internal energy of the gas is 0.25 kJ. The piston and cylinder walls are fabricated from heat-resistant material, and the piston moves smoothly in the cylinder. The local atmospheric pressure is 1 bar.

- (a) For the gas as the system, evaluate work and heat transfer, each in kJ.
- (b) For the piston as the system, evaluate work and change in potential energy, each in kJ.

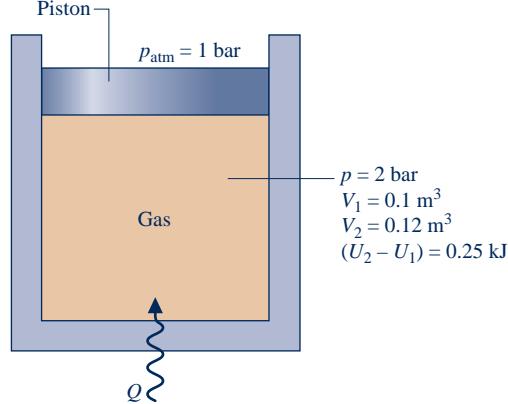


Fig. P2.56

**2.57** A gas contained in a piston–cylinder assembly undergoes two processes, A and B, between *the same end states*, 1 and 2, where  $p_1 = 1 \text{ bar}$ ,  $V_1 = 1 \text{ m}^3$ ,  $U_1 = 400 \text{ kJ}$  and  $p_2 = 10 \text{ bar}$ ,  $V_2 = 0.1 \text{ m}^3$ ,  $U_2 = 450 \text{ kJ}$ :

**Process A:** Constant-volume process from state 1 to a pressure of 10 bar, followed by a constant-pressure process to state 2.

**Process B:** Process from 1 to 2 during which the pressure–volume relation is  $pV = \text{constant}$ .

Kinetic and potential effects can be ignored. For each of the processes A and B, (a) sketch the process on  $p$ – $V$  coordinates, (b) evaluate the work, in kJ, and (c) evaluate the heat transfer, in kJ.

**2.58** A gas contained within a piston–cylinder assembly undergoes two processes, A and B, between *the same end states*, 1 and 2, where  $p_1 = 10 \text{ bar}$ ,  $V_1 = 0.1 \text{ m}^3$ ,  $U_1 = 400 \text{ kJ}$  and  $p_2 = 1 \text{ bar}$ ,  $V_2 = 1.0 \text{ m}^3$ ,  $U_2 = 200 \text{ kJ}$ :

**Process A:** Process from 1 to 2 during which the pressure–volume relation is  $pV = \text{constant}$ .

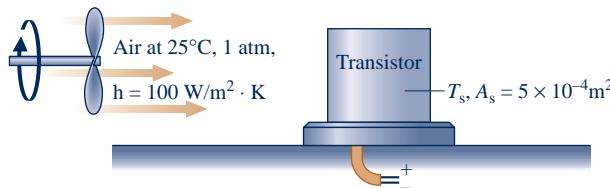
**Process B:** Constant-volume process from state 1 to a pressure of 2 bar, followed by a linear pressure–volume process to state 2.

Kinetic and potential energy effects can be ignored. For each of the processes A and B, (a) sketch the process on  $p$ – $V$  coordinates, (b) evaluate the work, in kJ, and (c) evaluate the heat transfer, in kJ.

**2.59** An electric motor draws a current of 10 amp with a voltage of 110 V. The output shaft develops a torque of  $10.2 \text{ N} \cdot \text{m}$  and a rotational speed of 1000 RPM. For operation at steady state, determine for the motor, each in kW

- (a) the electric power required.
- (b) the power developed by the output shaft.
- (c) the rate of heat transfer.

**2.60** As shown in Fig. P2.60, the outer surface of a transistor is cooled convectively by a fan-induced flow of air at a temperature of  $25^\circ\text{C}$  and a pressure of 1 atm. The transistor's outer surface area is  $5 \times 10^{-4} \text{ m}^2$ . At steady state, the electrical power to the transistor is 3 W. Negligible heat transfer occurs through the base of the transistor. The convective heat transfer coefficient is  $100 \text{ W/m}^2 \cdot \text{K}$ . Determine (a) the rate of heat transfer between the transistor and the air, in W, and (b) the temperature at the transistor's outer surface, in  $^\circ\text{C}$ .



**Fig. P2.60**

**2.61** One kg of Refrigerant 22, initially at  $p_1 = 0.9 \text{ MPa}$ ,  $u_1 = 232.92 \text{ kJ/kg}$ , is contained within a rigid closed tank. The tank is fitted with a paddle wheel that transfers energy *to* the refrigerant at a constant rate of 0.1 kW. Heat transfer *from*

the refrigerant *to* its surroundings occurs at a rate  $Kt$ , in kW, where  $K$  is a constant, in kW per minute, and  $t$  is time, in minutes. After 20 minutes of stirring, the refrigerant is at  $p_2 = 1.2 \text{ MPa}$ ,  $u_2 = 276.67 \text{ kJ/kg}$ . No overall changes in kinetic or potential energy occur. (a) For the refrigerant, determine the work and heat transfer, each in kJ. (b) Determine the value of the constant  $K$  appearing in the given heat transfer relation, in kW/min.

**2.62** A gas is contained in a vertical piston–cylinder assembly by a piston with a face area of  $40 \text{ in.}^2$  and weight of 100 lbf. The atmosphere exerts a pressure of  $14.7 \text{ lbf/in.}^2$  on top of the piston. A paddle wheel transfers 3 Btu of energy to the gas during a process in which the elevation of the piston increases by 1 ft. The piston and cylinder are poor thermal conductors, and friction between them can be neglected. Determine the change in internal energy of the gas, in Btu.

**2.63** A gas is compressed in a piston–cylinder assembly from  $p_1 = 2 \text{ bar}$  to  $p_2 = 8 \text{ bar}$ ,  $V_2 = 0.02 \text{ m}^3$  in a process during which the relation between pressure and volume is  $pV^{1.3} = \text{constant}$ . The mass of the gas is 0.2 kg. If the specific internal energy of the gas increases by 50 kJ/kg during the process, determine the heat transfer, in kJ. Kinetic and potential energy changes are negligible.

**2.64** Four kilograms of carbon monoxide (CO) is contained in a rigid tank with a volume of  $1 \text{ m}^3$ . The tank is fitted with a paddle wheel that transfers energy to the CO at a constant rate of 14 W for 1 h. During the process, the specific internal energy of the carbon monoxide increases by 10 kJ/kg. If no overall changes in kinetic and potential energy occur, determine

- (a) the specific volume at the final state, in  $\text{m}^3/\text{kg}$ .
- (b) the energy transfer by work, in kJ.
- (c) the energy transfer by heat transfer, in kJ, and the direction of the heat transfer.

**2.65** Helium gas is contained in a closed rigid tank. An electric resistor in the tank transfers energy *to* the gas at a constant rate of 1 kW. Heat transfer *from* the gas to its surroundings occurs at a rate of  $5t$  watts, where  $t$  is time, in minutes. Plot the change in energy of the helium, in kJ, for  $t \geq 0$  and comment.

**2.66** Steam in a piston–cylinder assembly undergoes a polytropic process, with  $n = 2$ , from an initial state where  $V_1 = 2 \text{ ft}^3$ ,  $p_1 = 450 \text{ lbf/in.}^2$ , and  $u_1 = 1322.4 \text{ Btu/lb}$  to a final state where  $u_2 = 1036.0 \text{ Btu/lb}$  and  $v_2 = 3.393 \text{ ft}^3/\text{lb}$ . The mass of the steam is 1.14 lb. Neglecting changes in kinetic and potential energy, determine the initial specific volume, in  $\text{ft}^3/\text{lb}$ , and the energy transfers by work and heat transfer, each in Btu.

**2.67** A gas undergoes a process from state 1, where  $p_1 = 40 \text{ lbf/in.}^2$ ,  $v_1 = 4.0 \text{ ft}^3/\text{lb}$ , to state 2, where  $p_2 = 14 \text{ lbf/in.}^2$ , according to  $pv^{1.2} = \text{constant}$ . The relationship between pressure, specific volume, and specific internal energy is

$$u = \left( 0.464 \frac{\text{Btu} \cdot \text{in.}^2}{\text{lbf} \cdot \text{ft}^3} \right) pv - 0.7095 \frac{\text{Btu}}{\text{lb}}$$

where  $p$  is in  $\text{lbf/in.}^2$ ,  $v$  is in  $\text{ft}^3/\text{lb}$ , and  $u$  is in  $\text{Btu/lb}$ . Neglecting kinetic and potential energy effects, determine the heat transfer per unit mass, in  $\text{Btu/lb}$ .

**2.68** A vertical piston–cylinder assembly with a piston of mass 25 kg and having a face area of  $0.005 \text{ m}^2$  contains air. The mass of air is 2.5 g, and initially the air occupies a volume of 2.5 liters. The atmosphere exerts a pressure of 100 kPa on the top of the piston. The volume of the air slowly decreases to  $0.001 \text{ m}^3$  as energy with a magnitude of 1 kJ is slowly removed by heat transfer. Neglecting friction between the piston and the cylinder wall, determine the change in specific internal energy of the air, in kJ/kg. Let  $g = 9.8 \text{ m/s}^2$ .

**2.69** Gaseous  $\text{CO}_2$  is contained in a vertical piston–cylinder assembly by a piston of mass 50 kg and having a face area of  $0.01 \text{ m}^2$ . The mass of the  $\text{CO}_2$  is 4 g. The  $\text{CO}_2$  initially occupies a volume of  $0.005 \text{ m}^3$  and has a specific internal energy of 657 kJ/kg. The atmosphere exerts a pressure of 100 kPa on the top of the piston. Heat transfer in the amount of 1.95 kJ occurs slowly from the  $\text{CO}_2$  to the surroundings, and the volume of the  $\text{CO}_2$  decreases to  $0.0025 \text{ m}^3$ . Friction between the piston and the cylinder wall can be neglected. The local acceleration of gravity is  $9.81 \text{ m/s}^2$ . For the  $\text{CO}_2$  determine (a) the pressure, in kPa, and (b) the final specific internal energy, in kJ/kg.

**2.70** Figure P2.70 shows a gas contained in a vertical piston–cylinder assembly. A vertical shaft whose cross-sectional area is  $0.8 \text{ cm}^2$  is attached to the top of the piston. The total mass of the piston and shaft is 25 kg. While the gas is slowly heated, the internal energy of the gas increases by 0.1 kJ, the potential energy of the piston–shaft combination increases by 0.2 kJ, and a force of 1334 N is exerted on the shaft as shown in the figure. The piston and cylinder are poor conductors, and friction between them is negligible. The local atmospheric pressure is 1 bar and  $g = 9.81 \text{ m/s}^2$ . Determine, (a) the work done by the shaft, (b) the work done in displacing the atmosphere, and (c) the heat transfer to the gas, all in kJ. (d) Using calculated and given data, develop a detailed accounting of the heat transfer of energy to the gas.

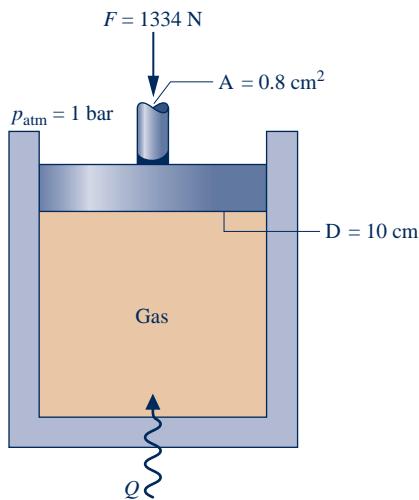


Fig. P2.70

### Analyzing Thermodynamic Cycles

**2.71** The following table gives data, in kJ, for a system undergoing a power cycle consisting of four processes in series. Determine, the (a) missing table entries, each in kJ, and (b) the thermal efficiency.

Process	$\Delta E$	$Q$	$W$
1-2	-1200	0	
2-3		800	
3-4		-200	-200
4-1	400		600

**2.72** The following table gives data, in Btu, for a system undergoing a power cycle consisting of four processes in series. Determine (a) the missing table entries, each in Btu, and (b) the thermal efficiency.

Process	$\Delta U$	$\Delta KE$	$\Delta PE$	$\Delta E$	$Q$	$W$
1-2	950	50	0		1000	
2-3		0	50	-450		450
3-4	-650		0	-600		0
4-1	200	-100	-50			0

**2.73** Figure P2.73 shows a power cycle executed by a gas in a piston–cylinder assembly. For process 1–2,  $U_2 - U_1 = 15 \text{ kJ}$ . For process 3–1,  $Q_{31} = 10 \text{ kJ}$ . There are no changes in kinetic or potential energy. Determine (a) the work for each process, in kJ, (b) the heat transfer for processes 1–2 and 2–3, each in kJ, and (c) the thermal efficiency.

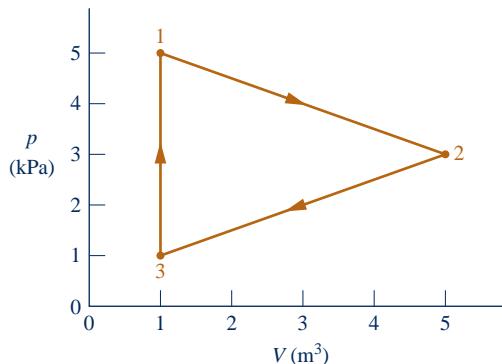


Fig. P2.73

**2.74** A gas within a piston–cylinder assembly undergoes a thermodynamic cycle consisting of three processes in series, beginning at state 1 where  $p_1 = 1 \text{ bar}$ ,  $V_1 = 1.5 \text{ m}^3$ , as follows:

**Process 1–2:** Compression with  $pV = \text{constant}$ ,  $W_{12} = -104 \text{ kJ}$ ,  $U_1 = 512 \text{ kJ}$ ,  $U_2 = 690 \text{ kJ}$ .

**Process 2–3:**  $W_{23} = 0$ ,  $Q_{23} = -150 \text{ kJ}$ .

**Process 3–1:**  $W_{31} = +50 \text{ kJ}$ .

There are no changes in kinetic or potential energy. (a) Determine  $Q_{12}$ ,  $Q_{31}$ , and  $U_3$ , each in kJ. (b) Can this cycle be a power cycle? Explain.

**2.75** A gas within a piston–cylinder assembly undergoes a thermodynamic cycle consisting of three processes:

**Process 1–2:** Compression with  $pV = \text{constant}$ , from  $p_1 = 1 \text{ bar}$ ,  $V_1 = 2 \text{ m}^3$  to  $V_2 = 0.2 \text{ m}^3$ ,  $U_2 - U_1 = 100 \text{ kJ}$ .

**Process 2–3:** Constant volume to  $p_3 = p_1$ .

**Process 3–1:** Constant-pressure and adiabatic process.

There are no significant changes in kinetic or potential energy. Determine the net work of the cycle, in kJ, and the heat transfer for process 2–3, in kJ. Is this a power cycle or a refrigeration cycle? Explain.

**2.76** A gas within a piston–cylinder assembly undergoes a thermodynamic cycle consisting of three processes:

**Process 1–2:** Constant volume,  $V = 0.028 \text{ m}^3$ ,  $U_2 - U_1 = 26.4 \text{ kJ}$ .

**Process 2–3:** Expansion with  $pV = \text{constant}$ ,  $U_3 = U_2$ .

**Process 3–1:** Constant pressure,  $p = 1.4 \text{ bar}$ ,  $W_{31} = -10.5 \text{ kJ}$ .

There are no significant changes in kinetic or potential energy.

(a) Sketch the cycle on a  $p$ – $V$  diagram.

(b) Calculate the net work for the cycle, in kJ.

(c) Calculate the heat transfer for process 2–3, in kJ.

(d) Calculate the heat transfer for process 3–1, in kJ.

Is this a power cycle or a refrigeration cycle?

**2.77** As shown in Fig. P2.77, a gas within a piston–cylinder assembly undergoes a thermodynamic cycle consisting of three processes in series:

**Process 1–2:** Compression with  $U_2 = U_1$ .

**Process 2–3:** Constant-volume cooling to  $p_3 = 140 \text{ kPa}$ ,  $V_3 = 0.028 \text{ m}^3$ .

**Process 3–1:** Constant-pressure expansion with  $W_{31} = 10.5 \text{ kJ}$ .

For the cycle,  $W_{\text{cycle}} = -8.3 \text{ kJ}$ . There are no changes in kinetic or potential energy. Determine (a) the volume at state 1, in  $\text{m}^3$ , (b) the work and heat transfer for process 1–2, each in kJ. (c) Can this be a power cycle? A refrigeration cycle? Explain.

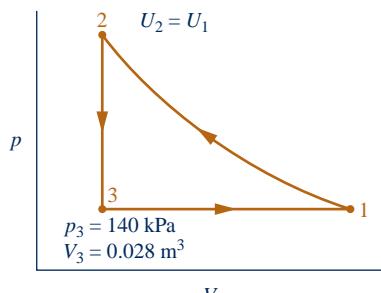


Fig. P2.77

**2.78** For a power cycle operating as in Fig. 2.17a, the heat transfers are  $Q_{\text{in}} = 75 \text{ kJ}$  and  $Q_{\text{out}} = 50 \text{ kJ}$ . Determine the net work, in kJ, and the thermal efficiency.

**2.79** The thermal efficiency of a power cycle operating as shown in Fig. 2.17a is 30%, and  $Q_{\text{out}}$  is 20 kJ. Determine the net work developed and the heat transfer  $Q_{\text{in}}$ , each in kJ.

**2.80** For a power cycle operating as in Fig. 2.17a,  $W_{\text{cycle}} = 800 \text{ Btu}$  and  $Q_{\text{out}} = 1800 \text{ Btu}$ . What is the thermal efficiency?

**2.81** A system undergoing a power cycle requires an energy input by heat transfer of  $10^4 \text{ Btu}$  for each  $\text{kW} \cdot \text{h}$  of net work developed. Determine the thermal efficiency.

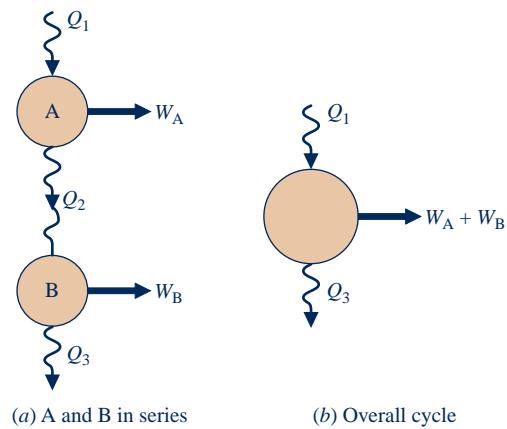
**2.82** A power cycle receives energy by heat transfer from the combustion of fuel and develops power at a net rate of 150 MW. The thermal efficiency of the cycle is 40%.

(a) Determine the net rate at which the cycle receives energy by heat transfer, in MW.

(b) For 8000 hours of operation annually, determine the net work output, in  $\text{kW} \cdot \text{h}$  per year.

(c) Evaluating the net work output at \$0.08 per  $\text{kW} \cdot \text{h}$ , determine the value of net work, in \$ per year.

**2.83** Figure P2.83 shows two power cycles, A and B, operating in series, with the energy transfer by heat *into* cycle B equal in magnitude to the energy transfer by heat *from* cycle A. All energy transfers are positive in the directions of the arrows. Determine an expression for the thermal efficiency of an *overall* cycle consisting of cycles A and B together in terms of their individual thermal efficiencies.



(a) A and B in series

(b) Overall cycle

Fig. P2.83

**2.84** Shown in Fig. P2.84 is a *cogeneration* power plant operating in a thermodynamic cycle at steady state. The plant provides electricity to a community at a rate of 80 MW. The energy discharged from the power plant by heat transfer is denoted on the figure by  $\dot{Q}_{\text{out}}$ . Of this, 70 MW is provided to the community for water heating and the remainder is discarded to the environment without use. The electricity is valued at \$0.08 per  $\text{kW} \cdot \text{h}$ . If the cycle thermal efficiency is 40%, determine the (a) rate energy is added by heat transfer,  $\dot{Q}_{\text{in}}$ , in MW, (b) rate energy is discarded to the environment, in MW, and (c) value of the electricity generated, in \$ per year.

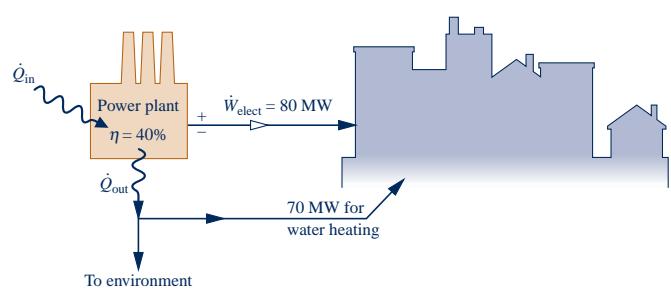


Fig. P2.84

**2.85** A refrigeration cycle operating as shown in Fig. 2.17b has  $Q_{\text{out}} = 1000 \text{ Btu}$  and  $W_{\text{cycle}} = 300 \text{ Btu}$ . Determine the coefficient of performance for the cycle.

**2.86** A refrigeration cycle operating as shown in Fig. 2.17b has a coefficient of performance  $\beta = 1.8$ . For the cycle,  $Q_{\text{out}} = 250 \text{ kJ}$ . Determine  $Q_{\text{in}}$  and  $W_{\text{cycle}}$ , each in kJ.

**2.87** The refrigerator shown in Fig. P2.87 steadily receives a power input of 0.15 kW while rejecting energy by heat transfer to the surroundings at a rate of 0.6 kW. Determine the rate at which energy is removed by heat transfer from the refrigerated space, in kW, and the refrigerator's coefficient of performance.

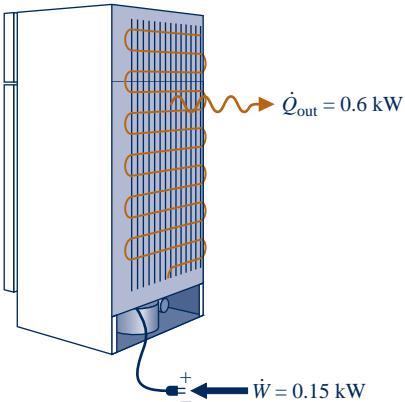


Fig. P2.87

**2.88** For a refrigerator with automatic defrost and a top-mounted freezer, the annual cost of electricity is \$55. (a) Evaluating electricity at 8 cents per  $\text{kW} \cdot \text{h}$ , determine the refrigerator's annual electricity requirement, in  $\text{kW} \cdot \text{h}$ . (b) If the refrigerator's coefficient of performance is 3, determine the amount of energy removed from its refrigerated space annually, in MJ.

**2.89** A household refrigerator operating steadily and with a coefficient of performance of 2.4 removes energy from a refrigerated space at a rate of 600 Btu/h. Evaluating electricity at \$0.08 per  $\text{kW} \cdot \text{h}$ , determine the cost of electricity in a month when the refrigerator operates for 360 hours.

**2.90** A heat pump cycle operating at steady state receives energy by heat transfer from well water at  $10^\circ\text{C}$  and discharges energy by heat transfer to a building at the rate of  $1.2 \times 10^5 \text{ kJ/h}$ . Over a period of 14 days, an electric meter records that  $1490 \text{ kW} \cdot \text{h}$  of electricity is provided to the heat pump. These are the only energy transfers involved. Determine (a) the amount of energy that the heat pump receives over the 14-day period from the well water by heat transfer, in kJ, and (b) the heat pump's coefficient of performance.

**2.91** A heat pump maintains a dwelling at  $68^\circ\text{F}$ . When operating steadily, the power input to the heat pump is 5 hp, and the heat pump receives energy by heat transfer from  $55^\circ\text{F}$  well water at a rate of 500 Btu/min.

- Determine the coefficient of performance.
- Evaluating electricity at \$0.10 per  $\text{kW} \cdot \text{h}$ , determine the cost of electricity in a month when the heat pump operates for 300 hours.

**2.92** A heat pump cycle delivers energy by heat transfer to a dwelling at a rate of 40,000 Btu/h. The coefficient of performance of the cycle is 2.8.

- Determine the power input to the cycle, in hp.
- Evaluating electricity at \$0.085 per  $\text{kW} \cdot \text{h}$ , determine the cost of electricity during the heating season when the heat pump operates for 2000 hours.

**2.93** An air-conditioning unit with a coefficient of performance of 2.93 provides 5000 Btu/h of cooling while operating during the cooling season 8 hours per day for 125 days. If you pay 10 cents per  $\text{kW} \cdot \text{h}$  for electricity, determine the cost, in dollars, for the cooling season.

### Reviewing Concepts

**2.94** Answer the following true or false. Explain.

- As a spring is compressed adiabatically, its internal energy increases.
- Energy transfers by heat are induced *only* as a result of a temperature difference between a system and its surroundings.
- The total energy of a closed system can change as a result of energy transfer across the system boundary by heat and work and energy transfer accompanying mass flow across the boundary.
- The change in kinetic energy, in Btu, of a 10-lb mass whose velocity decreases from 100 ft/s to 50 ft/s is 1.5 Btu.
- In this book, heat transfer *to* a closed system and work done *on* a closed system are each considered positive:  $Q > 0$  and  $W > 0$ , respectively.

**2.95** Answer the following true or false. Explain.

- In principle, expansion work can be evaluated using  $\int p dV$  for both actual and quasiequilibrium expansion processes.
- The change in the *internal energy* of a system between two states is the change in the total energy of the system between the two states less the changes of the system's kinetic and gravitational potential energies between these states.
- For heat pumps, the value of the coefficient of performance is *never* greater than 1.
- The change in gravitational potential energy of a 2-lb mass whose elevation decreases by 40 ft where  $g = 32.2 \text{ ft/s}^2$  is  $-2576 \text{ ft} \cdot \text{lbf}$ .
- The rate of heat transfer from a hot baked potato to ambient air is greater with forced convection than natural convection.

**2.96** Answer the following true or false. Explain.

- A system is at *steady state* if no more than one of its properties changes with time.
- Only *changes* in the energy of a system between two states have significance; no significance can be attached to the energy *at* a state.
- The rate of heat transfer by conduction through a plane wall is greater if the wall is fabricated from plywood than from brick, assuming the same wall area and temperature gradient.

- (d) If a system undergoes a process involving heat transfer with its surroundings but no work, that process is said to be *adiabatic*.
- (e) Thermal radiation can occur in a vacuum.

**2.97** Answer the following true or false. Explain.

- (a) Work is done by a system on its surroundings if the sole effect on everything external to the system could have been the raising of a weight.

- (b) Cooling of computer components achieved by a fan-induced flow of air falls in the realm of radiation heat transfer.
- (c) For every thermodynamic cycle, the *net* amounts of energy transfer by heat and work per cycle are equal.
- (d) A flywheel spinning owing to an input of electricity stores energy as internal energy.
- (e) Kinetic and potential energy are each extensive properties of a system.

## ► DESIGN & OPEN-ENDED PROBLEMS: EXPLORING ENGINEERING PRACTICE

**2.1D** Visit a local appliance store and collect data on energy requirements for different models within various classes of appliances, including but not limited to refrigerators with and without ice makers, dishwashers, and clothes washers and dryers. Prepare a memorandum ranking the different models in each class on an energy-use basis together with an accompanying discussion considering retail cost and other pertinent issues.

**2.2D** Select an item that can be produced using recycled materials such as an aluminum can, a glass bottle, or a plastic or paper grocery bag. Research the materials, energy requirements, manufacturing methods, environmental impacts, and costs associated with producing the item from raw materials versus recycled materials. Write a report including at least three references.

**2.3D** Design a go-anywhere, use-anywhere wind screen for outdoor recreational and casual-living activities, including sunbathing, reading, cooking, and picnicking. The wind screen must be lightweight, portable, easy to deploy, and low cost. A key constraint is that the wind screen can be set up anywhere, including hard surfaces such as parking lots for tailgating, wood decks, brick and concrete patios, and at the beach. A cost analysis should accompany the design.

**2.4D** In living things, energy is stored in the molecule *adenosine triphosphate*, called ATP for short. ATP is said to *act like a battery*, storing energy when it is not needed and instantly releasing energy when it is required. Investigate how energy is stored and the role of ATP in biological processes. Write a report including at least three references.

**2.5D** The global reach of the Internet supports a rapid increase in consumer and business *e-commerce*. Some say e-commerce will result in net reductions in both energy use and global climate change. Using the Internet, interviews with experts, and design-group *brainstorming*, identify several major ways e-commerce can lead to such reductions. Report your findings in a memorandum having at least three references.

**2.6D** Develop a list of the most common residential cooling options in your locale. For these options and assuming a 2300-ft<sup>2</sup> home, compare installation cost, carbon footprint, and annual electricity charges. Which option is the most

economical if a 12-year life is assumed? What if electricity costs twice its current cost? Prepare a poster presentation of your findings.

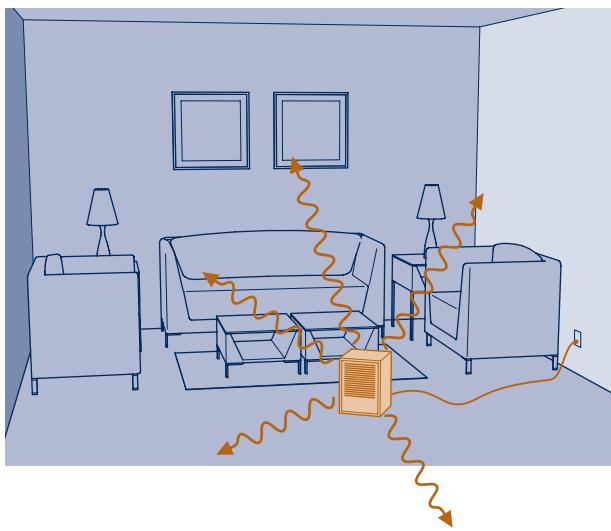
**2.7D** Homeowners concerned about interruption of electrical power from their local utility because of weather-related and utility system outages can acquire a standby generator that produces electricity using the home's existing natural gas or liquid propane (LP) fuel source. For a single-family dwelling of your choice, identify a standby generator that would provide electricity during an outage to a set of essential devices and appliances you specify. Summarize your findings in a memorandum including installed-cost and operating-cost data.

**2.8D** Despite the promise of nanotechnology (see *Horizons* in Secs. 1.6 and 2.2), some say it involves risks requiring scrutiny. For instance, the tiny size of nanoparticles may allow them to evade the natural defenses of the human body, and manufacturing at the nanoscale may lead to environmental burdens and excessive energy resource use. Research the risks that accompany widespread production and deployment of nanotechnology. For each risk identified, develop policy recommendations on safeguards for consumers and the environment. Write a report with at least three references.

**2.9D** The object of this project is to create a preliminary design of an energy-efficient dwelling at a locale of your choice. Consider factors including, but not limited to, placement of the dwelling on the lot, means for heating and cooling the dwelling, means for providing hot water, appliances, and building materials. The total cost must be no more than the average of newly constructed dwellings in the locale selected. Prepare a PowerPoint presentation of your design, including at least three references.

**2.10D** An advertisement describes a portable heater claimed to cut home heating bills by up to 50%. The heater is said to be able to heat large rooms in minutes without having a high outer-surface temperature, reducing humidity and oxygen levels, or producing carbon monoxide. A typical deployment is shown in Fig. P2.10D. The heater is an enclosure containing electrically-powered quartz infrared lamps that shine on copper tubes. Air drawn into the enclosure by a fan flows over the tubes and then is directed back into the living space. According to the advertisement, a heater capable of heating a room with up to 300 ft<sup>2</sup> of floor area costs about \$400 while

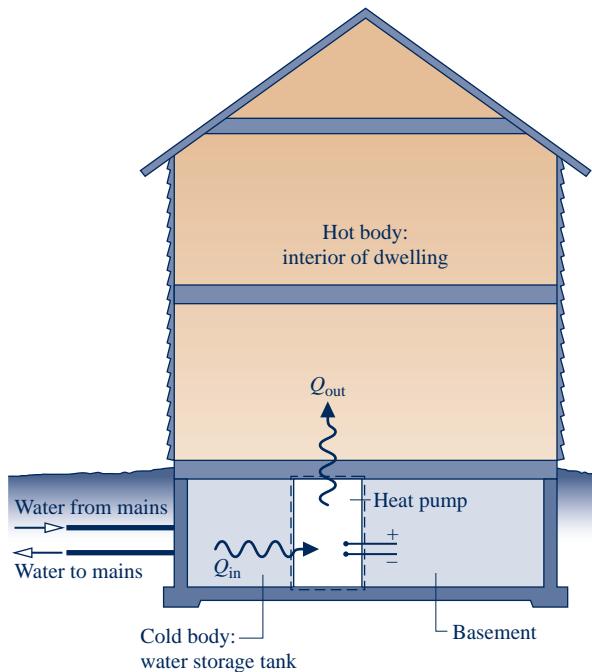
one for a room with up to 1000 ft<sup>2</sup> of floor area costs about \$500. Critically evaluate the technical and economic merit of such heaters. Write a report including at least three references.



**Fig. P2.10D**

**2.11D** An inventor proposes *borrowing* water from municipal water mains and storing it *temporarily* in a tank on the premises of a dwelling equipped with a heat pump. As shown in Fig. P2.11D, the stored water serves as the cold body for the heat pump and the dwelling itself serves as the hot body. To maintain the cold body temperature within a proper operating range, water is drawn from the mains periodically and an equal amount of water is returned to the mains. As

the invention requires no *net* water from the mains, the inventor maintains that nothing should be paid for water usage. The inventor also maintains that this approach not only gives a coefficient of performance superior to those of *air-source* heat pumps but also avoids the installation costs associated with *ground-source* heat pumps. In all, significant cost savings result, the inventor says. Critically evaluate the inventor's claims. Write a report including at least three references.



**Fig. P2.11D**





**Phases of matter—solid, liquid, vapor, are considered in Sec. 3.2.** Daryl Benson/Getty Images, Inc.

**ENGINEERING CONTEXT** To apply the energy balance to a system of interest requires knowledge of the properties of the system and how the properties are related. The **objectives** of this chapter are to introduce property relations relevant to engineering thermodynamics and provide several examples illustrating the use of the closed system energy balance together with the property relations considered in this chapter.



# 3

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# Evaluating Properties

## ► LEARNING OUTCOMES

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

- ▶ demonstrate understanding of key concepts . . . including phase and pure substance, state principle for simple compressible systems,  $p$ - $v$ - $T$  surface, saturation temperature and saturation pressure, two-phase liquid-vapor mixture, quality, enthalpy, and specific heats.
- ▶ apply the closed system energy balance with property data.
- ▶ sketch  $T$ - $v$ ,  $p$ - $v$ , and phase diagrams, and locate states on these diagrams.
- ▶ retrieve property data from Tables A-1 through A-23.
- ▶ apply the ideal gas model for thermodynamic analysis, including determining when use of the model is warranted.

## 3.1 Getting Started

In this section, we introduce concepts that support our study of property relations, including phase, pure substance, and the state principle for simple systems.

### 3.1.1 • Phase and Pure Substance

#### phase



The term **phase** refers to a quantity of matter that is homogeneous throughout in both chemical composition and physical structure. Homogeneity in physical structure means that the matter is all *solid*, or all *liquid*, or all *vapor* (or equivalently all *gas*). A system can contain one or more phases.

► **FOR EXAMPLE** a system of liquid water and water vapor (steam) contains *two* phases. A system of liquid water and ice, including the case of *slush*, also contains *two* phases. Gases, oxygen and nitrogen for instance, can be mixed in any proportion to form a *single* gas phase. Certain liquids, such as alcohol and water, can be mixed to form a *single* liquid phase. But liquids such as oil and water, which are not miscible, form *two* liquid phases. ◀◀◀◀◀

Two phases coexist during the *changes in phase* called *vaporization*, *melting*, and *sublimation*.

A **pure substance** is one that is uniform and invariable in chemical composition. A pure substance can exist in more than one phase, but its chemical composition must be the same in each phase.

► **FOR EXAMPLE** if liquid water and water vapor form a system with two phases, the system can be regarded as a pure substance because each phase has the same composition. A uniform mixture of gases can be regarded as a pure substance provided it remains a gas and doesn't react chemically. Air can be regarded as a pure substance as long as it is a mixture of gases; but if a liquid phase should form on cooling, the liquid would have a different composition than the gas phase, and the system would no longer be considered a pure substance. ◀◀◀◀◀

Changes in composition due to chemical reaction are considered in Chap. 13.

#### TAKE NOTE...

Temperature  $T$ , pressure  $p$ , specific volume  $v$ , specific internal energy  $u$ , and specific enthalpy  $h$ , are all *intensive properties*. See Secs. 1.3.3, 1.5–1.7, and 3.6.1.

#### state principle

#### simple compressible systems

### 3.1.2 • Fixing the State

The *intensive* state of a closed system at *equilibrium* is its condition as described by the values of its intensive thermodynamic properties. From observation of many thermodynamic systems, we know that not all of these properties are independent of one another, and the state can be uniquely determined by giving the values of a subset of the *independent* intensive properties. Values for all other intensive thermodynamic properties are determined once this independent subset is specified. A general rule known as the **state principle** has been developed as a guide in determining the number of independent properties required to fix the state of a system.

For the applications considered in this book, we are interested in what the state principle says about the intensive states of systems of commonly encountered pure substances, such as water or a uniform mixture of nonreacting gases. These systems are called **simple compressible systems**. Experience shows simple compressible systems occur in a wide range of engineering applications. For such systems, the state principle indicates that specification of the values for *any two independent* intensive thermodynamic properties will fix the values of all other intensive thermodynamic properties.

► **FOR EXAMPLE** in the case of a gas, temperature and another intensive property such as a specific volume might be selected as the two independent properties. The state principle then affirms that pressure, specific internal energy, and all other pertinent *intensive* properties are functions of  $T$  and  $v$ :  $p = p(T, v)$ ,  $u = u(T, v)$ , and so on. The functional relations would be developed using experimental data and would depend explicitly on the particular chemical identity of the substances making up the system. The development of such functions is discussed in Chap. 11. ◀◀◀◀◀

Intensive properties such as velocity and elevation that are assigned values relative to datums *outside* the system are excluded from present considerations. Also, as suggested by the name, changes in volume can have a significant influence on the energy of *simple compressible systems*. The only mode of energy transfer by work that can occur as a simple compressible system undergoes *quasiequilibrium* processes (Sec. 2.2.5) is associated with volume change, and is given by  $\int p \, dV$ . For further discussion of simple systems and the state principle, see the box.

#### TAKE NOTE...

For a *simple compressible system*, specification of the values for any two independent intensive thermodynamic properties will fix the values of all other intensive thermodynamic properties.

### State Principle for Simple Systems

Based on empirical evidence, there is one independent property for each way a system's energy can be varied independently. We saw in Chap. 2 that the energy of a closed system can be altered independently by heat or by work. Accordingly, an independent property can be associated with heat transfer as one way of varying the energy, and another independent property can be counted for each relevant way the energy can be changed through work. On the basis of experimental evidence, therefore, the *state principle* asserts that the number of independent properties is one plus the number of *relevant* work interactions. When counting the number of relevant work interactions, only those that would be significant in *quasiequilibrium* processes of the system need to be considered.

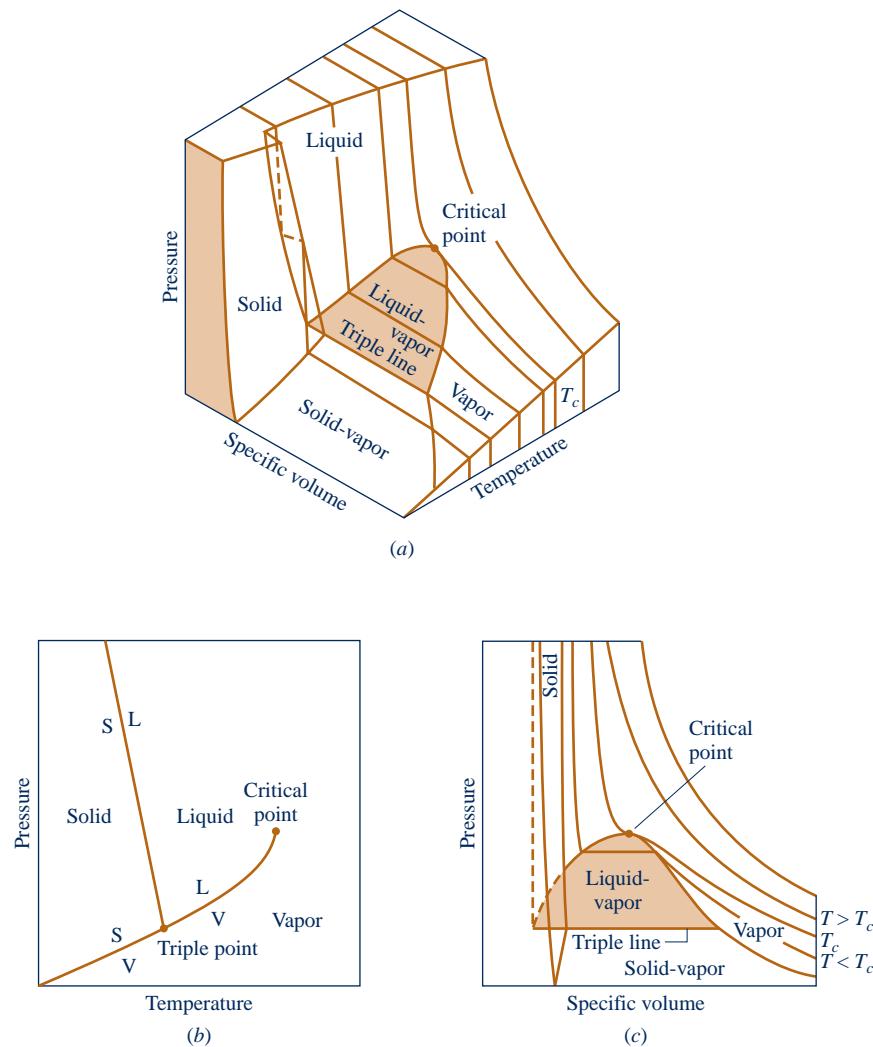
The term *simple system* is applied when there is only *one* way the system energy can be significantly altered by work as the system undergoes quasiequilibrium processes. Therefore, counting one independent property for heat transfer and another for the single work mode gives a total of two independent properties needed to fix the state of a simple system. *This is the state principle for simple systems.* Although no system is ever truly simple, many systems can be modeled as simple systems for the purpose of thermodynamic analysis. The most important of these models for the applications considered in this book is the *simple compressible system*. Other types of simple systems are simple *elastic* systems and simple *magnetic* systems.

## Evaluating Properties: General Considerations

The first part of the chapter is concerned generally with the thermodynamic properties of simple compressible systems consisting of *pure* substances. A pure substance is one of uniform and invariable chemical composition. In the second part of this chapter, we consider property evaluation for a special case: the *ideal gas model*. Property relations for systems in which composition changes by chemical reaction are considered in Chap. 13.

### 3.2 *p-v-T* Relation

We begin our study of the properties of pure, simple compressible substances and the relations among these properties with pressure, specific volume, and temperature. From experiment it is known that temperature and specific volume can be regarded



**Fig. 3.1**  $p$ - $v$ - $T$  surface and projections for a substance that expands on freezing.  
**(a)** Three-dimensional view. **(b)** Phase diagram. **(c)**  $p$ - $v$  diagram.

**$p$ - $v$ - $T$  surface**

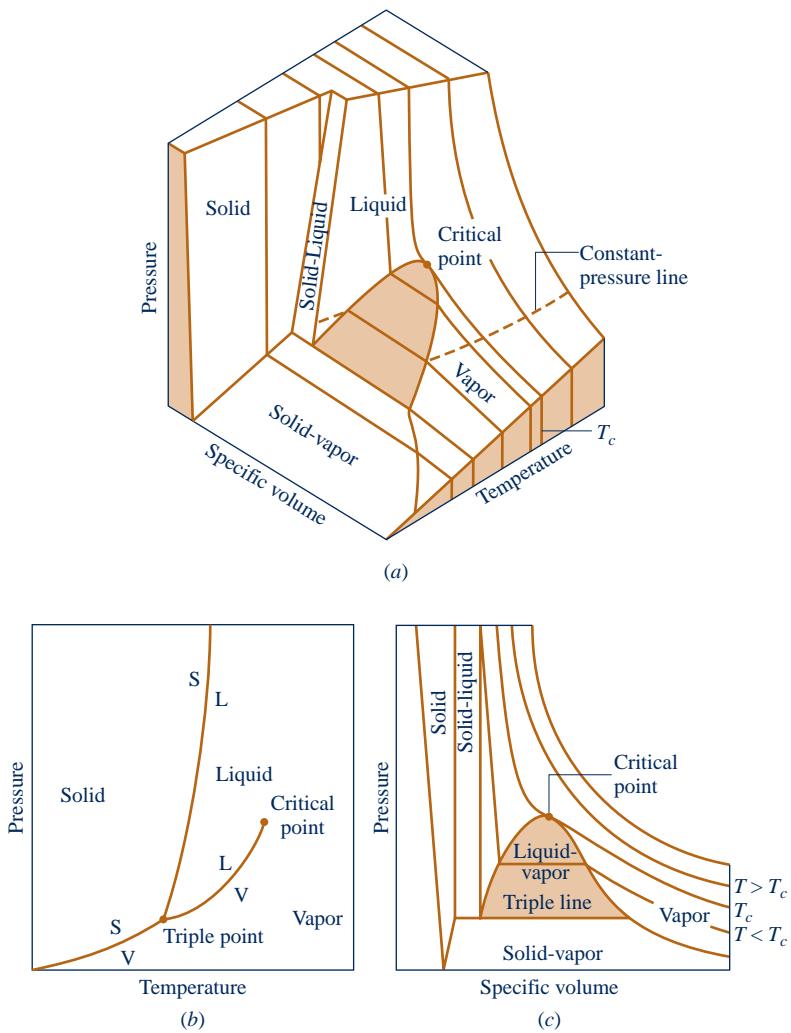
as independent and pressure determined as a function of these two:  $p = p(T, v)$ . The graph of such a function is a **surface**, the  **$p$ - $v$ - $T$  surface**.

### 3.2.1 • $p$ - $v$ - $T$ Surface

Figure 3.1 is the  $p$ - $v$ - $T$  surface of a substance such as water that expands on freezing. Figure 3.2 is for a substance that contracts on freezing, and most substances exhibit this characteristic. The coordinates of a point on the  $p$ - $v$ - $T$  surfaces represent the values that pressure, specific volume, and temperature would assume when the substance is at equilibrium.

There are regions on the  $p$ - $v$ - $T$  surfaces of Figs. 3.1 and 3.2 labeled *solid*, *liquid*, and *vapor*. In these *single-phase* regions, the state is fixed by *any* two of the properties: pressure, specific volume, and temperature, since all of these are independent when there is a single phase present. Located between the single-phase regions are **two-phase regions** where two phases exist in equilibrium: liquid-vapor, solid-liquid, and solid-vapor. Two phases can coexist during changes in phase such as vaporization, melting, and sublimation. Within the two-phase regions pressure and temperature are

**two-phase regions**



**Fig. 3.2**  $p$ - $v$ - $T$  surface and projections for a substance that contracts on freezing.

(a) Three-dimensional view. (b) Phase diagram. (c)  $p$ - $v$  diagram.

not independent; one cannot be changed without changing the other. In these regions the state cannot be fixed by temperature and pressure alone; however, the state can be fixed by specific volume and either pressure or temperature. Three phases can exist in equilibrium along the line labeled **triple line**.

A state at which a phase change begins or ends is called a **saturation state**. The dome-shaped region composed of the two-phase liquid-vapor states is called the **vapor dome**. The lines bordering the vapor dome are called saturated liquid and saturated vapor lines. At the top of the dome, where the saturated liquid and saturated vapor lines meet, is the **critical point**. The *critical temperature*  $T_c$  of a pure substance is the maximum temperature at which liquid and vapor phases can coexist in equilibrium. The pressure at the critical point is called the *critical pressure*,  $p_c$ . The specific volume at this state is the *critical specific volume*. Values of the critical point properties for a number of substances are given in Tables A-1 located in the Appendix.

The three-dimensional  $p$ - $v$ - $T$  surface is useful for bringing out the general relationships among the three phases of matter normally under consideration. However, it is often more convenient to work with two-dimensional projections of the surface. These projections are considered next.

**triple line**  
**saturation state**

**vapor dome**

**critical point**

### 3.2.2 Projections of the $p$ - $v$ - $T$ Surface

**phase diagram**

**saturation temperature**  
**saturation pressure**

**triple point**

**$p$ - $v$  diagram**

**$T$ - $v$  diagram**

#### The Phase Diagram

If the  $p$ - $v$ - $T$  surface is projected onto the pressure-temperature plane, a property diagram known as a **phase diagram** results. As illustrated by Figs. 3.1b and 3.2b, when the surface is projected in this way, the two-phase *regions* reduce to *lines*. A point on any of these lines represents all two-phase mixtures at that particular temperature and pressure.

The term **saturation temperature** designates the temperature at which a phase change takes place at a given pressure, and this pressure is called the **saturation pressure** for the given temperature. It is apparent from the phase diagrams that for each saturation pressure there is a unique saturation temperature, and conversely.

The triple *line* of the three-dimensional  $p$ - $v$ - $T$  surface projects onto a *point* on the phase diagram. This is called the **triple point**. Recall that the triple point of water is used as a reference in defining temperature scales (Sec. 1.73). By agreement, the temperature *assigned* to the triple point of water is 273.16 K (491.69°R). The *measured* pressure at the triple point of water is 0.6113 kPa (0.00602 atm).

The line representing the two-phase solid-liquid region on the phase diagram slopes to the left for substances that expand on freezing and to the right for those that contract. Although a single solid phase region is shown on the phase diagrams of Figs. 3.1 and 3.2, solids can exist in different solid phases. For example, seven different crystalline forms have been identified for water as a solid (ice).

#### $p$ - $v$ Diagram

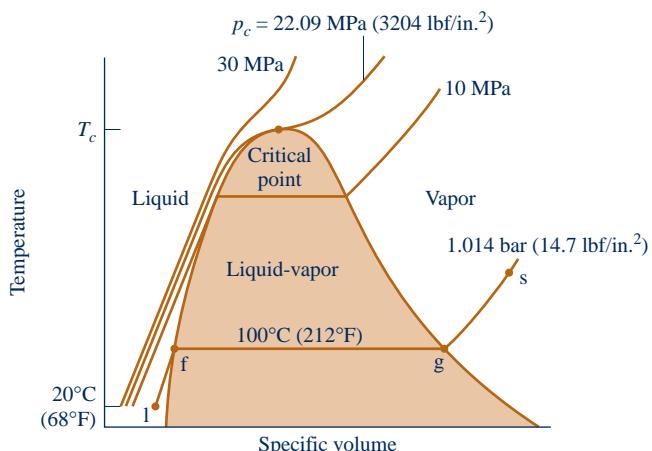
Projecting the  $p$ - $v$ - $T$  surface onto the pressure-specific volume plane results in a  **$p$ - $v$  diagram**, as shown by Figs. 3.1c and 3.2c. The figures are labeled with terms that have already been introduced.

When solving problems, a sketch of the  $p$ - $v$  diagram is frequently convenient. To facilitate the use of such a sketch, note the appearance of constant-temperature lines (isotherms). By inspection of Figs. 3.1c and 3.2c, it can be seen that for any specified temperature *less than* the critical temperature, pressure remains constant as the two-phase liquid-vapor region is traversed, but in the single-phase liquid and vapor regions the pressure decreases at fixed temperature as specific volume increases. For temperatures greater than or equal to the critical temperature, pressure decreases continuously at fixed temperature as specific volume increases. There is no passage across the two-phase liquid-vapor region. The critical isotherm passes through a point of inflection at the critical point and the slope is zero there.

#### $T$ - $v$ Diagram

Projecting the liquid, two-phase liquid-vapor, and vapor regions of the  $p$ - $v$ - $T$  surface onto the temperature-specific volume plane results in a  **$T$ - $v$  diagram** as in Fig. 3.3. Since consistent patterns are revealed in the  $p$ - $v$ - $T$  behavior of all pure substances, Fig. 3.3 showing a  $T$ - $v$  diagram for water can be regarded as representative.

As for the  $p$ - $v$  diagram, a sketch of the  $T$ - $v$  diagram is often convenient for problem solving. To facilitate the use of such a sketch, note the appearance of constant-pressure lines (isobars). For pressures *less than* the critical pressure, such as the 10 MPa isobar on Fig. 3.3, the pressure remains constant with temperature as the two-phase region is traversed. In the single-phase liquid and vapor regions the temperature increases at fixed pressure as the specific volume increases. For pressures greater than or equal to the critical pressure, such as the one marked 30 MPa on Fig. 3.3, temperature increases continuously at fixed pressure as the specific volume increases. There is no passage across the two-phase liquid-vapor region.



**Fig. 3.3** Sketch of a temperature–specific volume diagram for water showing the liquid, two-phase liquid–vapor, and vapor regions (not to scale).

The projections of the  $p$ – $v$ – $T$  surface used in this book to illustrate processes are not generally drawn to scale. A similar comment applies to other property diagrams introduced later.

## 3.3 Studying Phase Change

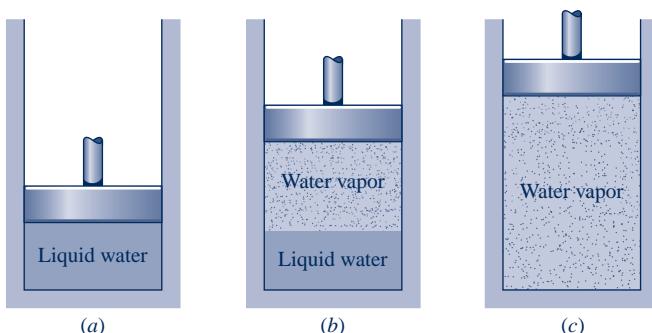
It is instructive to study the events that occur as a pure substance undergoes a phase change. To begin, consider a closed system consisting of a unit mass (1 kg or 1 lb) of liquid water at 20°C (68°F) contained within a piston–cylinder assembly, as illustrated in Fig. 3.4a. This state is represented by point l on Fig. 3.3. Suppose the water is slowly heated while its pressure is kept constant and uniform throughout at 1.014 bar (14.7 lbf/in.<sup>2</sup>).

### Liquid States

As the system is heated at constant pressure, the temperature increases considerably while the specific volume increases slightly. Eventually, the system is brought to the state represented by f on Fig. 3.3. This is the saturated liquid state corresponding to the specified pressure. For water at 1.014 bar (14.7 lbf/in.<sup>2</sup>) the saturation temperature is 100°C (212°F). The liquid states along the line segment l–f of Fig. 3.3 are sometimes referred to as **subcooled liquid** states because the temperature at these states is less than the saturation temperature at the given pressure. These states are also referred to as **compressed liquid** states because the pressure at each state is higher than the saturation pressure corresponding to the temperature at the state. The names liquid, subcooled liquid, and compressed liquid are used interchangeably.

**subcooled liquid**

**compressed liquid**



**Fig. 3.4** Illustration of constant-pressure change from liquid to vapor for water.

### two-phase liquid-vapor mixture

### quality

### superheated vapor

### Two-Phase, Liquid-Vapor Mixture

When the system is at the saturated liquid state (state f of Fig. 3.3), additional heat transfer at fixed pressure results in the formation of vapor without any change in temperature but with a considerable increase in specific volume. As shown in Fig. 3.4b, the system would now consist of a two-phase liquid–vapor mixture. When a mixture of liquid and vapor exists in equilibrium, the liquid phase is a saturated liquid and the vapor phase is a saturated vapor. If the system is heated further until the last bit of liquid has vaporized, it is brought to point g on Fig. 3.3, the saturated vapor state. The intervening **two-phase liquid–vapor mixture** states can be distinguished from one another by the *quality*, an intensive property.

For a two-phase liquid–vapor mixture, the ratio of the mass of vapor present to the total mass of the mixture is its **quality**,  $x$ . In symbols,

$$x = \frac{m_{\text{vapor}}}{m_{\text{liquid}} + m_{\text{vapor}}} \quad (3.1)$$

The value of the quality ranges from zero to unity: at saturated liquid states,  $x = 0$ , and at saturated vapor states,  $x = 1.0$ . Although defined as a ratio, the quality is frequently given as a percentage. Examples illustrating the use of quality are provided in Sec. 3.5. Similar parameters can be defined for two-phase solid–vapor and two-phase solid–liquid mixtures.

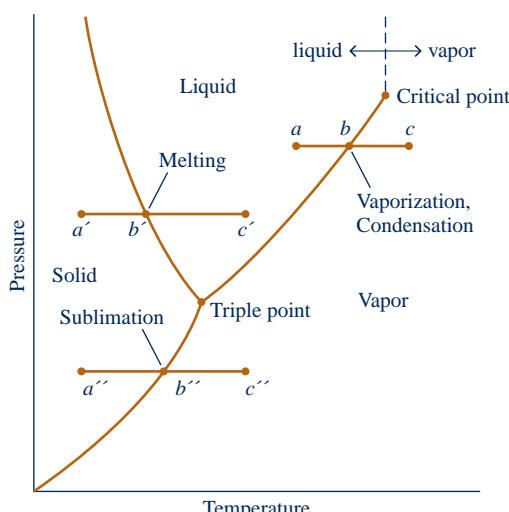
### Vapor States

Let us return to Figs. 3.3 and 3.4. When the system is at the saturated vapor state (state g on Fig. 3.3), further heating at fixed pressure results in increases in both temperature and specific volume. The condition of the system would now be as shown in Fig. 3.4c. The state labeled s on Fig. 3.3 is representative of the states that would be attained by further heating while keeping the pressure constant. A state such as s is often referred to as a **superheated vapor** state because the system would be at a temperature greater than the saturation temperature corresponding to the given pressure.

Consider next the same thought experiment at the other constant pressures labeled on Fig. 3.3, 10 MPa (1450 lbf/in.<sup>2</sup>), 22.09 MPa (3204 lbf/in.<sup>2</sup>), and 30 MPa (4351 lbf/in.<sup>2</sup>). The first of these pressures is less than the critical pressure of water, the second is the critical pressure, and the third is greater than the critical pressure. As before, let the system initially contain a liquid at 20°C (68°F). First, let us study the system if it were heated slowly at 10 MPa (1450 lbf/in.<sup>2</sup>). At this pressure, vapor would form at a higher temperature than in the previous example, because the saturation pressure is higher (refer to Fig. 3.3). In addition, there would be somewhat less of an increase in specific volume from saturated liquid to saturated vapor, as evidenced by the narrowing of the vapor dome. Apart from this, the general behavior would be the same as before.

Consider next the behavior of the system if it were heated at the critical pressure, or higher. As seen by following the critical isobar on Fig. 3.3, there would be no change in phase from liquid to vapor. At all states there would be only one phase. As shown by line a-b-c of the phase diagram sketched in Fig. 3.5, *vaporization* and the inverse process of *condensation* can occur only when the pressure is less than the critical pressure. Thus, at states where pressure is greater than the critical pressure, the terms liquid and vapor tend to lose their significance. Still, for ease of reference to such states, we use the term liquid when the temperature is less than the critical temperature and vapor when the temperature is greater than the critical temperature. This convention is labeled on Fig. 3.5.

While condensation of water vapor to liquid and further cooling to lower-temperature liquid are easily imagined and even a part of our



**Fig. 3.5** Phase diagram for water (not to scale).

### Nitrogen, Unsung Workhorse

Nitrogen is obtained using commercial air-separation technology that extracts oxygen and nitrogen from air. While applications for oxygen are widely recognized, uses for nitrogen tend to be less heralded but still touch on things people use every day.

Liquid nitrogen is used to fast-freeze foods. Tunnel freezers employ a conveyor belt to pass food through a liquid-nitrogen spray, while batch freezers immerse food in a liquid-nitrogen bath. Each freezer type operates at temperatures less than about  $-185^{\circ}\text{C}$  ( $-300^{\circ}\text{F}$ ). Liquid nitrogen is also used to preserve specimens employed in medical research and by dermatologists to remove lesions (see BIOCONNECTIONS in the next box).

As a gas, nitrogen, with other gases, is inserted into food packaging to replace oxygen-bearing air, thereby prolonging shelf-life—examples include gas-inflated bags of potato chips, salad greens, and shredded cheese. For improved tire performance, nitrogen is used to inflate the tires of airplanes and race cars. Nitrogen is among several alternative substances injected into underground rock formations to stimulate flow of trapped oil and natural gas to the surface—a procedure known as hydraulic fracturing. Chemical plants and refineries use nitrogen gas as a blanketing agent to prevent explosion. Laser-cutting machines also use nitrogen and other specialty gases.

everyday experience, liquefying gases other than water vapor may not be so familiar. Still, there are important applications for liquefied gases. See the above box for applications of nitrogen in liquid *and* gas forms.

### Melting and Sublimation

Although the phase changes from liquid to vapor (vaporization) and vapor to liquid (condensation) are of principal interest in this book, it is also instructive to consider the phase changes from solid to liquid (melting) and from solid to vapor (sublimation). To study these transitions, consider a system consisting of a unit mass of ice at a temperature below the triple point temperature. Let us begin with the case where the pressure is greater than the triple point pressure and the system is at state  $a'$  of Fig. 3.5. Suppose the system is slowly heated while maintaining the pressure constant and uniform throughout. The temperature increases with heating until point  $b'$  on Fig. 3.5 is attained. At this state the ice is a saturated solid. Additional heat transfer at fixed pressure results in the formation of liquid without any change in temperature. As the system is heated further, the ice continues to melt until eventually the last bit melts, and the system contains only saturated liquid. During the melting process the temperature and pressure remain constant. For most substances, the specific volume increases during melting, but for water the specific volume of the liquid is less than the specific volume of the solid. Further heating at fixed pressure results in an increase in temperature as the system is brought to point  $c'$  on Fig. 3.5. Next, consider the case where the pressure is less than the triple point pressure and the system is at state  $a''$  of Fig. 3.5. In this case, if the system is heated at constant pressure it passes through the two-phase solid–vapor region into the vapor region along the line  $a''-b''-c''$  shown on Fig. 3.5. That is, sublimation occurs.



**BIOCONNECTIONS** As discussed in the box devoted to nitrogen in this section, nitrogen has many applications, including medical applications. One medical application is the practice of *cryosurgery* by dermatologists. Cryosurgery entails the localized freezing of skin tissue for the removal of unwanted lesions, including precancerous lesions. For this type of surgery, liquid nitrogen is applied as a spray or with a probe. Cryosurgery is quickly performed and generally without anesthetic. Dermatologists store liquid nitrogen required for up to several months in containers called *Dewar flasks* that are similar to vacuum bottles.

**Liq\_to\_Vapor**  
A.13 – Tabs a & b  
**Vapor\_to\_Liq**  
A.14 – Tabs a & b

A

## 3.4 Retrieving Thermodynamic Properties

Thermodynamic property data can be retrieved in various ways, including tables, graphs, equations, and computer software. The emphasis of Secs. 3.5 and 3.6 to follow is on the use of *tables* of thermodynamic properties, which are commonly available for pure, simple compressible substances of engineering interest. The use of these tables is an important skill. The ability to locate states on property diagrams is an important related skill. The software available with this text, *Interactive Thermodynamics: IT*, is introduced in Sec. 3.7. *IT* is used selectively in examples and end-of-chapter problems throughout the book. Skillful use of tables and property diagrams is prerequisite for the effective use of software to retrieve thermodynamic property data.

### steam tables

Since tables for different substances are frequently set up in the same general format, the present discussion centers mainly on Tables A-2 through A-6 giving the properties of water; these are commonly referred to as the **steam tables**. Tables A-7 through A-9 for Refrigerant 22, Tables A-10 through A-12 for Refrigerant 134a, Tables A-13 through A-15 for ammonia, and Tables A-16 through A-18 for propane are used similarly, as are tables for other substances found in the engineering literature. Tables are provided in the Appendix in SI and English units. Tables in English units are designated with a letter E. For example, the steam tables in English units are Tables A-2E through A-6E.

The substances for which tabulated data are provided in this book have been selected because of their importance in current practice. Still, they are merely representative of a wide range of industrially-important substances. To meet changing requirements and address special needs, new substances are frequently introduced while others become obsolete.



**ENERGY & ENVIRONMENT** Development in the twentieth century of chlorine-containing refrigerants such as Refrigerant 12 helped pave the way for the refrigerators and air conditioners we enjoy today. Still, concern over the effect of chlorine on the earth's protective ozone layer led to international agreements to phase out these refrigerants. Substitutes for them also have come under criticism as being environmentally harmful. Accordingly, a search is on for alternatives, and *natural refrigerants* are getting a close look. Natural refrigerants include ammonia, certain hydrocarbons—propane, for example—carbon dioxide, water, and air.

Ammonia, once widely used as a refrigerant for domestic applications but dropped owing to its toxicity, is receiving renewed interest because it is both effective as a refrigerant and chlorine free. Refrigerators using propane are available on the global market despite lingering worries over flammability. Carbon dioxide is well suited for small, lightweight systems such as automotive and portable air-conditioning units. Although CO<sub>2</sub> released to the environment contributes to global climate change, only a tiny amount is present in a typical unit, and ideally even this would be contained under proper maintenance and refrigeration unit disposal protocols.

## 3.5 Evaluating Pressure, Specific Volume, and Temperature

### 3.5.1 Vapor and Liquid Tables

The properties of water vapor are listed in Tables A-4 and of liquid water in Tables A-5. These are often referred to as the *superheated vapor tables* and *compressed liquid tables*, respectively. The sketch of the phase diagram shown in Fig. 3.6 brings out the structure of these tables. Since pressure and temperature are independent properties in the single-phase liquid and vapor regions, they can be used to fix the state

in these regions. Accordingly, Tables A-4 and A-5 are set up to give values of several properties as functions of pressure and temperature. The first property listed is specific volume. The remaining properties are discussed in subsequent sections.

For each pressure listed, the values given in the superheated vapor table (Tables A-4) begin with the saturated vapor state and then proceed to higher temperatures. The data in the compressed liquid table (Tables A-5) end with saturated liquid states. That is, for a given pressure the property values are given as the temperature increases to the saturation temperature. In these tables, the value shown in parentheses after the pressure in the table heading is the corresponding saturation temperature.

**► FOR EXAMPLE** in Tables A-4 and A-5, at a pressure of 10.0 MPa, the saturation temperature is listed as 311.06°C. In Tables A-4E and A-5E, at a pressure of 500 lbf/in.<sup>2</sup>, the saturation temperature is listed as 467.1°F. ◀◀◀◀◀

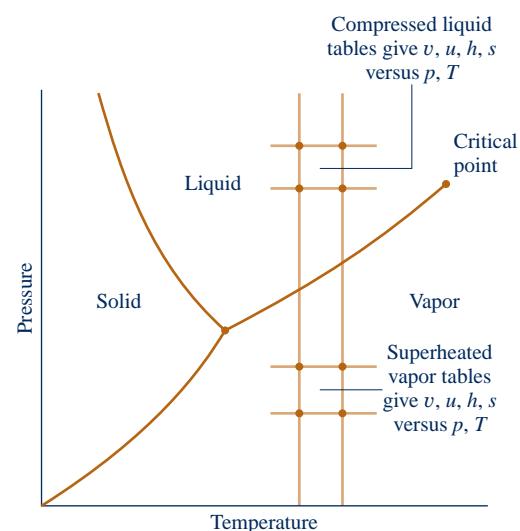
**► FOR EXAMPLE** to gain more experience with Tables A-4 and A-5 verify the following: Table A-4 gives the specific volume of water vapor at 10.0 MPa and 600°C as 0.03837 m<sup>3</sup>/kg. At 10.0 MPa and 100°C, Table A-5 gives the specific volume of liquid water as  $1.0385 \times 10^{-3}$  m<sup>3</sup>/kg. Table A-4E gives the specific volume of water vapor at 500 lbf/in.<sup>2</sup> and 600°F as 1.158 ft<sup>3</sup>/lb. At 500 lbf/in.<sup>2</sup> and 100°F, Table A-5E gives the specific volume of liquid water as 0.016106 ft<sup>3</sup>/lb. ◀◀◀◀◀

The states encountered when solving problems often do not fall exactly on the grid of values provided by property tables. *Interpolation* between adjacent table entries then becomes necessary. Care always must be exercised when interpolating table values. The tables provided in the Appendix are extracted from more extensive tables that are set up so that **linear interpolation**, illustrated in the following example, can be used with acceptable accuracy. Linear interpolation is assumed to remain valid when using the abridged tables of the text for the solved examples and end-of-chapter problems.

**► FOR EXAMPLE** let us determine the specific volume of water vapor at a state where  $p = 10$  bar and  $T = 215^\circ\text{C}$ . Shown in Fig. 3.7 is a sampling of data from Table A-4. At a pressure of 10 bar, the specified temperature of 215°C falls between the table values of 200 and 240°C, which are shown in boldface. The corresponding specific volume values are also shown in boldface. To determine the specific volume  $v$  corresponding to 215°C, we think of the *slope* of a straight line joining the adjacent table entries, as follows

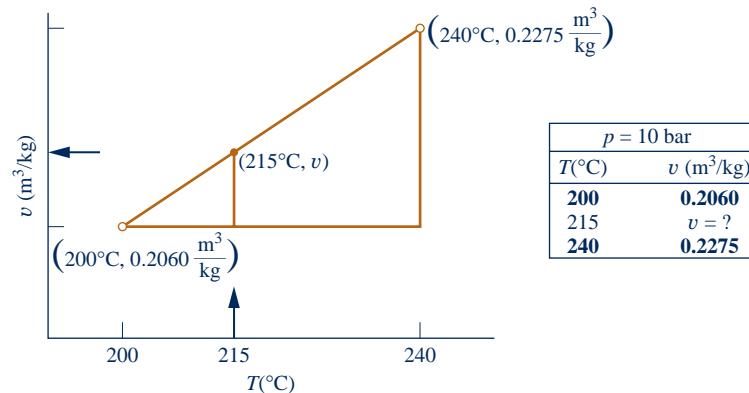
$$\text{slope} = \frac{(0.2275 - 0.2060) \text{ m}^3/\text{kg}}{(240 - 200)^\circ\text{C}} = \frac{(v - 0.2060) \text{ m}^3/\text{kg}}{(215 - 200)^\circ\text{C}}$$

Solving for  $v$ , the result is  $v = 0.2141 \text{ m}^3/\text{kg}$ . ◀◀◀◀◀



**Fig. 3.6** Sketch of the phase diagram for water used to discuss the structure of the superheated vapor and compressed liquid tables (not to scale).

**linear interpolation**



**Fig. 3.7** Illustration of linear interpolation.

The following example features the use of sketches of  $p-v$  and  $T-v$  diagrams in conjunction with tabular data to fix the end states of a process. In accord with the state principle, two independent intensive properties must be known to fix the states of the system under consideration.

### EXAMPLE 3.1

#### Heating Ammonia at Constant Pressure

A vertical piston–cylinder assembly containing 0.1 lb of ammonia, initially a saturated vapor, is placed on a hot plate. Due to the weight of the piston and the surrounding atmospheric pressure, the pressure of the ammonia is 20 lbf/in.<sup>2</sup> Heating occurs slowly, and the ammonia expands at constant pressure until the final temperature is 77°F. Show the initial and final states on  $T-v$  and  $p-v$  diagrams, and determine

- the volume occupied by the ammonia at each end state, in ft<sup>3</sup>.
- the work for the process, in Btu.

#### SOLUTION

**Known:** Ammonia is heated at constant pressure in a vertical piston–cylinder assembly from the saturated vapor state to a known final temperature.

**Find:** Show the initial and final states on  $T-v$  and  $p-v$  diagrams, and determine the volume at each end state and the work for the process.

#### Schematic and Given Data:

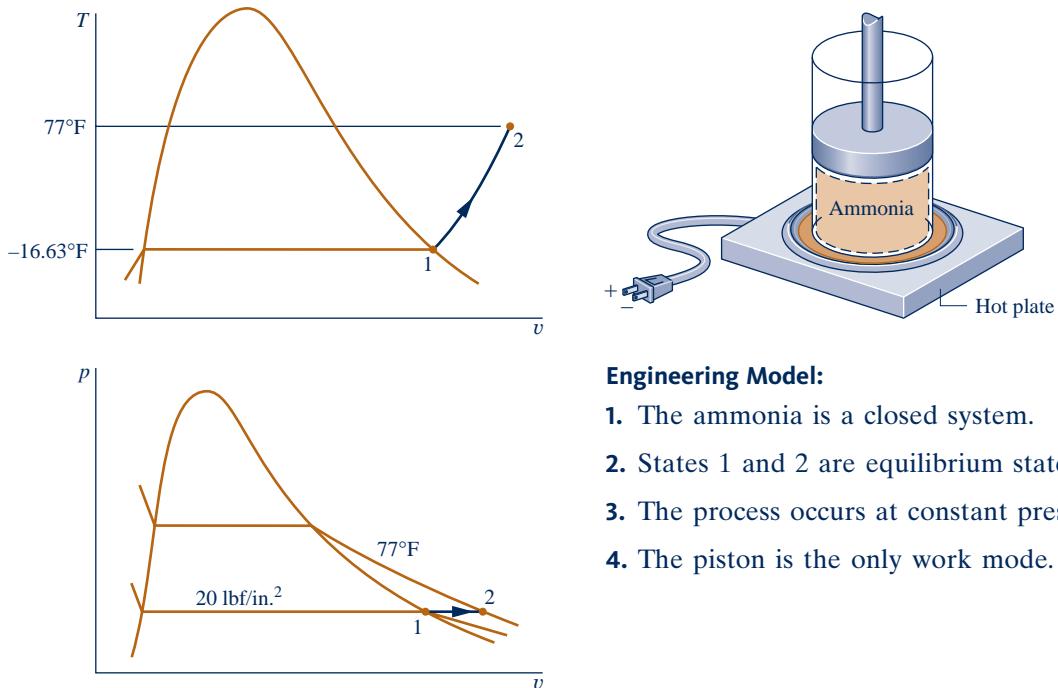


Fig. E3.1

**Analysis:** The initial state is a saturated vapor condition at 20 lbf/in.<sup>2</sup> Since the process occurs at constant pressure, the final state is in the superheated vapor region and is fixed by  $p_2 = 20$  lbf/in.<sup>2</sup> and  $T_2 = 77^\circ\text{F}$ . The initial and final states are shown on the  $T-v$  and  $p-v$  diagrams above.

- The volumes occupied by the ammonia at states 1 and 2 are obtained using the given mass and the respective specific volumes. From Table A-15E at  $p_1 = 20$  lbf/in.<sup>2</sup>, and corresponding to *Sat.* in the temperature column, we get  $v_1 = v_g = 13.497$  ft<sup>3</sup>/lb. Thus

$$\begin{aligned} V_1 &= mv_1 = (0.1 \text{ lb})(13.497 \text{ ft}^3/\text{lb}) \\ &= 1.35 \text{ ft}^3 \end{aligned}$$

#### Engineering Model:

- The ammonia is a closed system.
- States 1 and 2 are equilibrium states.
- The process occurs at constant pressure.
- The piston is the only work mode.

Interpolating in Table A-15E at  $p_2 = 20 \text{ lbf/in.}^2$  and  $T_2 = 77^\circ\text{F}$ , we get  $v_2 = 16.7 \text{ ft}^3/\text{lb}$ . Thus

$$V_2 = mv_2 = (0.1 \text{ lb})(16.7 \text{ ft}^3/\text{lb}) = 1.67 \text{ ft}^3$$

(b) In this case, the work can be evaluated using Eq. 2.17. Since the pressure is constant

$$W = \int_{V_1}^{V_2} p \, dV = p(V_2 - V_1)$$

Inserting values

$$\begin{aligned} 1 \quad W &= (20 \text{ lbf/in.}^2)(1.67 - 1.35) \text{ ft}^3 \left| \frac{144 \text{ in.}^2}{1 \text{ ft}^2} \right| \left| \frac{1 \text{ Btu}}{778 \text{ ft} \cdot \text{lbf}} \right| \\ &= 1.18 \text{ Btu} \end{aligned}$$

1 Note the use of conversion factors in this calculation.

### QuickQUIZ

If heating continues at  $20 \text{ lbf/in.}^2$  from  $T_2 = 77^\circ\text{F}$  to  $T_3 = 90^\circ\text{F}$ , determine the work for Process 2-3, in Btu. Ans. 0.15 Btu.



### Skills Developed

Ability to...

- define a closed system and identify interactions on its boundary.
- sketch  $T-v$  and  $p-v$  diagrams and locate states on them.
- evaluate work using Eq. 2.17.
- retrieve property data for ammonia at vapor states.

## 3.5.2 Saturation Tables

Tables A-2, A-3, and A-6 provide property data for water at saturated liquid, saturated vapor, and saturated solid states. Tables A-2 and A-3 are the focus of the present discussion. Each of these tables gives saturated liquid and saturated vapor data. Property values at saturated liquid and saturated vapor states are denoted by the subscripts f and g, respectively. Table A-2 is called the *temperature table*, because temperatures are listed in the first column in convenient increments. The second column gives the corresponding saturation pressures. The next two columns give, respectively, the specific volume of saturated liquid,  $v_f$ , and the specific volume of saturated vapor,  $v_g$ . Table A-3 is called the *pressure table*, because pressures are listed in the first column in convenient increments. The corresponding saturation temperatures are given in the second column. The next two columns give  $v_f$  and  $v_g$ , respectively.

The specific volume of a two-phase liquid–vapor mixture can be determined by using the saturation tables and the definition of quality given by Eq. 3.1 as follows. The total volume of the mixture is the sum of the volumes of the liquid and vapor phases

$$V = V_{\text{liq}} + V_{\text{vap}}$$

Dividing by the total mass of the mixture,  $m$ , an *average* specific volume for the mixture is obtained

$$v = \frac{V}{m} = \frac{V_{\text{liq}}}{m} + \frac{V_{\text{vap}}}{m}$$

Since the liquid phase is a saturated liquid and the vapor phase is a saturated vapor,  $V_{\text{liq}} = m_{\text{liq}}v_f$  and  $V_{\text{vap}} = m_{\text{vap}}v_g$ , so

$$v = \left( \frac{m_{\text{liq}}}{m} \right) v_f + \left( \frac{m_{\text{vap}}}{m} \right) v_g$$

Introducing the definition of quality,  $x = m_{\text{vap}}/m$ , and noting that  $m_{\text{liq}}/m = 1 - x$ , the above expression becomes

$$v = (1 - x)v_f + xv_g = v_f + x(v_g - v_f) \quad (3.2)$$

The increase in specific volume on vaporization ( $v_g - v_f$ ) is also denoted by  $v_{fg}$ .

► **FOR EXAMPLE** consider a system consisting of a two-phase liquid–vapor mixture of water at 100°C and a quality of 0.9. From Table A-2 at 100°C,  $v_f = 1.0435 \times 10^{-3} \text{ m}^3/\text{kg}$  and  $v_g = 1.673 \text{ m}^3/\text{kg}$ . The specific volume of the mixture is

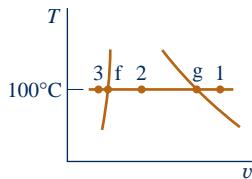
$$v = v_f + x(v_g - v_f) = 1.0435 \times 10^{-3} + (0.9)(1.673 - 1.0435 \times 10^{-3}) = 1.506 \text{ m}^3/\text{kg}$$

Similarly, the specific volume of a two-phase liquid–vapor mixture of water at 212°F and a quality of 0.9 is

$$v = v_f + x(v_g - v_f) = 0.01672 + (0.9)(26.80 - 0.01672) = 24.12 \text{ ft}^3/\text{lb}$$

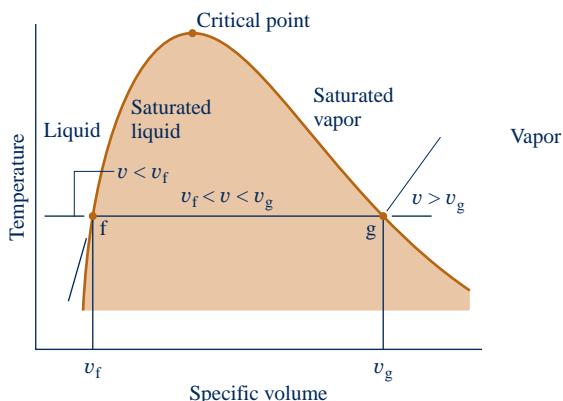
where the  $v_f$  and  $v_g$  values are obtained from Table A-2E. ◀◀◀◀◀

To facilitate locating states in the tables, it is often convenient to use values from the saturation tables together with a sketch of a  $T$ – $v$  or  $p$ – $v$  diagram. For example, if the specific volume  $v$  and temperature  $T$  are known, refer to the appropriate temperature table, Table A-2 or A-2E, and determine the values of  $v_f$  and  $v_g$ . A  $T$ – $v$  diagram illustrating these data is given in Fig. 3.8. If the given specific volume falls between  $v_f$  and  $v_g$ , the system consists of a two-phase liquid–vapor mixture, and the pressure is the saturation pressure corresponding to the given temperature. The quality can be found by solving Eq. 3.2. If the given specific volume is greater than  $v_g$ , the state is in the superheated vapor region. Then, by interpolating in Table A-4 or A-4E, the pressure and other properties listed can be determined. If the given specific volume is less than  $v_f$ , Table A-5 or A-5E would be used to determine the pressure and other properties.



► **FOR EXAMPLE** let us determine the pressure of water at each of three states defined by a temperature of 100°C and specific volumes, respectively, of  $v_1 = 2.434 \text{ m}^3/\text{kg}$ ,  $v_2 = 1.0 \text{ m}^3/\text{kg}$ , and  $v_3 = 1.0423 \times 10^{-3} \text{ m}^3/\text{kg}$ . Using the known temperature, Table A-2 provides the values of  $v_f$  and  $v_g$ :  $v_f = 1.0435 \times 10^{-3} \text{ m}^3/\text{kg}$ ,  $v_g = 1.673 \text{ m}^3/\text{kg}$ . Since  $v_1$  is greater than  $v_g$ , state 1 is in the vapor region. Table A-4 gives the pressure as 0.70 bar. Next, since  $v_2$  falls between  $v_f$  and  $v_g$ , the pressure is the saturation pressure corresponding to 100°C, which is 1.014 bar. Finally, since  $v_3$  is less than  $v_f$ , state 3 is in the liquid region. Table A-5 gives the pressure as 25 bar. ◀◀◀◀◀

The following example features the use of a sketch of the  $T$ – $v$  diagram in conjunction with tabular data to fix the end states of processes. In accord with the state principle, two independent intensive properties must be known to fix the states of the system under consideration.



**Fig. 3.8** Sketch of a  $T$ – $v$  diagram for water used to discuss locating states in the tables.

**EXAMPLE 3.2 ▶****Heating Water at Constant Volume**

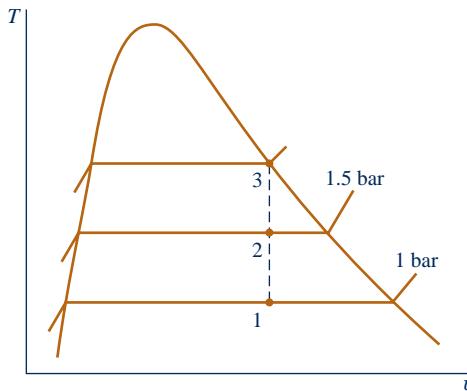
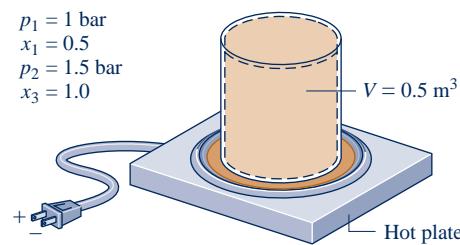
A closed, rigid container of volume  $0.5 \text{ m}^3$  is placed on a hot plate. Initially, the container holds a two-phase mixture of saturated liquid water and saturated water vapor at  $p_1 = 1 \text{ bar}$  with a quality of 0.5. After heating, the pressure in the container is  $p_2 = 1.5 \text{ bar}$ . Indicate the initial and final states on a  $T-v$  diagram, and determine

- the temperature, in  $^{\circ}\text{C}$ , at states 1 and 2.
- the mass of vapor present at states 1 and 2, in kg.
- If heating continues, determine the pressure, in bar, when the container holds only saturated vapor.

**SOLUTION**

**Known:** A two-phase liquid–vapor mixture of water in a closed, rigid container is heated on a hot plate. The initial pressure and quality and the final pressure are known.

**Find:** Indicate the initial and final states on a  $T-v$  diagram and determine at each state the temperature and the mass of water vapor present. Also, if heating continues, determine the pressure when the container holds only saturated vapor.

**Schematic and Given Data:****Engineering Model:**

- The water in the container is a closed system.
- States 1, 2, and 3 are equilibrium states.
- The volume of the container remains constant.

**Fig. E3.2**

**Analysis:** Two independent properties are required to fix states 1 and 2. At the initial state, the pressure and quality are known. As these are independent, the state is fixed. State 1 is shown on the  $T-v$  diagram in the two-phase region. The specific volume at state 1 is found using the given quality and Eq. 3.2. That is,

$$v_1 = v_{f1} + x(v_{g1} - v_{f1})$$

From Table A-3 at  $p_1 = 1 \text{ bar}$ ,  $v_{f1} = 1.0432 \times 10^{-3} \text{ m}^3/\text{kg}$  and  $v_{g1} = 1.694 \text{ m}^3/\text{kg}$ . Thus,

$$v_1 = 1.0432 \times 10^{-3} + 0.5(1.694 - 1.0432 \times 10^{-3}) = 0.8475 \text{ m}^3/\text{kg}$$

At state 2, the pressure is known. The other property required to fix the state is the specific volume  $v_2$ . Volume and mass are each constant, so  $v_2 = v_1 = 0.8475 \text{ m}^3/\text{kg}$ . For  $p_2 = 1.5 \text{ bar}$ , Table A-3 gives  $v_{f2} = 1.0582 \times 10^{-3} \text{ m}^3/\text{kg}$  and  $v_{g2} = 1.59 \text{ m}^3/\text{kg}$ . Since

①

$$v_f < v_2 < v_{g2}$$

② state 2 must be in the two-phase region as well. State 2 is also shown on the  $T-v$  diagram above.

- (a) Since states 1 and 2 are in the two-phase liquid–vapor region, the temperatures correspond to the saturation temperatures for the given pressures. Table A-3 gives

$$T_1 = 99.63^\circ\text{C} \quad \text{and} \quad T_2 = 111.4^\circ\text{C}$$

- (b) To find the mass of water vapor present, we first use the volume and the specific volume to find the *total* mass,  $m$ . That is

$$m = \frac{V}{v} = \frac{0.5 \text{ m}^3}{0.8475 \text{ m}^3/\text{kg}} = 0.59 \text{ kg}$$

Then, with Eq. 3.1 and the given value of quality, the mass of vapor at state 1 is

$$m_{g1} = x_1 m = 0.5(0.59 \text{ kg}) = 0.295 \text{ kg}$$

The mass of vapor at state 2 is found similarly using the quality  $x_2$ . To determine  $x_2$ , solve Eq. 3.2 for quality and insert specific volume data from Table A-3 at a pressure of 1.5 bar, along with the known value of  $v$ , as follows

$$\begin{aligned} x_2 &= \frac{v - v_{f2}}{v_{g2} - v_{f2}} \\ &= \frac{0.8475 - 1.0528 \times 10^{-3}}{1.159 - 1.0528 \times 10^{-3}} = 0.731 \end{aligned}$$

Then, with Eq. 3.1

$$m_{g2} = 0.731(0.59 \text{ kg}) = 0.431 \text{ kg}$$

- (c) If heating continued, state 3 would be on the saturated vapor line, as shown on the  $T$ – $v$  diagram of Fig. E3.2. Thus, the pressure would be the corresponding saturation pressure. Interpolating in Table A-3 at  $v_g = 0.8475 \text{ m}^3/\text{kg}$ , we get  $p_3 = 2.11 \text{ bar}$ .

- ① The procedure for fixing state 2 is the same as illustrated in the discussion of Fig. 3.8.
- ② Since the process occurs at constant specific volume, the states lie along a vertical line.

### Skills Developed

Ability to...

- define a closed system and identify interactions on its boundary.
- sketch a  $T$ – $v$  diagram and locate states on it.
- retrieve property data for water at liquid–vapor states, using quality.

### QuickQUIZ

If heating continues at constant specific volume from state 3 to a state where pressure is 3 bar, determine the temperature at that state, in  $^\circ\text{C}$ . **Ans.**  $282^\circ\text{C}$

## 3.6 Evaluating Specific Internal Energy and Enthalpy

### 3.6.1 Introducing Enthalpy

enthalpy

In many thermodynamic analyses the sum of the internal energy  $U$  and the product of pressure  $p$  and volume  $V$  appears. Because the sum  $U + pV$  occurs so frequently in subsequent discussions, it is convenient to give the combination a name, **enthalpy**, and a distinct symbol,  $H$ . By definition

$$H = U + pV \tag{3.3}$$

Since  $U$ ,  $p$ , and  $V$  are all properties, this combination is also a property. Enthalpy can be expressed on a unit mass basis

$$h = u + pv \tag{3.4}$$

and per mole

$$\bar{h} = \bar{u} + p\bar{v} \quad (3.5)$$

Units for enthalpy are the same as those for internal energy.

### 3.6.2 • Retrieving $u$ and $h$ Data

The property tables introduced in Sec. 3.5 giving pressure, specific volume, and temperature also provide values of specific internal energy  $u$ , enthalpy  $h$ , and entropy  $s$ . Use of these tables to evaluate  $u$  and  $h$  is described in the present section; the consideration of entropy is deferred until it is introduced in Chap. 6.

Data for specific internal energy  $u$  and enthalpy  $h$  are retrieved from the property tables in the same way as for specific volume. For saturation states, the values of  $u_f$  and  $u_g$ , as well as  $h_f$  and  $h_g$ , are tabulated versus both saturation pressure and saturation temperature. The specific internal energy for a two-phase liquid–vapor mixture is calculated for a given quality in the same way the specific volume is calculated

$$u = (1 - x)u_f + xu_g = u_f + x(u_g - u_f) \quad (3.6)$$

The increase in specific internal energy on vaporization ( $u_g - u_f$ ) is often denoted by  $u_{fg}$ . Similarly, the specific enthalpy for a two-phase liquid–vapor mixture is given in terms of the quality by

$$h = (1 - x)h_f + xh_g = h_f + x(h_g - h_f) \quad (3.7)$$

The increase in enthalpy during vaporization ( $h_g - h_f$ ) is often tabulated for convenience under the heading  $h_{fg}$ .

**► FOR EXAMPLE** to illustrate the use of Eqs. 3.6 and 3.7, we determine the specific enthalpy of Refrigerant 22 when its temperature is 12°C and its specific internal energy is 144.58 kJ/kg. Referring to Table A-7, the given internal energy value falls between  $u_f$  and  $u_g$  at 12°C, so the state is a two-phase liquid–vapor mixture. The quality of the mixture is found by using Eq. 3.6 and data from Table A-7 as follows:

$$x = \frac{u - u_f}{u_g - u_f} = \frac{144.58 - 58.77}{230.38 - 58.77} = 0.5$$

Then, with the values from Table A-7, Eq. 3.7 gives

$$\begin{aligned} h &= (1 - x)h_f + xh_g \\ &= (1 - 0.5)(59.35) + 0.5(253.99) = 156.67 \text{ kJ/kg} \end{aligned}$$

In the superheated vapor tables,  $u$  and  $h$  are tabulated along with  $v$  as functions of temperature and pressure.

**► FOR EXAMPLE** let us evaluate  $T$ ,  $v$ , and  $h$  for water at 0.10 MPa and a specific internal energy of 2537.3 kJ/kg. Turning to Table A-3, note that the given value of  $u$  is greater than  $u_g$  at 0.1 MPa ( $u_g = 2506.1$  kJ/kg). This suggests that the state lies in the superheated vapor region. By inspection of Table A-4 we get  $T = 120^\circ\text{C}$ ,  $v = 1.793 \text{ m}^3/\text{kg}$ , and  $h = 2716.6$  kJ/kg. Alternatively,  $h$  and  $u$  are related by the definition of  $h$

$$\begin{aligned} h &= u + pv \\ &= 2537.3 \frac{\text{kJ}}{\text{kg}} + \left(10^5 \frac{\text{N}}{\text{m}^2}\right) \left(1.793 \frac{\text{m}^3}{\text{kg}}\right) \left| \frac{1 \text{ kJ}}{10^3 \text{ N} \cdot \text{m}} \right| \\ &= 2537.3 + 179.3 = 2716.6 \text{ kJ/kg} \end{aligned}$$

As another illustration, consider water at a state fixed by a pressure equal to 14.7 lbf/in.<sup>2</sup> and a temperature of 250°F. From Table A-4E,  $v = 28.42 \text{ ft}^3/\text{lb}$ ,  $u = 1091.5 \text{ Btu/lb}$ , and  $h = 1168.8 \text{ Btu/lb}$ . As shown,  $h$  may be calculated from  $u$ . Thus

$$\begin{aligned} h &= u + pv \\ &= 1091.5 \frac{\text{Btu}}{\text{lb}} + \left( 14.7 \frac{\text{lbf}}{\text{in.}^2} \right) \left( 28.42 \frac{\text{ft}^3}{\text{lb}} \right) \left| \frac{144 \text{ in.}^2}{1 \text{ ft}^2} \right| \left| \frac{1 \text{ Btu}}{778 \text{ ft} \cdot \text{lbf}} \right| \\ &= 1091.5 + 77.3 = 1168.8 \text{ Btu/lb} \end{aligned}$$

**reference states**  
**reference values**

Specific internal energy and enthalpy data for liquid states of water are presented in Tables A-5. The format of these tables is the same as that of the superheated vapor tables considered previously. Accordingly, property values for liquid states are retrieved in the same manner as those of vapor states.

For water, Tables A-6 give the equilibrium properties of saturated solid and saturated vapor. The first column lists the temperature, and the second column gives the corresponding saturation pressure. These states are at pressures and temperatures *below* those at the triple point. The next two columns give the specific volume of saturated solid,  $v_i$ , and saturated vapor,  $v_g$ , respectively. The table also provides the specific internal energy, enthalpy, and entropy values for the saturated solid and the saturated vapor at each of the temperatures listed.

### 3.6.3 • Reference States and Reference Values

The values of  $u$ ,  $h$ , and  $s$  given in the property tables are not obtained by direct measurement but are calculated from other data that can be more readily determined experimentally. The computational procedures require use of the second law of thermodynamics, so consideration of these procedures is deferred to Chap. 11 after the second law has been introduced. However, because  $u$ ,  $h$ , and  $s$  are calculated, the matter of **reference states** and **reference values** becomes important and is considered briefly in the following paragraphs.

When applying the energy balance, it is *differences* in internal, kinetic, and potential energy between two states that are important, and *not* the values of these energy quantities at each of the two states.

**► FOR EXAMPLE** consider the case of potential energy. The numerical value of potential energy determined relative to the surface of the earth is not the same as the value relative to the top of a tall building at the same location. However, the difference in potential energy between any two elevations is precisely the same regardless of the datum selected, because the datum cancels in the calculation. ◀◀◀◀◀

Similarly, values can be assigned to specific internal energy and enthalpy relative to arbitrary reference values at arbitrary reference states. As for the case of potential energy considered above, the use of values of a particular property determined relative to an arbitrary reference is unambiguous as long as the calculations being performed involve only differences in that property, for then the reference value cancels. When chemical reactions take place among the substances under consideration, special attention must be given to the matter of reference states and values, however. A discussion of how property values are assigned when analyzing reactive systems is given in Chap. 13.

The tabular values of  $u$  and  $h$  for water, ammonia, propane, and Refrigerants 22 and 134a provided in the Appendix are relative to the following reference states and values. For water, the reference state is saturated liquid at 0.01°C (32.02°F). At this state, the specific internal energy is set to zero. Values of the specific enthalpy are calculated from  $h = u + pv$ , using the tabulated values for  $p$ ,  $v$ , and  $u$ . For ammonia, propane, and the refrigerants, the reference state is saturated liquid at -40°C (-40°F for the tables with English units). At this reference state the specific enthalpy is set

to zero. Values of specific internal energy are calculated from  $u = h - pv$  by using the tabulated values for  $p$ ,  $v$ , and  $h$ . Notice in Table A-7 that this leads to a negative value for internal energy at the reference state, which emphasizes that it is not the numerical values assigned to  $u$  and  $h$  at a given state that are important but their *differences* between states. The values assigned to particular states change if the reference state or reference values change, but the differences remain the same.

## 3.7 Evaluating Properties Using Computer Software

The use of computer software for evaluating thermodynamic properties is becoming prevalent in engineering. Computer software falls into two general categories: those that provide data only at individual states and those that provide property data as part of a more general simulation package. The software available with this text, *Interactive Thermodynamics: IT*, is a tool that can be used not only for routine problem solving by providing data at individual state points, but also for simulation and analysis. Software other than *IT* also can be used for these purposes. See the box for discussion of software use in engineering thermodynamics.

### Using Software In Thermodynamics

The computer software tool *Interactive Thermodynamics: IT* is available for use with this text. Used properly, *IT* provides an important adjunct to learning engineering thermodynamics and solving engineering problems. The program is built around an equation solver enhanced with thermodynamic property data and other valuable features. With *IT* you can obtain a single numerical solution or vary parameters to investigate their effects. You also can obtain graphical output, and the Windows-based format allows you to use any Windows word-processing software or spreadsheet to generate reports. Additionally, functions in *IT* can be called from *Excel* through use of the *Excel Add-in Manager*, allowing you to use these thermodynamic functions while working within *Excel*. Other features of *IT* include:

- ▶ a guided series of help screens and a number of sample solved examples to help you learn how to use the program.
- ▶ drag-and-drop templates for many of the standard problem types, including a list of assumptions that you can customize to the problem at hand.
- ▶ predetermined scenarios for power plants and other important applications.
- ▶ thermodynamic property data for water, refrigerants 22 and 134a, ammonia, air-water vapor mixtures, and a number of ideal gases.
- ▶ the capability to input user-supplied data.
- ▶ the capability to interface with user-supplied routines.

Many features of *IT* are found in the popular *Engineering Equation Solver (EES)*. Readers already proficient with *EES* may prefer its use for solving problems in this text.

The use of computer software for engineering analysis is a powerful approach. Still, there are some rules to observe:

- ▶ Software *complements* and *extends* careful analysis, but does not substitute for it.
- ▶ Computer-generated values should be checked selectively against hand-calculated, or otherwise independently determined values.
- ▶ Computer-generated plots should be studied to see if the curves appear reasonable and exhibit expected trends.

*IT* provides data for substances represented in the Appendix tables. Generally, data are retrieved by simple call statements that are placed in the workspace of the program.

► **FOR EXAMPLE** consider the two-phase, liquid–vapor mixture at state 1 of Example 3.2 for which  $p = 1 \text{ bar}$ ,  $v = 0.8475 \text{ m}^3/\text{kg}$ . The following illustrates how data for saturation temperature, quality, and specific internal energy are retrieved using *IT*. The functions for  $T$ ,  $v$ , and  $u$  are obtained by selecting Water/Steam from the **Properties** menu. Choosing SI units from the **Units** menu, with  $p$  in bar,  $T$  in  $^\circ\text{C}$ , and amount of substance in kg, the *IT* program is

```
p = 1//bar
v = 0.8475//m3/kg
T = Tsat_P("Water/Steam",p)
v = vsat_Px("Water/Steam",p,x)
u = usat_Px("Water/Steam",p,x)
```

Clicking the **Solve** button, the software returns values of  $T = 99.63^\circ\text{C}$ ,  $x = 0.5$ , and  $u = 1462 \text{ kJ/kg}$ . These values can be verified using data from Table A-3. Note that text inserted between the symbol // and a line return is treated as a comment. ◀◀◀◀◀

The previous example illustrates an important feature of *IT*. Although the quality,  $x$ , is implicit in the list of arguments in the expression for specific volume, there is no need to solve the expression algebraically for  $x$ . Rather, the program can solve for  $x$  as long as the number of equations equals the number of unknowns.

*IT* also retrieves property values in the superheat region.

► **FOR EXAMPLE** consider the superheated ammonia vapor at state 2 in Example 3.1, for which  $p = 20 \text{ lbf/in.}^2$  and  $T = 77^\circ\text{F}$ . Selecting Ammonia from the **Properties** menu and choosing English units from the **Units** menu, data for specific volume, internal energy, and enthalpy are obtained from *IT* as follows:

```
p = 20//lbf/in2
T = 77//°F
v = v_PT("Ammonia",p,T)
u = u_PT("Ammonia",p,T)
h = h_PT("Ammonia",p,T)
```

Clicking the **Solve** button, the software returns values of  $v = 16.67 \text{ ft}^3/\text{lb}$ ,  $u = 593.7 \text{ Btu/lb}$ , and  $h = 655.3 \text{ Btu/lb}$ , respectively. These values agree closely with the respective values obtained by interpolation in Table A-15E. ◀◀◀◀◀

## 3.8 Applying the Energy Balance Using Property Tables and Software

The energy balance for closed systems is introduced in Sec. 2.5. Alternative expressions are given by Eqs. 2.35a and 2.35b, which are forms applicable to processes between end states denoted 1 and 2, and by Eq. 2.37, the time rate form. In applications where changes in kinetic energy and gravitational potential energy between the end states can be ignored, Eq. 2.35b reduces to

$$U_2 - U_1 = Q - W \quad (\text{a})$$

where  $Q$  and  $W$  account, respectively, for the transfer of energy by heat and work between the system and its surroundings during the process. The term  $U_2 - U_1$  accounts for change in internal energy between the end states.

Taking water for simplicity, let's consider how the internal energy term is evaluated in three representative cases of systems involving a *single* substance.

**Case 1:** Consider a system consisting initially and finally of a single phase of water, vapor or liquid. Then Eq. (a) takes the form

$$m(u_2 - u_1) = Q - W \quad (\text{b})$$

where  $m$  is the system mass and  $u_1$  and  $u_2$  denote, respectively, the initial and final specific internal energies. When the initial and final temperatures  $T_1$ ,  $T_2$  and pressures  $p_1$ ,  $p_2$  are known, for instance, the internal energies  $u_1$  and  $u_2$  can be readily obtained from the *steam tables* or using computer software.

**Case 2:** Consider a system consisting initially of water vapor and finally as a two-phase mixture of liquid water and water vapor. As in Case 1, we write  $U_1 = mu_1$  in Eq. (a), but now

$$\begin{aligned} U_2 &= (U_{\text{liq}} + U_{\text{vap}}) \\ &= m_{\text{liq}}u_f + m_{\text{vap}}u_g \end{aligned} \quad (\text{c})$$

where  $m_{\text{liq}}$  and  $m_{\text{vap}}$  account, respectively, for the masses of saturated liquid and saturated vapor present finally, and  $u_f$  and  $u_g$  are the corresponding specific internal energies determined by the final temperature  $T_2$  (or final pressure  $p_2$ ).

If quality  $x_2$  is known, Eq. 3.6 can be invoked to evaluate the specific internal energy of the two-phase liquid–vapor mixture,  $u_2$ . Then,  $U_2 = mu_2$ , thereby preserving the form of the energy balance expressed by Eq. (b).

**Case 3:** Consider a system consisting initially of two separate masses of water vapor that mix to form a total mass of water vapor. In this case

$$U_1 = m'u(T', p') + m''u(T'', p'') \quad (\text{d})$$

$$\begin{aligned} U_2 &= (m' + m'')u(T_2, p_2) \\ &= mu(T_2, p_2) \end{aligned} \quad (\text{e})$$

where  $m'$  and  $m''$  are masses of water vapor initially separate at  $T'$ ,  $p'$  and  $T''$ ,  $p''$ , respectively, that mix to form a total mass,  $m = m' + m''$ , at a final state where temperature is  $T_2$  and pressure is  $p_2$ . When temperatures and pressures at the respective states are known, for instance, the specific internal energies of Eqs. (d) and (e) can be readily obtained from the *steam tables* or using computer software.

These cases show that when applying the energy balance, an important consideration is whether the system has one or two phases. A pertinent application is that of *thermal energy storage*, considered in the box.

### Thermal Energy Storage

Energy is often available at one time but more valuable or used more effectively at another. These considerations underlie various means for storing energy, including methods introduced in Sec. 2.7 and those discussed here.

Solar energy is collected during daylight hours but often needed at other times of the day—to heat buildings overnight, for example. Accordingly, *thermal energy storage* systems have been developed to meet solar and other similar energy storage needs. The term *thermal energy* here should be understood as *internal energy*.

Mediums used in thermal energy storage systems change temperature and/or change phase. Some storage systems simply store energy by heating water, mineral oil, or other substances held in a storage tank, usually pressurized, until the stored energy is needed. Solids such as concrete can also be the medium. *Phase-change* systems store energy by melting or freezing a substance, often water or a *molten (eutectic) salt*. The choice of

**TAKE NOTE...**

On property diagrams, solid lines are reserved for processes that pass through equilibrium states: quasi-equilibrium processes (Sec. 2.2.5). A dashed line on a property diagram signals only that a process has occurred between initial and final equilibrium states, and does not define a path for the process.

storage medium is determined by the temperature requirements of the storage application at hand together with capital and operating costs related to the storage system.

The availability of relatively inexpensive electricity generated in low-demand periods, usually overnight or during weekends, gives rise to storage strategies. In one approach, low-cost electricity is provided to a refrigeration system that chills water and/or produces ice during cooler nighttime hours when less refrigerator power is required. The chilled water and/or ice are stored in tanks until needed—for instance, to satisfy building-cooling needs during the warmest part of summer days when electricity is more costly.

### 3.8.1 Using Property Tables

In Examples 3.3 and 3.4, closed systems undergoing processes are analyzed using the energy balance. In each case, sketches of  $p-v$  and/or  $T-v$  diagrams are used in conjunction with appropriate tables to obtain the required property data. Using property diagrams and table data introduces an additional level of complexity compared to similar problems in Chap. 2.

#### EXAMPLE 3.3

#### Stirring Water at Constant Volume

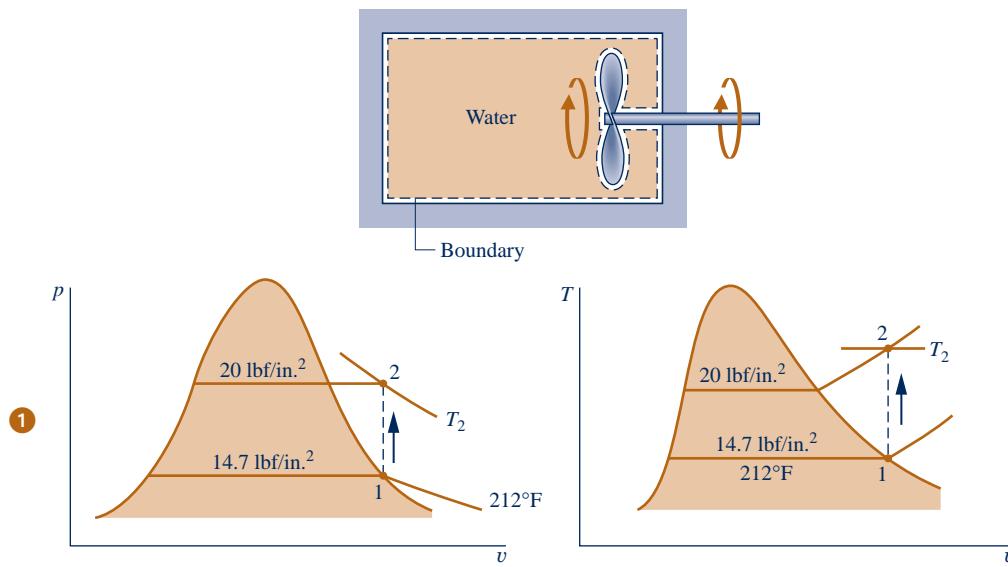
A well-insulated rigid tank having a volume of  $10 \text{ ft}^3$  contains saturated water vapor at  $212^\circ\text{F}$ . The water is rapidly stirred until the pressure is  $20 \text{ lbf/in.}^2$ . Determine the temperature at the final state, in  $^\circ\text{F}$ , and the work during the process, in Btu.

#### SOLUTION

**Known:** By rapid stirring, water vapor in a well-insulated rigid tank is brought from the saturated vapor state at  $212^\circ\text{F}$  to a pressure of  $20 \text{ lbf/in.}^2$ .

**Find:** Determine the temperature at the final state and the work.

#### Schematic and Given Data:



#### Engineering Model:

1. The water is a closed system.
2. The initial and final states are at equilibrium. There is no net change in kinetic or potential energy.
3. There is no heat transfer with the surroundings.
4. The tank volume remains constant.

Fig. E3.3

**Analysis:** To determine the final equilibrium state, the values of two independent intensive properties are required. One of these is pressure,  $p_2 = 20 \text{ lbf/in.}^2$ , and the other is the specific volume:  $v_2 = v_1$ . The initial and final specific

volumes are equal because the total mass and total volume are unchanged in the process. The initial and final states are located on the accompanying  $T-v$  and  $p-v$  diagrams.

From Table A-2E,  $v_1 = v_g(212^\circ\text{F}) = 26.80 \text{ ft}^3/\text{lb}$ ,  $u_1 = u_g(212^\circ\text{F}) = 1077.6 \text{ Btu/lb}$ . By using  $v_2 = v_1$  and interpolating in Table A-4E at  $p_2 = 20 \text{ lbf/in.}^2$

$$T_2 = 445^\circ\text{F}, \quad u_2 = 1161.6 \text{ Btu/lb}$$

Next, with assumptions 2 and 3 an energy balance for the system reduces to

$$\Delta U + \Delta KE + \Delta PE = \dot{Q} - W$$

On rearrangement

$$W = -(U_2 - U_1) = -m(u_2 - u_1)$$

To evaluate  $W$  requires the system mass. This can be determined from the volume and specific volume

$$m = \frac{V}{v_1} = \left( \frac{10 \text{ ft}^3}{26.8 \text{ ft}^3/\text{lb}} \right) = 0.373 \text{ lb}$$

Finally, by inserting values into the expression for  $W$

$$W = -(0.373 \text{ lb})(1161.6 - 1077.6) \text{ Btu/lb} = -31.3 \text{ Btu}$$

where the minus sign signifies that the energy transfer by work is to the system.

- 1 Although the initial and final states are equilibrium states, the intervening states are not at equilibrium. To emphasize this, the process has been indicated on the  $T-v$  and  $p-v$  diagrams by a dashed line. Solid lines on property diagrams are reserved for processes that pass through equilibrium states only (quasiequilibrium processes). The analysis illustrates the importance of carefully sketched property diagrams as an adjunct to problem solving.



### Skills Developed

*Ability to...*

- define a closed system and identify interactions on its boundary.
- apply the energy balance with steam table data.
- sketch  $T-v$  and  $p-v$  diagrams and locate states on them.

### QuickQUIZ

If insulation were removed from the tank and the water cooled at constant volume from  $T_2 = 445^\circ\text{F}$  to  $T_3 = 300^\circ\text{F}$  while no stirring occurs, determine the heat transfer, in Btu. **Ans.**  $-19.5 \text{ Btu}$

### EXAMPLE 3.4

## Analyzing Two Processes in Series

Water contained in a piston–cylinder assembly undergoes two processes in series from an initial state where the pressure is 10 bar and the temperature is  $400^\circ\text{C}$ .

**Process 1–2:** The water is cooled as it is compressed at a constant pressure of 10 bar to the saturated vapor state.

**Process 2–3:** The water is cooled at constant volume to  $150^\circ\text{C}$ .

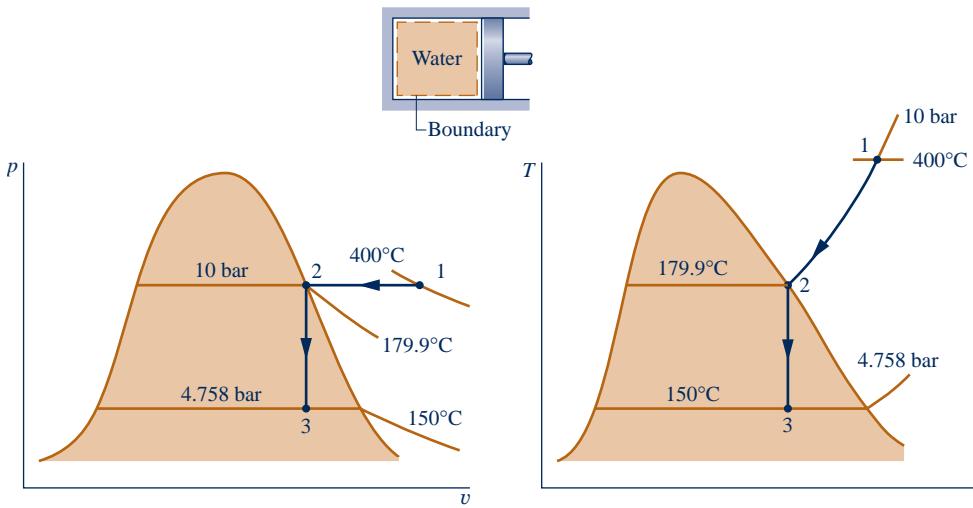
- (a) Sketch both processes on  $T-v$  and  $p-v$  diagrams.
- (b) For the overall process determine the work, in kJ/kg.
- (c) For the overall process determine the heat transfer, in kJ/kg.

### SOLUTION

**Known:** Water contained in a piston–cylinder assembly undergoes two processes: It is cooled and compressed while keeping the pressure constant, and then cooled at constant volume.

**Find:** Sketch both processes on  $T-v$  and  $p-v$  diagrams. Determine the net work and the net heat transfer for the overall process per unit of mass contained within the piston–cylinder assembly.

• Schematic and Given Data:



**Engineering Model:**

1. The water is a closed system.
2. The piston is the only work mode.
3. There are no changes in kinetic or potential energy.

Fig. E3.4

**Analysis:**

(a) The accompanying  $T-v$  and  $p-v$  diagrams show the two processes. Since the temperature at state 1,  $T_1 = 400^\circ\text{C}$ , is greater than the saturation temperature corresponding to  $p_1 = 10 \text{ bar}$ :  $179.9^\circ\text{C}$ , state 1 is located in the superheat region.

(b) Since the piston is the only work mechanism

$$W = \int_1^3 p \, dV = \int_1^2 p \, dV + \int_2^3 p \, dV^0$$

The second integral vanishes because the volume is constant in Process 2–3. Dividing by the mass and noting that the pressure is constant for Process 1–2

$$\frac{W}{m} = p(v_2 - v_1)$$

The specific volume at state 1 is found from Table A-4 using  $p_1 = 10 \text{ bar}$  and  $T_1 = 400^\circ\text{C}$ :  $v_1 = 0.3066 \text{ m}^3/\text{kg}$ . Also,  $u_1 = 2957.3 \text{ kJ/kg}$ . The specific volume at state 2 is the saturated vapor value at 10 bar:  $v_2 = 0.1944 \text{ m}^3/\text{kg}$ , from Table A-3. Hence

$$\begin{aligned} \frac{W}{m} &= (10 \text{ bar})(0.1944 - 0.3066) \left( \frac{\text{m}^3}{\text{kg}} \right) \left| \frac{10^5 \text{ N/m}^2}{1 \text{ bar}} \right| \left| \frac{1 \text{ kJ}}{10^3 \text{ N} \cdot \text{m}} \right| \\ &= -112.2 \text{ kJ/kg} \end{aligned}$$

The minus sign indicates that work is done *on* the water vapor by the piston.

(c) An energy balance for the *overall* process reduces to

$$m(u_3 - u_1) = Q - W$$

By rearranging

$$\frac{Q}{m} = (u_3 - u_1) + \frac{W}{m}$$

To evaluate the heat transfer requires  $u_3$ , the specific internal energy at state 3. Since  $T_3$  is given and  $v_3 = v_2$ , two independent intensive properties are known that together fix state 3. To find  $u_3$ , first solve for the quality

$$x_3 = \frac{v_3 - v_{f3}}{v_{g3} - v_{f3}} = \frac{0.1944 - 1.0905 \times 10^{-3}}{0.3928 - 1.0905 \times 10^{-3}} = 0.494$$

where  $v_{f3}$  and  $v_{g3}$  are from Table A-2 at 150°C. Then

$$\begin{aligned} u_3 &= u_{f3} + x_3(u_{g3} - u_{f3}) = 631.68 + 0.494(2559.5 - 631.68) \\ &= 1584.0 \text{ kJ/kg} \end{aligned}$$

where  $u_{f3}$  and  $u_{g3}$  are from Table A-2 at 150°C.

Substituting values into the energy balance

$$\frac{Q}{m} = 1584.0 - 2957.3 + (-112.2) = -1485.5 \text{ kJ/kg}$$

The minus sign shows that energy is transferred *out* by heat transfer.



### Skills Developed

*Ability to...*

- define a closed system and identify interactions on its boundary.
- evaluate work using Eq. 2.17.
- apply the energy balance with steam table data.
- sketch  $T-v$  and  $p-v$  diagrams and locate states on them.

### QuickQUIZ

If the two specified processes were followed by Process 3-4, during which the water expands at a constant temperature of 150°C to saturated vapor, determine the work, in kJ/kg, for the *overall* process from 1 to 4. **Ans.**  $W/m = -17.8 \text{ kJ/kg}$ .

## 3.8.2 Using Software

Example 3.5 illustrates the use of *Interactive Thermodynamics: IT* for solving problems. In this case, the software evaluates the property data, calculates the results, and displays the results graphically.

### EXAMPLE 3.5

#### Plotting Thermodynamic Data Using Software

For the system of Example 3.2, plot the heat transfer, in kJ, and the mass of saturated vapor present, in kg, each versus pressure at state 2 ranging from 1 to 2 bar. Discuss the results.

#### SOLUTION

**Known:** A two-phase liquid-vapor mixture of water in a closed, rigid container is heated on a hot plate. The initial pressure and quality are known. The pressure at the final state ranges from 1 to 2 bar.

**Find:** Plot the heat transfer and the mass of saturated vapor present, each versus pressure at the final state. Discuss.

**Schematic and Given Data:** See Figure E3.2.

**Engineering Model:**

1. There is no work.
2. Kinetic and potential energy effects are negligible.
3. See Example 3.2 for other assumptions.

**Analysis:** The heat transfer is obtained from the energy balance. With assumptions 1 and 2, the energy balance reduces to

$$\Delta U + \Delta \overset{0}{KE} + \Delta \overset{0}{PE} = Q - W^0$$

or

$$Q = m(u_2 - u_1)$$

Selecting Water/Steam from the **Properties** menu and choosing SI Units from the **Units** menu, the *IT* program for obtaining the required data and making the plots is

// Given data—State 1

$p_1 = 1/\text{bar}$

$x_1 = 0.5$

$V = 0.5/\text{m}^3$

```

// Evaluate property data—State 1
v1 = vsat_Px("Water/Steam", p1,x1)
u1 = usat_Px("Water/Steam", p1,x1)
// Calculate the mass
m = V/v1
// Fix state 2
v2 = v1
p2 = 1.5//bar
// Evaluate property data—State 2
v2 = vsat_Px ("Water/Steam", p2,x2)
u2 = usat_Px("Water/Steam", p2,x2)

// Calculate the mass of saturated vapor present
mg2 = x2 * m
// Determine the pressure for which the quality is unity
v3 = v1
v3 = vsat_Px( "Water/Steam",p3,1)
// Energy balance to determine the heat transfer
m * (u2 - u1) = Q - W
W = o

```

1

Click the **Solve** button to obtain a solution for  $p_2 = 1.5$  bar. The program returns values of  $v_1 = 0.8475 \text{ m}^3/\text{kg}$  and  $m = 0.59 \text{ kg}$ . Also, at  $p_2 = 1.5$  bar, the program gives  $m_{g2} = 0.4311 \text{ kg}$ . These values agree with the values determined in Example 3.2.

Now that the computer program has been verified, use the **Explore** button to vary pressure from 1 to 2 bar in steps of 0.1 bar. Then, use the **Graph** button to construct the required plots. The results are:

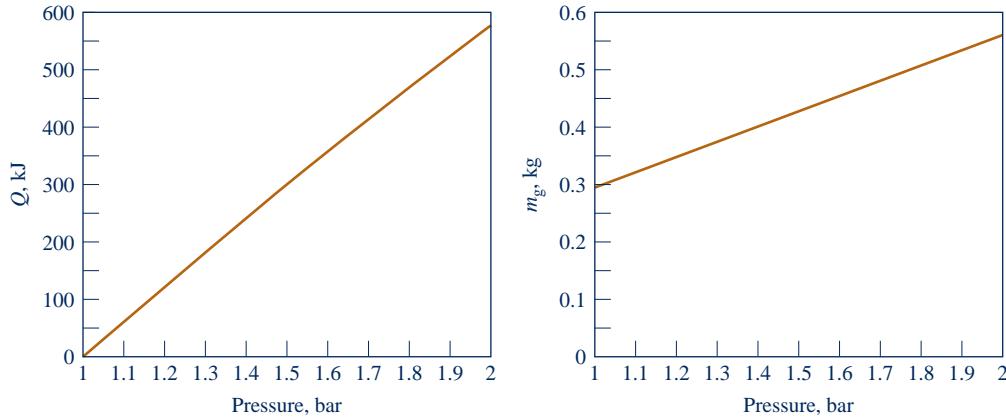


Fig. E3.5

We conclude from the first of these graphs that the heat transfer to the water varies directly with the pressure. The plot of  $m_g$  shows that the mass of saturated vapor present also increases as the pressure increases. Both of these results are in accord with expectations for the process.

- 1 Using the **Browse** button, the computer solution indicates that the pressure for which the quality becomes unity is 2.096 bar. Thus, for pressures ranging from 1 to 2 bar, all of the states are in the two-phase liquid-vapor region.

### Skills Developed

Ability to...

- apply the closed system energy balance.
- use IT to retrieve property data for water and plot calculated data.

### QuickQUIZ

If heating continues at constant specific volume to a state where the pressure is 3 bar, modify the IT program to give the temperature at that state, in °C.

Ans.  $v_4 = v_1$

$p_4 = 3//\text{bar}$

$v_4 = v_{\text{PT}} (\text{"Water/Steam"}, p_4, T_4)$

$T_4 = 282.4^\circ\text{C}$



**BIO CONNECTIONS** What do first responders, military flight crews, costumed characters at theme parks, and athletes have in common? They share a need to avoid heat stress while performing their duty, job, and past-time, respectively. To meet this need, *wearable coolers* have been developed such as cooling vests and cooling collars. Wearable coolers may feature ice pack inserts, channels through which a cool liquid is circulated, encapsulated *phase-change materials*, or a combination. A familiar example of a phase-change material (PCM) is ice, which on melting at 0°C absorbs energy of about 334 kJ/kg.

When worn close to the body, PCM-laced apparel absorbs energy from persons working or exercising in hot environments, keeping them cool. When specifying a PCM for a wearable cooler, the material must change phase at the desired cooler operating temperature. Hydrocarbons known as *paraffins* are frequently used for such duty. Many coolers available today employ PCM beads with diameters as small as 0.5 microns, encapsulated in a durable polymer shell. Encapsulated phase-change materials also are found in other products.

### 3.9

## Introducing Specific Heats $c_v$ and $c_p$

Several properties related to internal energy are important in thermodynamics. One of these is the property enthalpy introduced in Sec. 3.6.1. Two others, known as **specific heats**, are considered in this section. The specific heats, denoted  $c_v$  and  $c_p$ , are particularly useful for thermodynamic calculations involving the *ideal gas model* introduced in Sec. 3.12.

The intensive properties  $c_v$  and  $c_p$  are defined for pure, simple compressible substances as partial derivatives of the functions  $u(T, v)$  and  $h(T, p)$ , respectively

$$c_v = \left( \frac{\partial u}{\partial T} \right)_v \quad (3.8)$$

$$c_p = \left( \frac{\partial h}{\partial T} \right)_p \quad (3.9)$$

specific heats

where the subscripts  $v$  and  $p$  denote, respectively, the variables held fixed during differentiation. Values for  $c_v$  and  $c_p$  can be obtained via statistical mechanics using *spectroscopic* measurements. They also can be determined macroscopically through exacting property measurements. Since  $u$  and  $h$  can be expressed either on a unit mass basis or per mole, values of the specific heats can be similarly expressed. SI units are kJ/kg · K or kJ/kmol · K. English units are Btu/lb · °R or Btu/lbmol · °R.

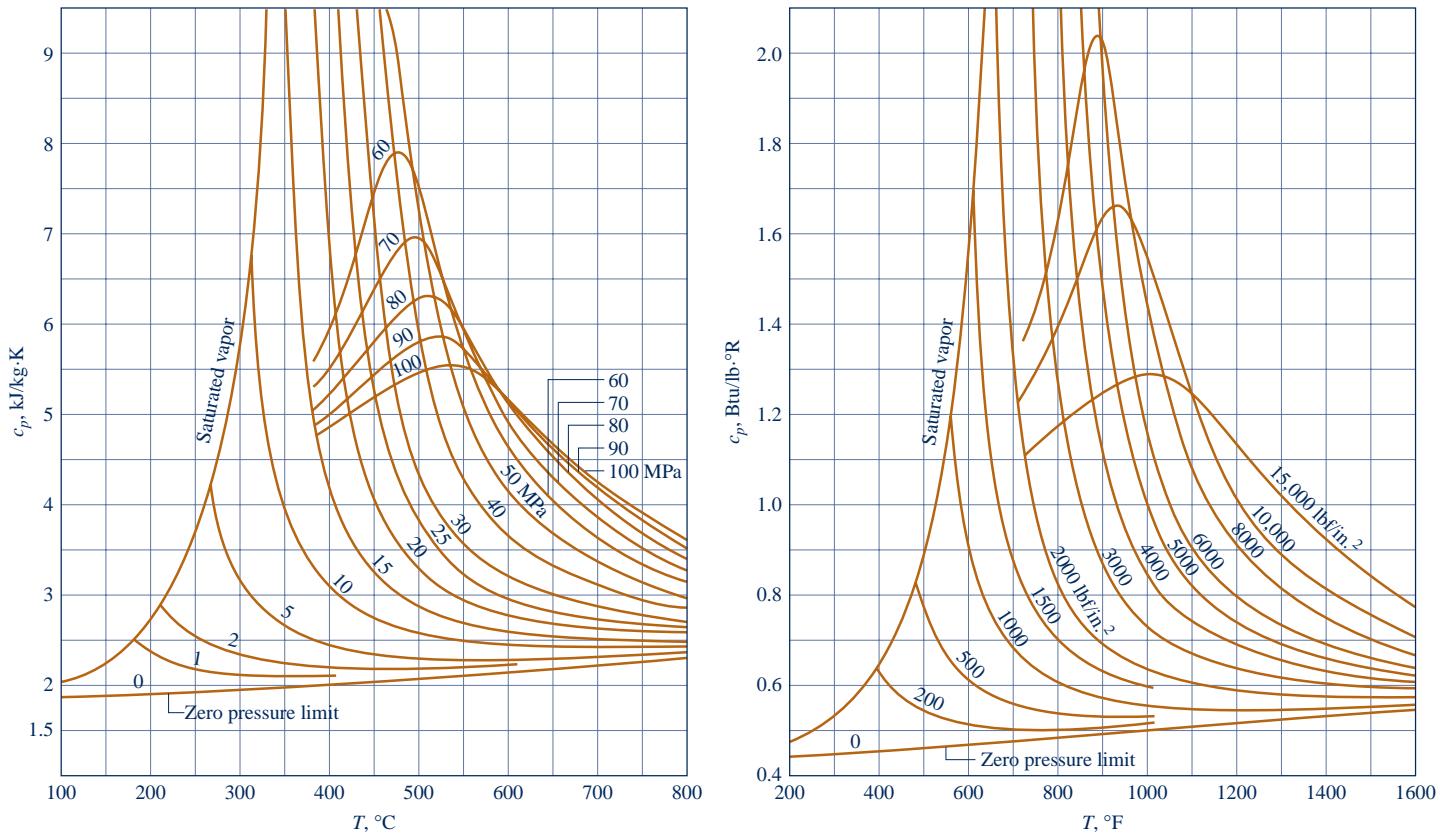
The property  $k$ , called the *specific heat ratio*, is simply the ratio

$$k = \frac{c_p}{c_v} \quad (3.10)$$

The properties  $c_v$  and  $c_p$  are referred to as *specific heats* (or *heat capacities*) because under certain *special conditions* they relate the temperature change of a system to the amount of energy added by heat transfer. However, it is generally preferable to think of  $c_v$  and  $c_p$  in terms of their definitions, Eqs. 3.8 and 3.9, and not with reference to this limited interpretation involving heat transfer.

In general,  $c_v$  is a function of  $v$  and  $T$  (or  $p$  and  $T$ ), and  $c_p$  depends on both  $p$  and  $T$  (or  $v$  and  $T$ ). Figure 3.9 shows how  $c_p$  for water vapor varies as a function of temperature and pressure. The vapor phases of other substances exhibit similar behavior. Note that the figure gives the variation of  $c_p$  with temperature in the limit as pressure tends to zero. In this limit,  $c_p$  increases with increasing temperature, which is a characteristic exhibited by other gases as well. We will refer again to such *zero-pressure* values for  $c_v$  and  $c_p$  in Sec. 3.13.2.

Specific heat data are available for common gases, liquids, and solids. Data for gases are introduced in Sec. 3.13.2 as a part of the discussion of the ideal gas model.



**Fig. 3.9**  $c_p$  of water vapor as a function of temperature and pressure.

Specific heat values for some common liquids and solids are introduced in Sec. 3.10.2 as a part of the discussion of the incompressible substance model.

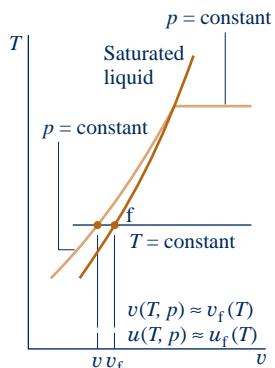
### 3.10

## Evaluating Properties of Liquids and Solids

Special methods often can be used to evaluate properties of liquids and solids. These methods provide simple, yet accurate, approximations that do not require exact compilations like the compressed liquid tables for water, Tables A-5. Two such special methods are discussed next: approximations using saturated liquid data and the incompressible substance model.

### 3.10.1 • Approximations for Liquids Using Saturated Liquid Data

Approximate values for  $v$ ,  $u$ , and  $h$  at liquid states can be obtained using saturated liquid data. To illustrate, refer to the compressed liquid tables, Tables A-5. These tables show that the specific volume and specific internal energy change very little with pressure *at a fixed temperature*. Because the values of  $v$  and  $u$  vary only gradually as pressure changes at fixed temperature, the following approximations are reasonable for many engineering calculations:



$$v(T, p) \approx v_f(T) \quad (3.11)$$

$$u(T, p) \approx u_f(T) \quad (3.12)$$

That is, for liquids  $v$  and  $u$  may be evaluated at the saturated liquid state corresponding to the temperature at the given state.

An approximate value of  $h$  at liquid states can be obtained by using Eqs. 3.11 and 3.12 in the definition  $h = u + pv$ ; thus

$$h(T, p) \approx u_f(T) + p v_f(T)$$

This can be expressed alternatively as

$$h(T, p) \approx h_f(T) + \underline{v_f(T)[p - p_{\text{sat}}(T)]} \quad (3.13)$$

where  $p_{\text{sat}}$  denotes the saturation pressure at the given temperature. The derivation is left as an exercise. When the contribution of the underlined term of Eq. 3.13 is small, the specific enthalpy can be approximated by the saturated liquid value, as for  $v$  and  $u$ . That is

$$h(T, p) \approx h_f(T) \quad (3.14)$$

Although the approximations given here have been presented with reference to liquid water, they also provide plausible approximations for other substances *when the only liquid data available are for saturated liquid states*. In this text, compressed liquid data are presented only for water (Tables A-5). Also note that *Interactive Thermodynamics: IT* does not provide compressed liquid data for *any* substance, but uses Eqs. 3.11, 3.12, and 3.14 to return liquid values for  $v$ ,  $u$ , and  $h$ , respectively. When greater accuracy is required than provided by these approximations, other data sources should be consulted for more complete property compilations for the substance under consideration.

### 3.10.2 • Incompressible Substance Model

As noted above, there are regions where the specific volume of liquid water varies little and the specific internal energy varies mainly with temperature. The same general behavior is exhibited by the liquid phases of other substances and by solids. The approximations of Eqs. 3.11–3.14 are based on these observations, as is the **incompressible substance model** under present consideration.

To simplify evaluations involving liquids or solids, the specific volume (density) is often assumed to be constant and the specific internal energy assumed to vary only with temperature. A substance idealized in this way is called *incompressible*.

Since the specific internal energy of a substance modeled as incompressible depends only on temperature, the specific heat  $c_v$  is also a function of temperature alone

$$c_v(T) = \frac{du}{dT} \quad (\text{incompressible}) \quad (3.15)$$

This is expressed as an ordinary derivative because  $u$  depends only on  $T$ .

Although the specific volume is constant and internal energy depends on temperature only, enthalpy varies with both pressure and temperature according to

$$h(T, p) = u(T) + pv \quad (\text{incompressible}) \quad (3.16)$$

For a substance modeled as incompressible, the specific heats  $c_v$  and  $c_p$  are equal. This is seen by differentiating Eq. 3.16 with respect to temperature while holding pressure fixed to obtain

$$\left(\frac{\partial h}{\partial T}\right)_p = \frac{du}{dT}$$

The left side of this expression is  $c_p$  by definition (Eq. 3.9), so using Eq. 3.15 on the right side gives

$$c_p = c_v \quad (\text{incompressible}) \quad (3.17)$$

**incompressible substance model**

#### TAKE NOTE...

For a substance modeled as incompressible,  
 $v = \text{constant}$   
 $u = u(T)$

Thus, for an incompressible substance it is unnecessary to distinguish between  $c_p$  and  $c_v$ , and both can be represented by the same symbol,  $c$ . Specific heats of some common liquids and solids are given in Tables A-19. Over limited temperature intervals the variation of  $c$  with temperature can be small. In such instances, the specific heat  $c$  can be treated as constant without a serious loss of accuracy.

Using Eqs. 3.15 and 3.16, the changes in specific internal energy and specific enthalpy between two states are given, respectively, by

$$u_2 - u_1 = \int_{T_1}^{T_2} c(T) dT \quad (\text{incompressible}) \quad (3.18)$$

$$\begin{aligned} h_2 - h_1 &= u_2 - u_1 + v(p_2 - p_1) \\ &= \int_{T_1}^{T_2} c(T) dT + v(p_2 - p_1) \quad (\text{incompressible}) \end{aligned} \quad (3.19)$$

If the specific heat  $c$  is taken as constant, Eqs. 3.18 and 3.19 become, respectively,

$$u_2 - u_1 = c(T_2 - T_1) \quad (3.20a)$$

$$h_2 - h_1 = c(T_2 - T_1) + \underline{v(p_2 - p_1)} \quad (\text{incompressible, constant } c) \quad (3.20b)$$

In Eq. 3.20b, the underlined term is often small relative to the first term on the right side and then may be dropped.

The next example illustrates use of the incompressible substance model in an application involving the constant-volume calorimeter considered in the box on p. 60.

### EXAMPLE 3.6

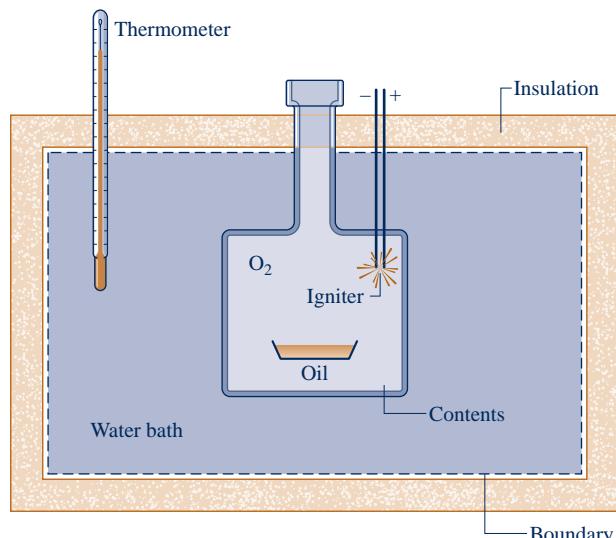
#### Measuring the Calorie Value of Cooking Oil

One-tenth milliliter of cooking oil is placed in the chamber of a constant-volume calorimeter filled with sufficient oxygen for the oil to be completely burned. The chamber is immersed in a water bath. The mass of the water bath is 2.15 kg. For the purpose of this analysis, the metal parts of the apparatus are modeled as equivalent to an additional 0.5 kg of water. The calorimeter is well-insulated, and initially the temperature throughout is 25°C. The oil is ignited by a spark. When equilibrium is again attained, the temperature throughout is 25.3°C. Determine the change in internal energy of the chamber contents, in kcal per mL of cooking oil and in kcal per tablespoon of cooking oil.

**Known:** Data are provided for a constant-volume calorimeter testing cooking oil for caloric value.

**Find:** Determine the change in internal energy of the contents of the calorimeter chamber.

#### Schematic and Given Data:



#### Engineering Model:

1. The closed system is shown by the dashed line in the accompanying figure.
2. The total volume remains constant, including the chamber, water bath, and the amount of water modeling the metal parts.
3. Water is modeled as incompressible with constant specific heat  $c$ .
4. Heat transfer with the surroundings is negligible, and there is no change in kinetic or potential energy.

Fig. E3.6

**Analysis:** With the assumptions listed, the closed system energy balance reads

$$\Delta U + \Delta KE^0 + \Delta PE^0 = Q^0 - W^0$$

or

$$(\Delta U)_{contents} + (\Delta U)_{water} = 0$$

thus

$$(\Delta U)_{contents} = -(\Delta U)_{water} \quad (a)$$

The change in internal energy of the contents is equal and opposite to the change in internal energy of the water.

Since water is modeled as incompressible, Eq. 3.20a is used to evaluate the right side of Eq. (a), giving

① ②

$$(\Delta U)_{contents} = -m_w c_w (T_2 - T_1) \quad (b)$$

With  $m_w = 2.15 \text{ kg} + 0.5 \text{ kg} = 2.65 \text{ kg}$ ,  $(T_2 - T_1) = 0.3 \text{ K}$ , and  $c_w = 4.18 \text{ kJ/kg} \cdot \text{K}$  from Table A-19, Eq. (b) gives

$$(\Delta U)_{contents} = -(2.65 \text{ kg})(4.18 \text{ kJ/kg} \cdot \text{K})(0.3 \text{ K}) = -3.32 \text{ kJ}$$

Converting to kcal, and expressing the result on a per milliliter of oil basis using the oil volume, 0.1 mL, we get

$$\begin{aligned} \frac{(\Delta U)_{contents}}{V_{oil}} &= \frac{-3.32 \text{ kJ}}{0.1 \text{ mL}} \left| \frac{1 \text{ kcal}}{4.1868 \text{ kJ}} \right| \\ &= -7.9 \text{ kcal/mL} \end{aligned}$$

The calorie value of the cooking oil is the magnitude—that is, 7.9 kcal/mL. Labels on cooking oil containers usually give calorie value for a serving size of 1 tablespoon (15 mL). Using the calculated value, we get 119 kcal per tablespoon.

- ① The change in internal energy for water can be found alternatively using Eq. 3.12 together with saturated liquid internal energy data from Table A-2.
- ② The change in internal energy of the chamber contents cannot be evaluated using a specific heat because specific heats are defined (Sec. 3.9) only for *pure* substances—that is, substances that are unchanging in composition.



### Skills Developed

Ability to...

- define a closed system and identify interactions within it and on its boundary.
- apply the energy balance using the incompressible substance model.

### QuickQUIZ

Using Eq. 3.12 together with saturated liquid internal energy data from Table A-2 find the change in internal energy of the water, in kJ, and compare with the value obtained assuming water is incompressible. **Ans.** 3.32 kJ

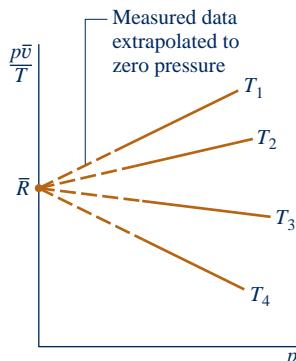


**BIO CONNECTIONS** Is your diet bad for the environment? It could be. The fruits, vegetables, and animal products found in grocery stores require a lot of fossil fuel just to get there. While study of the linkage of the human diet to the environment is in its infancy, some preliminary findings are interesting.

One study of U.S. dietary patterns evaluated the amount of fossil fuel—and implicitly, the level of greenhouse gas production—required to support several different diets. Diets rich in meat and fish were found to require the most fossil fuel, owing to the significant energy resources required to produce these products and bring them to market. But for those who enjoy meat and fish, the news is not all bad. Only a fraction of the fossil fuel needed to get food to stores is used to grow the food; most is spent on processing and distribution. Accordingly, eating favorite foods originating close to home can be a good choice environmentally.

Still, the connection between the food we eat, energy resource use, and accompanying environmental impact requires further study, including the vast amounts of agricultural land needed, huge water requirements, emissions related to fertilizer production and use, methane emitted from waste produced by billions of animals raised for food annually, and fuel for transporting food to market.

## 3.11

**Generalized Compressibility Chart**

**Fig. 3.10** Sketch of  $p\bar{v}/T$  versus pressure for a gas at several specified values of temperature.

**universal gas constant**

The object of the present section is to gain a better understanding of the relationship among pressure, specific volume, and temperature of gases. This is important not only as a basis for analyses involving gases but also for the discussions of the second part of the chapter, where the *ideal gas model* is introduced. The current presentation is conducted in terms of the *compressibility factor* and begins with the introduction of the *universal gas constant*.

**3.11.1 Universal Gas Constant,  $\bar{R}$** 

Let a gas be confined in a cylinder by a piston and the entire assembly held at a constant temperature. The piston can be moved to various positions so that a series of equilibrium states at constant temperature can be visited. Suppose the pressure and specific volume are measured at each state and the value of the ratio  $p\bar{v}/T$  ( $\bar{v}$  is volume per mole) determined. These ratios can then be plotted versus pressure at constant temperature. The results for several temperatures are sketched in Fig. 3.10. When the ratios are extrapolated to zero pressure, *precisely the same limiting value is obtained* for each curve. That is,

$$\lim_{p \rightarrow 0} \frac{p\bar{v}}{T} = \bar{R} \quad (3.21)$$

where  $\bar{R}$  denotes the common limit for all temperatures. If this procedure were repeated for other gases, it would be found in every instance that the limit of the ratio  $p\bar{v}/T$  as  $p$  tends to zero at fixed temperature is the same, namely  $\bar{R}$ . Since the same limiting value is exhibited by all gases,  $\bar{R}$  is called the **universal gas constant**. Its value as determined experimentally is

$$\bar{R} = \begin{cases} 8.314 \text{ kJ/kmol} \cdot \text{K} \\ 1.986 \text{ Btu/lbmol} \cdot {}^\circ\text{R} \\ 1545 \text{ ft} \cdot \text{lbf/lbmol} \cdot {}^\circ\text{R} \end{cases} \quad (3.22)$$

Having introduced the universal gas constant, we turn next to the compressibility factor.

**3.11.2 Compressibility Factor,  $Z$** 

**compressibility factor**

The dimensionless ratio  $p\bar{v}/\bar{R}T$  is called the **compressibility factor** and is denoted by  $Z$ . That is,

$$Z = \frac{p\bar{v}}{\bar{R}T} \quad (3.23)$$

As illustrated by subsequent calculations, when values for  $p$ ,  $\bar{v}$ ,  $\bar{R}$  and  $T$  are used in consistent units,  $Z$  is unitless.

With  $\bar{v} = Mv$  (Eq. 1.9), where  $M$  is the atomic or molecular weight, the compressibility factor can be expressed alternatively as

$$Z = \frac{pv}{RT} \quad (3.24)$$

where

$$R = \frac{\bar{R}}{M} \quad (3.25)$$

**TABLE 3.1****Values of the Gas Constant  $R$  of Selected Elements and Compounds**

Substance	Chemical Formula	$R$ (kJ/kg · K)	$R$ (Btu/lb · °R)
Air	—	0.2870	0.06855
Ammonia	NH <sub>3</sub>	0.4882	0.11662
Argon	Ar	0.2082	0.04972
Carbon dioxide	CO <sub>2</sub>	0.1889	0.04513
Carbon monoxide	CO	0.2968	0.07090
Helium	He	2.0769	0.49613
Hydrogen	H <sub>2</sub>	4.1240	0.98512
Methane	CH <sub>4</sub>	0.5183	0.12382
Nitrogen	N <sub>2</sub>	0.2968	0.07090
Oxygen	O <sub>2</sub>	0.2598	0.06206
Water	H <sub>2</sub> O	0.4614	0.11021

Source:  $R$  values are calculated in terms of the universal gas constant  $\bar{R} = 8.314 \text{ kJ/kmol} \cdot \text{K} = 1.986 \text{ Btu/lbmol} \cdot {}^\circ\text{R}$  and the molecular weight  $M$  provided in Table A-1 using  $R = \bar{R}/M$  (Eq. 3.25).

$R$  is a constant for the particular gas whose molecular weight is  $M$ . Alternative units for  $R$  are kJ/kg · K, Btu/lb · °R, and ft · lbf/lb · °R. Table 3.1 provides a sampling of values for the gas constant  $R$  calculated from Eq. 3.25.

Equation 3.21 can be expressed in terms of the compressibility factor as

$$\lim_{p \rightarrow 0} Z = 1 \quad (3.26)$$

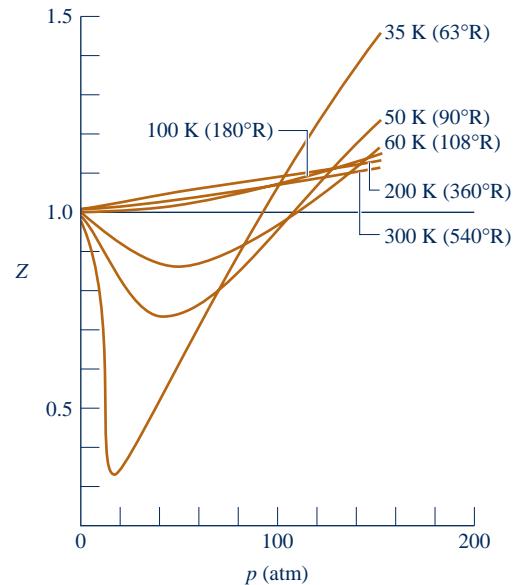
That is, the compressibility factor  $Z$  tends to unity as pressure tends to zero at fixed temperature. This can be illustrated by reference to Fig. 3.11, which shows  $Z$  for hydrogen plotted versus pressure at a number of different temperatures. In general, at states of a gas where pressure is small relative to the critical pressure,  $Z$  is approximately 1.

### 3.11.3 Generalized Compressibility Data, Z Chart

Figure 3.11 gives the compressibility factor for hydrogen versus pressure at specified values of temperature. Similar charts have been prepared for other gases. When these charts are studied, they are found to be *qualitatively* similar. Further study shows that when the coordinates are suitably modified, the curves for several different gases coincide closely when plotted together on the same coordinate axes, and so *quantitative* similarity also can be achieved. This is referred to as the *principle of corresponding states*. In one such approach, the compressibility factor  $Z$  is plotted versus a dimensionless **reduced pressure**  $p_R$  and **reduced temperature**  $T_R$ , defined as

$$p_R = p/p_c \quad (3.27)$$

$$T_R = T/T_c \quad (3.28)$$



**Fig. 3.11** Variation of the compressibility factor of hydrogen with pressure at constant temperature.

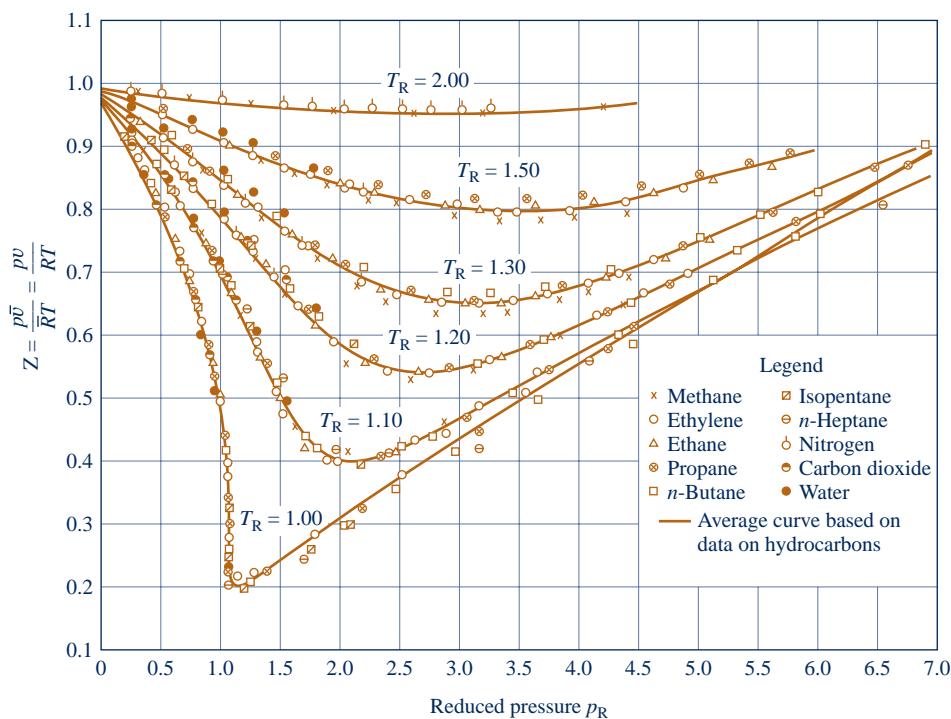
where  $p_c$  and  $T_c$  denote the critical pressure and temperature, respectively. This results in a **generalized compressibility chart** of the form  $Z = f(p_R, T_R)$ . Figure 3.12 shows experimental data for 10 different gases on a chart of this type. The solid lines denoting reduced isotherms represent the best curves fitted to the data. Observe that Tables A-1 provide the critical temperature and critical pressure for a sampling of substances.

reduced pressure  
and temperature

**generalized compressibility chart**
**TAKE NOTE...**

Study of Fig. A-2 shows that the value of  $Z$  tends to unity at fixed reduced temperature  $T_R$  as reduced pressure  $p_R$  tends to zero. That is,  $Z \rightarrow 1$

as  $p_R \rightarrow 0$  at fixed  $T_R$ . Figure A-2 also shows that  $Z$  tends to unity at fixed reduced pressure as reduced temperature becomes large.

**pseudoreduced specific volume**


**Fig. 3.12 Generalized compressibility chart for various gases.**

A generalized chart more suitable for problem solving than Fig. 3.12 is given in the Appendix as Figs. A-1, A-2, and A-3. In Fig. A-1,  $p_R$  ranges from 0 to 1.0; in Fig. A-2,  $p_R$  ranges from 0 to 10.0; and in Fig. A-3,  $p_R$  ranges from 10.0 to 40.0. At any one temperature, the deviation of observed values from those of the generalized chart increases with pressure. However, for the 30 gases used in developing the chart, the deviation is *at most* on the order of 5% and for most ranges is much less.<sup>1</sup>

Values of specific volume are included on the generalized chart through the variable  $v'_R$ , called the **pseudoreduced specific volume**, defined by

$$v'_R = \frac{\bar{v}}{RT_c/p_c} \quad (3.29)$$

The pseudoreduced specific volume gives a better correlation of the data than does the *reduced* specific volume  $v_R = \bar{v}/\bar{v}_c$ , where  $\bar{v}_c$  is the critical specific volume.

Using the critical pressure and critical temperature of a substance of interest, the generalized chart can be entered with various pairs of the variables  $T_R$ ,  $p_R$ , and  $v'_R$ :  $(T_R, p_R)$ ,  $(p_R, v'_R)$ , or  $(T_R, v'_R)$ . The merit of the generalized chart for relating  $p$ ,  $v$ , and  $T$  data for gases is simplicity coupled with accuracy. However, the generalized compressibility chart should not be used as a substitute for  $p-v-T$  data for a given substance as provided by tables or computer software. The chart is mainly useful for obtaining reasonable estimates in the absence of more accurate data.

The next example provides an illustration of the use of the generalized compressibility chart.

<sup>1</sup>To determine  $Z$  for hydrogen, helium, and neon above a  $T_R$  of 5, the reduced temperature and pressure should be calculated using  $T_R = T/(T_c + 8)$  and  $p_R = p/(p_c + 8)$ , where temperatures are in K and pressures are in atm.

**EXAMPLE 3.7****Using the Generalized Compressibility Chart**

A closed, rigid tank filled with water vapor, initially at 20 MPa, 520°C, is cooled until its temperature reaches 400°C. Using the compressibility chart, determine

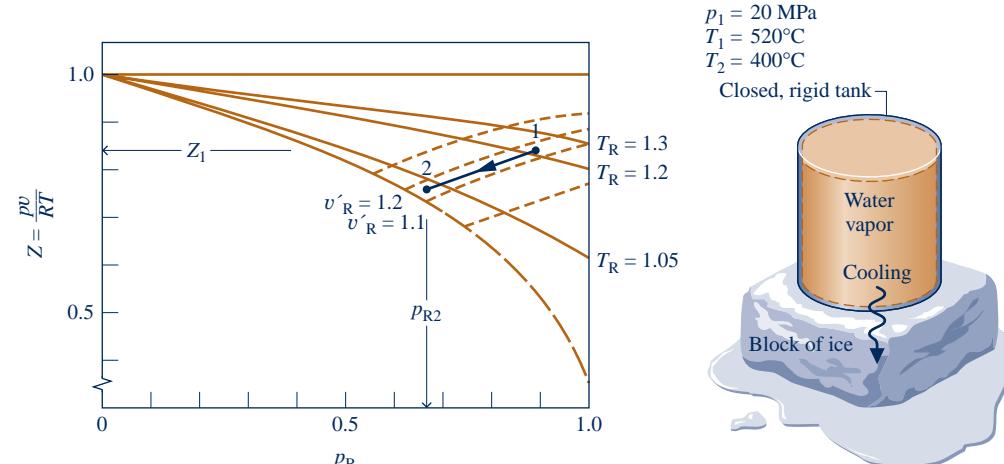
- the specific volume of the water vapor in  $\text{m}^3/\text{kg}$  at the initial state.
- the pressure in MPa at the final state.

Compare the results of parts (a) and (b) with the values obtained from the superheated vapor table, Table A-4.

**SOLUTION**

**Known:** Water vapor is cooled at constant volume from 20 MPa, 520°C to 400°C.

**Find:** Use the compressibility chart and the superheated vapor table to determine the specific volume and final pressure and compare the results.

**Schematic and Given Data:**

**Fig. E3.7**

**Analysis:**

- (a) From Table A-1,  $T_c = 647.3 \text{ K}$  and  $p_c = 22.09 \text{ MPa}$  for water. Thus

$$① \quad T_{R1} = \frac{793}{647.3} = 1.23, \quad p_{R1} = \frac{20}{22.09} = 0.91$$

With these values for the reduced temperature and reduced pressure, the value of  $Z$  obtained from Fig. A-1 is approximately 0.83. Since  $Z = pv/RT$ , the specific volume at state 1 can be determined as follows:

$$② \quad v_1 = Z_1 \frac{RT_1}{p_1} = 0.83 \frac{\bar{R}T_1}{Mp_1}$$

$$= 0.83 \left( \frac{8314 \frac{\text{N} \cdot \text{m}}{\text{kmol} \cdot \text{K}}}{18.02 \frac{\text{kg}}{\text{kmol}}} \right) \left( \frac{793 \text{ K}}{20 \times 10^6 \frac{\text{N}}{\text{m}^2}} \right) = 0.0152 \text{ m}^3/\text{kg}$$

The molecular weight of water is from Table A-1.

**Engineering Model:**

1. The water vapor is a closed system.
2. The initial and final states are at equilibrium.
3. The volume is constant.

Turning to Table A-4, the specific volume at the initial state is  $0.01551 \text{ m}^3/\text{kg}$ . This is in good agreement with the compressibility chart value, as expected.

(b) Since both mass and volume remain constant, the water vapor cools at constant specific volume, and thus at constant  $v'_R$ . Using the value for specific volume determined in part (a), the constant  $v'_R$  value is

$$v'_R = \frac{vp_c}{RT_c} = \frac{\left(0.0152 \frac{\text{m}^3}{\text{kg}}\right)\left(22.09 \times 10^6 \frac{\text{N}}{\text{m}^2}\right)}{\left(\frac{8314 \text{ N} \cdot \text{m}}{18.02 \text{ kg} \cdot \text{K}}\right)(647.3 \text{ K})} = 1.12$$

At state 2

$$T_{R2} = \frac{673}{647.3} = 1.04$$

Locating the point on the compressibility chart where  $v'_R = 1.12$  and  $T_R = 1.04$ , the corresponding value for  $p_R$  is about 0.69. Accordingly

$$p_2 = p_c(p_{R2}) = (22.09 \text{ MPa})(0.69) = 15.24 \text{ MPa}$$

Interpolating in the superheated vapor tables gives  $p_2 = 15.16 \text{ MPa}$ . As before, the compressibility chart value is in good agreement with the table value.

- 1 *Absolute* temperature and *absolute* pressure must be used in evaluating the compressibility factor  $Z$ , the reduced temperature  $T_R$ , and reduced pressure  $p_R$ .
- 2 Since  $Z$  is unitless, values for  $p$ ,  $v$ ,  $R$ , and  $T$  must be used in consistent units.

### Skills Developed

Ability to...

- retrieve  $p-v-T$  data from the generalized compressibility chart.
- retrieve  $p-v-T$  data from the steam tables..

#### QuickQUIZ

Using the compressibility chart, determine the specific volume, in  $\text{m}^3/\text{kg}$ , for water vapor at 14 MPa, 440°C. Compare with the steam table value. **Ans.**  $0.0195 \text{ m}^3/\text{kg}$

### 3.11.4 Equations of State

Considering the curves of Figs. 3.11 and 3.12, it is reasonable to think that the variation with pressure and temperature of the compressibility factor for gases might be expressible as an equation, at least for certain intervals of  $p$  and  $T$ . Two expressions can be written that enjoy a theoretical basis. One gives the compressibility factor as an infinite series expansion in pressure:

$$Z = 1 + \hat{B}(T)p + \hat{C}(T)p^2 + \hat{D}(T)p^3 + \dots \quad (3.30)$$

where the coefficients  $\hat{B}$ ,  $\hat{C}$ ,  $\hat{D}$ , ... depend on temperature only. The dots in Eq. 3.30 represent higher-order terms. The other is a series form entirely analogous to Eq. 3.30 but expressed in terms of  $1/\bar{v}$  instead of  $p$

$$Z = 1 + \frac{B(T)}{\bar{v}} + \frac{C(T)}{\bar{v}^2} + \frac{D(T)}{\bar{v}^3} + \dots \quad (3.31)$$

#### virial equations of state

Equations 3.30 and 3.31 are known as **virial equations of state**, and the coefficients  $\hat{B}$ ,  $\hat{C}$ ,  $\hat{D}$ , ... and  $B$ ,  $C$ ,  $D$ , ... are called **virial coefficients**. The word *virial* stems from the Latin word for force. In the present usage it is force interactions among molecules that are intended.

The virial expansions can be derived by the methods of statistical mechanics, and physical significance can be attributed to the coefficients:  $B/\bar{v}$  accounts for two-molecule interactions,  $C/\bar{v}^2$  accounts for three-molecule interactions, etc. In principle, the virial coefficients can be calculated by using expressions from statistical mechanics derived from consideration of the force fields around the molecules of a gas. The virial coefficients also can be determined from experimental  $p-v-T$  data. The virial expansions are used in Sec. 11.1 as a point of departure for the further study of analytical representations of the  $p-v-T$  relationship of gases known generically as *equations of state*.

The virial expansions and the physical significance attributed to the terms making up the expansions can be used to clarify the nature of gas behavior in the limit as pressure tends to zero at fixed temperature. From Eq. 3.30 it is seen that if pressure decreases at fixed temperature, the terms  $\hat{B}p$ ,  $\hat{C}p^2$ , etc. accounting for various molecular interactions tend to decrease, suggesting that the force interactions become weaker under these circumstances. In the limit as pressure approaches zero, these terms vanish, and the equation reduces to  $Z = 1$  in accordance with Eq. 3.26. Similarly, since specific volume increases when the pressure decreases at fixed temperature, the terms  $B/\bar{v}$ ,  $C/\bar{v}^2$ , etc. of Eq. 3.31 also vanish in the limit, giving  $Z = 1$  when the force interactions between molecules are no longer significant.

## Evaluating Properties Using the Ideal Gas Model

### 3.12 Introducing the Ideal Gas Model

In this section the ideal gas model is introduced. The ideal gas model has many applications in engineering practice and is frequently used in subsequent sections of this text.

#### 3.12.1 Ideal Gas Equation of State

As observed in Sec. 3.11.3, study of the generalized compressibility chart Fig. A-2 shows that at states where the pressure  $p$  is small relative to the critical pressure  $p_c$  (low  $p_R$ ) and/or the temperature  $T$  is large relative to the critical temperature  $T_c$  (high  $T_R$ ), the compressibility factor,  $Z = pv/RT$ , is approximately 1. At such states, we can assume with reasonable accuracy that  $Z = 1$ , or

$$pv = RT \quad (3.32)$$

Known as the **ideal gas equation of state**, Eq. 3.32 underlies the second part of this chapter dealing with the ideal gas model.

**ideal gas equation of state**

Alternative forms of the same basic relationship among pressure, specific volume, and temperature are obtained as follows. With  $v = V/m$ , Eq. 3.32 can be expressed as

$$pV = mRT \quad (3.33)$$

In addition, using  $v = \bar{v}/M$  and  $R = \bar{R}/M$ , which are Eqs. 1.9 and 3.25, respectively, where  $M$  is the molecular weight, Eq. 3.32 can be expressed as

$$p\bar{v} = \bar{R}T \quad (3.34)$$

or, with  $\bar{v} = V/n$ , as

$$pV = n\bar{R}T \quad (3.35)$$

**Ideal Gas**  
A.15 – Tab b

A

### 3.12.2 • Ideal Gas Model

#### ideal gas model

##### TAKE NOTE...

To expedite the solutions of many subsequent examples and end-of-chapter problems involving air, oxygen ( $O_2$ ), nitrogen ( $N_2$ ), carbon dioxide ( $CO_2$ ), carbon monoxide ( $CO$ ), hydrogen ( $H_2$ ), and other common gases, we indicate in the problem statements that the ideal gas model should be used. If not indicated explicitly, the suitability of the ideal gas model should be checked using the  $Z$  chart or other data.

For any gas whose equation of state is given *exactly* by  $pv = RT$ , the specific internal energy depends on temperature *only*. This conclusion is demonstrated formally in Sec. 11.4. It is also supported by experimental observations, beginning with the work of Joule, who showed in 1843 that the internal energy of air at low density (large specific volume) depends primarily on temperature. Further motivation from the microscopic viewpoint is provided shortly. The specific enthalpy of a gas described by  $pv = RT$  also depends on temperature only, as can be shown by combining the definition of enthalpy,  $h = u + pv$ , with  $u = u(T)$  and the ideal gas equation of state to obtain  $h = u(T) + RT$ . Taken together, these specifications constitute the **ideal gas model**, summarized as follows

$$pv = RT \quad (3.32)$$

$$u = u(T) \quad (3.36)$$

$$h = h(T) = u(T) + RT \quad (3.37)$$

The specific internal energy and enthalpy of gases generally depend on two independent properties, not just temperature as presumed by the ideal gas model. Moreover, the ideal gas equation of state does not provide an acceptable approximation at all states. Accordingly, whether the ideal gas model is used depends on the error acceptable in a given calculation. Still, gases often do *approach* ideal gas behavior, and a particularly simplified description is obtained with the ideal gas model.

To verify that a gas can be modeled as an ideal gas, the states of interest can be located on a compressibility chart to determine how well  $Z = 1$  is satisfied. As shown in subsequent discussions, other tabular or graphical property data can also be used to determine the suitability of the ideal gas model.

The next example illustrates the use of the ideal gas equation of state and reinforces the use of property diagrams to locate principal states during processes.

#### EXAMPLE 3.8

### Analyzing Air as an Ideal Gas Undergoing a Thermodynamic Cycle

One pound of air in a piston–cylinder assembly undergoes a thermodynamic cycle consisting of three processes.

**Process 1–2:** Constant specific volume

**Process 2–3:** Constant-temperature expansion

**Process 3–1:** Constant-pressure compression

At state 1, the temperature is  $540^{\circ}\text{R}$ , and the pressure is 1 atm. At state 2, the pressure is 2 atm. Employing the ideal gas equation of state,

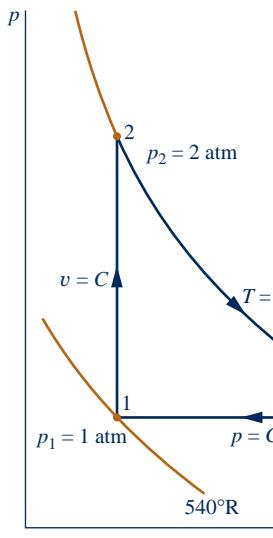
- (a) sketch the cycle on  $p$ – $v$  coordinates.
- (b) determine the temperature at state 2, in  $^{\circ}\text{R}$ .
- (c) determine the specific volume at state 3, in  $\text{ft}^3/\text{lb}$ .

#### SOLUTION

**Known:** Air executes a thermodynamic cycle consisting of three processes: Process 1–2,  $v = \text{constant}$ ; Process 2–3,  $T = \text{constant}$ ; Process 3–1,  $p = \text{constant}$ . Values are given for  $T_1$ ,  $p_1$ , and  $p_2$ .

**Find:** Sketch the cycle on  $p-v$  coordinates and determine  $T_2$  and  $v_3$ .

**Schematic and Given Data:**



**Engineering Model:**

1. The air is a closed system.
2. The air behaves as an ideal gas.
3. The piston is the only work mode.

**Fig. E3.8**

**Analysis:**

(a) The cycle is shown on  $p-v$  coordinates in the accompanying figure. Note that since  $p = RT/v$  and temperature is constant, the variation of  $p$  with  $v$  for the process from 2 to 3 is nonlinear.

(b) Using  $pv = RT$ , the temperature at state 2 is

$$T_2 = p_2 v_2 / R$$

To obtain the specific volume  $v_2$  required by this relationship, note that  $v_2 = v_1$ , so

$$(2) \quad v_2 = R T_1 / p_1$$

Combining these two results gives

$$T_2 = \frac{p_2}{p_1} T_1 = \left( \frac{2 \text{ atm}}{1 \text{ atm}} \right) (540^\circ\text{R}) = 1080^\circ\text{R}$$

(c) Since  $pv = RT$ , the specific volume at state 3 is

$$v_3 = R T_3 / p_3$$

Noting that  $T_3 = T_2$ ,  $p_3 = p_1$ , and  $R = \bar{R}/M$

$$\begin{aligned} v_3 &= \frac{\bar{R} T_2}{M p_1} \\ &= \left( \frac{1545 \frac{\text{ft} \cdot \text{lbf}}{\text{lbmol} \cdot {}^\circ\text{R}}}{28.97 \frac{\text{lb}}{\text{lbmol}}} \right) \frac{(1080^\circ\text{R})}{(14.7 \text{ lbf/in.}^2)} \left| \frac{1 \text{ ft}^2}{144 \text{ in.}^2} \right| \\ &= 27.2 \text{ ft}^3/\text{lb} \end{aligned}$$

where the molecular weight of air is from Table A-1E.

- 1 Table A-1E gives  $p_c = 37.2 \text{ atm}$ ,  $T_c = 239^\circ\text{R}$  for air. Therefore,  $p_{R2} = 0.054$ ,  $T_{R2} = 4.52$ . Referring to Fig. A-1, the value of the compressibility factor at this state is  $Z \approx 1$ . The same conclusion results when states 1 and 3 are checked. Accordingly,  $pv = RT$  adequately describes the  $p-v-T$  relation for the air at these states.
- 2 Carefully note that the equation of state  $pv = RT$  requires the use of *absolute* temperature  $T$  and *absolute* pressure  $p$ .

### Skills Developed

Ability to...

- evaluate  $p-v-T$  data using the ideal gas equation of state.
- sketch processes on a  $p-v$  diagram

### QuickQUIZ

Is the cycle sketched in Fig. E3.8 a power cycle or a refrigeration cycle? Explain. **Ans.** A power cycle. As represented by enclosed area 1-2-3-1, the net work is positive.

### 3.12.3 Microscopic Interpretation

A picture of the dependence of the internal energy of gases on temperature at low density (large specific volume) can be obtained with reference to the discussion of the virial equations: Eqs. 3.30 and 3.31. As  $p \rightarrow 0$  ( $\bar{v} \rightarrow \infty$ ), the force interactions between molecules of a gas become weaker, and the virial expansions approach  $Z = 1$  in the limit. The study of gases from the microscopic point of view shows that the dependence of the internal energy of a gas on pressure, or specific volume, at a specified temperature arises primarily because of molecular interactions. Accordingly, as the density of a gas decreases (specific volume increases) at fixed temperature, there comes a point where the effects of intermolecular forces are minimal. The internal energy is then determined principally by the temperature.

From the microscopic point of view, the ideal gas model adheres to several idealizations: The gas consists of molecules that are in random motion and obey the laws of mechanics; the total number of molecules is large, but the volume of the molecules is a negligibly small fraction of the volume occupied by the gas; and no appreciable forces act on the molecules except during collisions. Further discussion of the ideal gas using the microscopic approach is provided in Sec. 3.13.2.

## 3.13 Internal Energy, Enthalpy, and Specific Heats of Ideal Gases

### 3.13.1 $\Delta u$ , $\Delta h$ , $c_v$ , and $c_p$ Relations

For a gas obeying the ideal gas model, specific internal energy depends only on temperature. Hence, the specific heat  $c_v$ , defined by Eq. 3.8, is also a function of temperature alone. That is,

$$c_v(T) = \frac{du}{dT} \quad (\text{ideal gas}) \quad (3.38)$$

This is expressed as an ordinary derivative because  $u$  depends only on  $T$ .

By separating variables in Eq. 3.38

$$du = c_v(T) dT \quad (3.39)$$

On integration, the change in specific internal energy is

$$u(T_2) - u(T_1) = \int_{T_1}^{T_2} c_v(T) dT \quad (\text{ideal gas}) \quad (3.40)$$

Similarly, for a gas obeying the ideal gas model, the specific enthalpy depends only on temperature, so the specific heat  $c_p$ , defined by Eq. 3.9, is also a function of temperature alone. That is

$$c_p(T) = \frac{dh}{dT} \quad (\text{ideal gas}) \quad (3.41)$$

Separating variables in Eq. 3.41

$$dh = c_p(T) dT \quad (3.42)$$

On integration, the change in specific enthalpy is

$$h(T_2) - h(T_1) = \int_{T_1}^{T_2} c_p(T) dT \quad (\text{ideal gas}) \quad (3.43)$$

An important relationship between the ideal gas specific heats can be developed by differentiating Eq. 3.37 with respect to temperature

$$\frac{dh}{dT} = \frac{du}{dT} + R$$

and introducing Eqs. 3.38 and 3.41 to obtain

$$c_p(T) = c_v(T) + R \quad (\text{ideal gas}) \quad (3.44)$$

On a molar basis, this is written as

$$\bar{c}_p(T) = \bar{c}_v(T) + \bar{R} \quad (\text{ideal gas}) \quad (3.45)$$

Although each of the two ideal gas specific heats is a function of temperature, Eqs. 3.44 and 3.45 show that the specific heats differ by just a constant: the gas constant. Knowledge of either specific heat for a particular gas allows the other to be calculated by using only the gas constant. The above equations also show that  $c_p > c_v$  and  $\bar{c}_p > \bar{c}_v$ , respectively.

For an ideal gas, the specific heat ratio,  $k$ , is also a function of temperature only

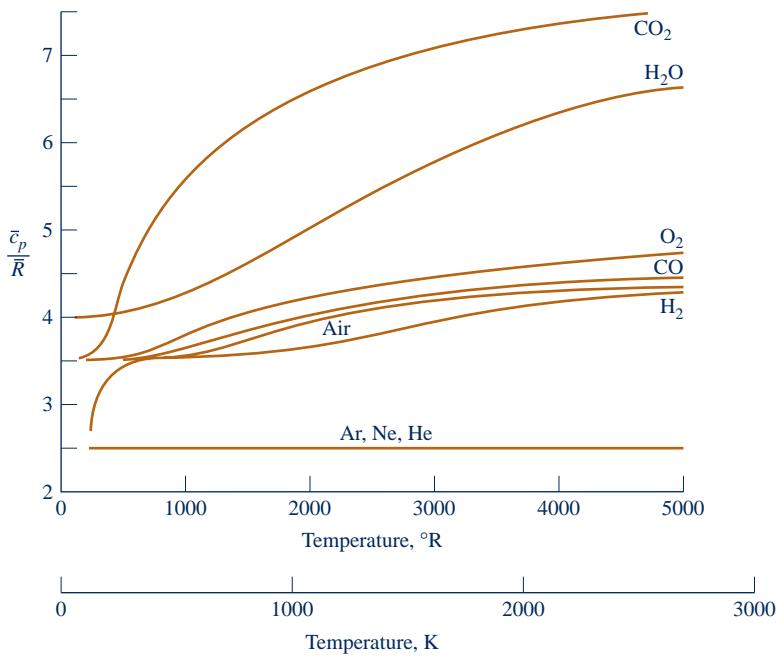
$$k = \frac{c_p(T)}{c_v(T)} \quad (\text{ideal gas}) \quad (3.46)$$

Since  $c_p > c_v$ , it follows that  $k > 1$ . Combining Eqs. 3.44 and 3.46 results in

$$c_p(T) = \frac{kR}{k - 1} \quad (\text{ideal gas}) \quad (3.47a)$$

$$c_v(T) = \frac{R}{k - 1} \quad (3.47b)$$

Similar expressions can be written for the specific heats on a molar basis, with  $R$  being replaced by  $\bar{R}$ .



**Fig. 3.13** Variation of  $\bar{c}_p/\bar{R}$  with temperature for a number of gases modeled as ideal gases.

### 3.13.2 Using Specific Heat Functions

The foregoing expressions require the ideal gas specific heats as functions of temperature. These functions are available for gases of practical interest in various forms, including graphs, tables, and equations. Figure 3.13 illustrates the variation of  $\bar{c}_p$  (molar basis) with temperature for a number of common gases. In the range of temperature shown,  $\bar{c}_p$  increases with temperature for all gases, except for the monatomic gases Ar, Ne, and He. For these,  $\bar{c}_p$  is constant at the value predicted by kinetic theory:  $\bar{c}_p = \frac{5}{2}\bar{R}$ . Tabular specific heat data for selected gases are presented versus temperature in Tables A-20. Specific heats are also available in equation form. Several alternative forms of such equations are found in the engineering literature. An equation that is relatively easy to integrate is the polynomial form

$$\frac{\bar{c}_p}{\bar{R}} = \alpha + \beta T + \gamma T^2 + \delta T^3 + \varepsilon T^4 \quad (3.48)$$

Values of the constants  $\alpha$ ,  $\beta$ ,  $\gamma$ ,  $\delta$ , and  $\varepsilon$  are listed in Tables A-21 for several gases in the temperature range 300 to 1000 K (540 to 1800°R).

► **FOR EXAMPLE** to illustrate the use of Eq. 3.48, let us evaluate the change in specific enthalpy, in kJ/kg, of air modeled as an ideal gas from a state where  $T_1 = 400$  K to a state where  $T_2 = 900$  K. Inserting the expression for  $\bar{c}_p(T)$  given by Eq. 3.48 into Eq. 3.43 and integrating with respect to temperature

$$\begin{aligned} h_2 - h_1 &= \frac{\bar{R}}{M} \int_{T_1}^{T_2} (\alpha + \beta T + \gamma T^2 + \delta T^3 + \varepsilon T^4) dT \\ &= \frac{\bar{R}}{M} \left[ \alpha(T_2 - T_1) + \frac{\beta}{2}(T_2^2 - T_1^2) + \frac{\gamma}{3}(T_2^3 - T_1^3) + \frac{\delta}{4}(T_2^4 - T_1^4) + \frac{\varepsilon}{5}(T_2^5 - T_1^5) \right] \end{aligned}$$

where the molecular weight  $M$  has been introduced to obtain the result on a unit mass basis. With values for the constants from Table A-21

$$\begin{aligned} h_2 - h_1 &= \frac{8.314}{28.97} \left\{ 3.653(900 - 400) - \frac{1.337}{2(10)^3} [(900)^2 - (400)^2] \right. \\ &\quad + \frac{3.294}{3(10)^6} [(900)^3 - (400)^3] - \frac{1.913}{4(10)^9} [(900)^4 - (400)^4] \\ &\quad \left. + \frac{0.2763}{5(10)^{12}} [(900)^5 - (400)^5] \right\} = 531.69 \text{ kJ/kg} \end{aligned}$$

Specific heat functions  $c_v(T)$  and  $c_p(T)$  are also available in *IT: Interactive Thermodynamics* in the PROPERTIES menu. These functions can be integrated using the integral function of the program to calculate  $\Delta u$  and  $\Delta h$ , respectively.

**► FOR EXAMPLE** let us repeat the immediately preceding example using *IT*. For air, the *IT* code is

```
cp = cp_T ("Air",T)
delh = Integral(cp,T)
```

Pushing SOLVE and sweeping T from 400 K to 900 K, the change in specific enthalpy is  $delh = 531.7 \text{ kJ/kg}$ , which agrees closely with the value obtained by integrating the specific heat function from Table A-21, as illustrated above. ◀◀◀◀◀

The source of ideal gas specific heat data is experiment. Specific heats can be determined macroscopically from painstaking property measurements. In the limit as pressure tends to zero, the properties of a gas tend to merge into those of its ideal gas model, so macroscopically determined specific heats of a gas extrapolated to very low pressures may be called either *zero-pressure* specific heats or *ideal gas* specific heats. Although zero-pressure specific heats can be obtained by extrapolating macroscopically determined experimental data, this is rarely done nowadays because ideal gas specific heats can be readily calculated with expressions from statistical mechanics by using *spectral* data, which can be obtained experimentally with precision. The determination of ideal gas specific heats is one of the important areas where the *microscopic approach* contributes significantly to the application of engineering thermodynamics.

3.14

## Applying the Energy Balance Using Ideal Gas Tables, Constant Specific Heats, and Software

Although changes in specific enthalpy and specific internal energy can be obtained by integrating specific heat expressions, as illustrated in Sec. 3.13.2, such evaluations are more easily conducted using ideal gas tables, the assumption of constant specific heats, and computer software, all introduced in the present section. These procedures are also illustrated in the present section via solved examples using the closed system energy balance.

### 3.14.1 Using Ideal Gas Tables

For a number of common gases, evaluations of specific internal energy and enthalpy changes are facilitated by the use of the *ideal gas tables*, Tables A-22 and A-23, which give  $u$  and  $h$  (or  $\bar{u}$  and  $\bar{h}$ ) versus temperature.

To obtain enthalpy versus temperature, write Eq. 3.43 as

$$h(T) = \int_{T_{\text{ref}}}^T c_p(T) dT + h(T_{\text{ref}})$$

where  $T_{\text{ref}}$  is an arbitrary reference temperature and  $h(T_{\text{ref}})$  is an arbitrary value for enthalpy at the reference temperature. Tables A-22 and A-23 are based on the selection  $h = 0$  at  $T_{\text{ref}} = 0$  K. Accordingly, a tabulation of enthalpy versus temperature is developed through the integral<sup>2</sup>

$$h(T) = \int_0^T c_p(T) dT \quad (3.49)$$

Tabulations of internal energy versus temperature are obtained from the tabulated enthalpy values by using  $u = h - RT$ .

For air as an ideal gas,  $h$  and  $u$  are given in Table A-22 with units of kJ/kg and in Table A-22E in units of Btu/lb. Values of molar specific enthalpy  $\bar{h}$  and internal energy  $\bar{u}$  for several other common gases modeled as ideal gases are given in Tables A-23 with units of kJ/kmol or Btu/lbmol. Quantities other than specific internal energy and enthalpy appearing in these tables are introduced in Chap. 6 and should be ignored at present. Tables A-22 and A-23 are convenient for evaluations involving ideal gases, not only because the variation of the specific heats with temperature is accounted for automatically but also because the tables are easy to use.

The next example illustrates the use of the ideal gas tables, together with the closed system energy balance.

<sup>2</sup>The simple specific heat variation given by Eq. 3.48 is valid only for a limited temperature range, so tabular enthalpy values are calculated from Eq. 3.49 using other expressions that enable the integral to be evaluated accurately over wider ranges of temperature.

### EXAMPLE 3.9

## Using the Energy Balance and Ideal Gas Tables

A piston–cylinder assembly contains 2 lb of air at a temperature of 540°R and a pressure of 1 atm. The air is compressed to a state where the temperature is 840°R and the pressure is 6 atm. During the compression, there is a heat transfer from the air to the surroundings equal to 20 Btu. Using the ideal gas model for air, determine the work during the process, in Btu.

### SOLUTION

**Known:** Two pounds of air are compressed between two specified states while there is heat transfer from the air of a known amount.

**Find:** Determine the work, in Btu.

### Schematic and Given Data:

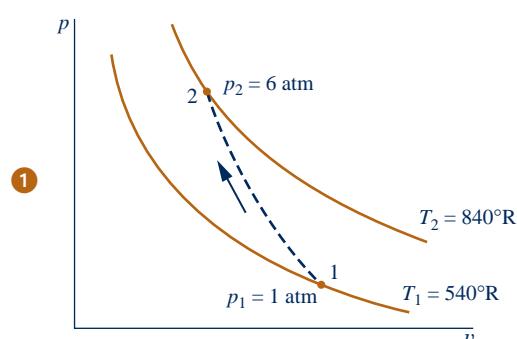
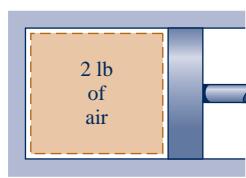


Fig. E3.9



### Engineering Model:

1. The air is a closed system.
2. The initial and final states are equilibrium states. There is no change in kinetic or potential energy.
3. The air is modeled as an ideal gas.
4. The piston is the only work mode.

**Analysis:** An energy balance for the closed system is

$$\Delta KE^0 + \Delta PE^0 + \Delta U = Q - W$$

where the kinetic and potential energy terms vanish by assumption 2. Solving for  $W$

$$③ \quad W = Q - \Delta U = Q - m(u_2 - u_1)$$

From the problem statement,  $Q = -20$  Btu. Also, from Table A-22E at  $T_1 = 540^\circ\text{R}$ ,  $u_1 = 92.04$  Btu/lb, and at  $T_2 = 840^\circ\text{R}$ ,  $u_2 = 143.98$  Btu/lb. Accordingly

$$W = -20 \text{ Btu} - (2 \text{ lb})(143.98 - 92.04) \text{ Btu/lb} = -123.9 \text{ Btu}$$

The minus sign indicates that work is done on the system in the process.

- ① Although the initial and final states are assumed to be equilibrium states, the intervening states are not necessarily equilibrium states, so the process has been indicated on the accompanying  $p$ - $v$  diagram by a dashed line. This dashed line does not define a “path” for the process.
- ② Table A-1E gives  $p_c = 37.2$  atm,  $T_c = 239^\circ\text{R}$  for air. Therefore, at state 1,  $p_{R1} = 0.03$ ,  $T_{R1} = 2.26$ , and at state 2,  $p_{R2} = 0.16$ ,  $T_{R2} = 3.51$ . Referring to Fig. A-1, we conclude that at these states  $Z \approx 1$ , as assumed in the solution.
- ③ In principle, the work could be evaluated through  $\int p dV$ , but because the variation of pressure at the piston face with volume is not known, the integration cannot be performed without more information.

### QuickQUIZ

Replacing air by carbon dioxide, but keeping all other problem statement details the same, evaluate work, in Btu. **Ans.**  $-125.1$  Btu



### Skills Developed

*Ability to...*

- define a closed system and identify interactions on its boundary.
- apply the energy balance using the ideal gas model.

## 3.14.2 • Using Constant Specific Heats

When the specific heats are taken as constants, Eqs. 3.40 and 3.43 reduce, respectively, to

$$u(T_2) - u(T_1) = c_v(T_2 - T_1) \quad (3.50)$$

$$h(T_2) - h(T_1) = c_p(T_2 - T_1) \quad (3.51)$$

Equations 3.50 and 3.51 are often used for thermodynamic analyses involving ideal gases because they enable simple closed-form equations to be developed for many processes.

The constant values of  $c_v$  and  $c_p$  in Eqs. 3.50 and 3.51 are, strictly speaking, mean values calculated as follows

$$c_v = \frac{\int_{T_1}^{T_2} c_v(T) dT}{T_2 - T_1}, \quad c_p = \frac{\int_{T_1}^{T_2} c_p(T) dT}{T_2 - T_1}$$

However, when the variation of  $c_v$  or  $c_p$  over a given temperature interval is slight, little error is normally introduced by taking the specific heat required by Eq. 3.50 or 3.51 as the arithmetic average of the specific heat values at the two end temperatures. Alternatively, the specific heat at the average temperature over the interval can be used. These methods are particularly convenient when tabular specific heat data are available, as in Tables A-20, for then the *constant* specific heat values often can be determined by inspection.

► **FOR EXAMPLE** assuming the specific heat  $c_v$  is a constant and using Eq. 3.50, the expression for work in the solution of Example 3.9 reads

$$W = Q - mc_v(T_2 - T_1)$$

Evaluating  $c_v$  at the average temperature, 690°F (230°C), Table A-20E gives  $c_v = 0.173 \text{ Btu/lb} \cdot ^\circ\text{R}$ . Inserting this value for  $c_v$  together with other data from Example 3.9

$$\begin{aligned} W &= -20 \text{ Btu} - (2 \text{ lb}) \left( 0.173 \frac{\text{Btu}}{\text{lb} \cdot ^\circ\text{R}} \right) (840 - 540)^\circ\text{R} \\ &= -123.8 \text{ Btu} \end{aligned}$$

which agrees closely with the answer obtained in Example 3.9 using Table A-22E data. ◀◀◀◀◀

The following example illustrates the use of the closed system energy balance, together with the ideal gas model and the assumption of constant specific heats.

### EXAMPLE 3.10

## Using the Energy Balance and Constant Specific Heats

Two tanks are connected by a valve. One tank contains 2 kg of carbon monoxide gas at 77°C and 0.7 bar. The other tank holds 8 kg of the same gas at 27°C and 1.2 bar. The valve is opened and the gases are allowed to mix while receiving energy by heat transfer from the surroundings. The final equilibrium temperature is 42°C. Using the ideal gas model with constant  $c_v$ , determine (a) the final equilibrium pressure, in bar (b) the heat transfer for the process, in kJ.

### SOLUTION

**Known:** Two tanks containing different amounts of carbon monoxide gas at initially different states are connected by a valve. The valve is opened and the gas allowed to mix while receiving energy by heat transfer. The final equilibrium temperature is known.

**Find:** Determine the final pressure and the heat transfer for the process.

### Schematic and Given Data:

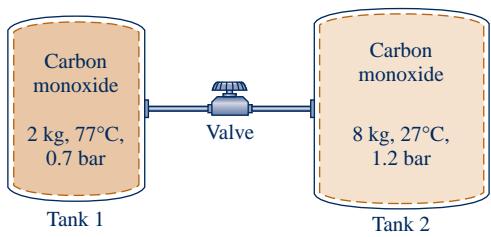


Fig. E3.10

### Engineering Model:

1. The total amount of carbon monoxide gas is a closed system.
2. The gas is modeled as an ideal gas with constant  $c_v$ .
3. The gas initially in each tank is in equilibrium. The final state is an equilibrium state.
4. No energy is transferred to, or from, the gas by work.
5. There is no change in kinetic or potential energy.

1

### Analysis:

(a) The final equilibrium pressure  $p_f$  can be determined from the ideal gas equation of state

$$p_f = \frac{mRT_f}{V}$$

where  $m$  is the sum of the initial amounts of mass present in the two tanks,  $V$  is the total volume of the two tanks, and  $T_f$  is the final equilibrium temperature. Thus

$$p_f = \frac{(m_1 + m_2)RT_f}{V_1 + V_2}$$

Denoting the initial temperature and pressure in tank 1 as  $T_1$  and  $p_1$ , respectively,  $V_1 = m_1RT_1/p_1$ . Similarly, if the initial temperature and pressure in tank 2 are  $T_2$  and  $p_2$ ,  $V_2 = m_2RT_2/p_2$ . Thus, the final pressure is

$$p_f = \frac{(m_1 + m_2)RT_f}{\left(\frac{m_1RT_1}{p_1}\right) + \left(\frac{m_2RT_2}{p_2}\right)} = \frac{(m_1 + m_2)T_f}{\left(\frac{m_1T_1}{p_1}\right) + \left(\frac{m_2T_2}{p_2}\right)}$$

Inserting values

$$p_f = \frac{(10 \text{ kg})(315 \text{ K})}{\frac{(2 \text{ kg})(350 \text{ K})}{0.7 \text{ bar}} + \frac{(8 \text{ kg})(300 \text{ K})}{1.2 \text{ bar}}} = 1.05 \text{ bar}$$

(b) The heat transfer can be found from an energy balance, which reduces with assumptions 4 and 5 to give

$$\Delta U = Q - W^0$$

or

$$Q = U_f - U_i$$

$U_i$  is the initial internal energy, given by

$$U_i = m_1u(T_1) + m_2u(T_2)$$

where  $T_1$  and  $T_2$  are the initial temperatures of the CO in tanks 1 and 2, respectively. The final internal energy is  $U_f$

$$U_f = (m_1 + m_2)u(T_f)$$

Introducing these expressions for internal energy, the energy balance becomes

$$Q = m_1[u(T_f) - u(T_1)] + m_2[u(T_f) - u(T_2)]$$

Since the specific heat  $c_v$  is constant (assumption 2)

$$Q = m_1c_v(T_f - T_1) + m_2c_v(T_f - T_2)$$

Evaluating  $c_v$  as the average of the values listed in Table A-20 at 300 K and 350 K,  $c_v = 0.745 \text{ kJ/kg} \cdot \text{K}$ . Hence

$$Q = (2 \text{ kg})\left(0.745 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}\right)(315 \text{ K} - 350 \text{ K}) + (8 \text{ kg})\left(0.745 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}\right)(315 \text{ K} - 300 \text{ K}) \\ = +37.25 \text{ kJ}$$

The plus sign indicates that the heat transfer is into the system.

- 1 By referring to a generalized compressibility chart, it can be verified that the ideal gas equation of state is appropriate for CO in this range of temperature and pressure. Since the specific heat  $c_v$  of CO varies little over the temperature interval from 300 to 350 K (Table A-20), it can be treated as constant with acceptable accuracy.

### Skills Developed

Ability to...

- define a closed system and identify interactions on its boundary.
- apply the energy balance using the ideal gas model when the specific heat  $c_v$  is constant.

### QuickQUIZ

Evaluate  $Q$  using specific internal energy values for CO from Table A-23. Compare with the result using constant  $c_v$ . **Ans.** 36.99 kJ

### 3.14.3 Using Computer Software

*Interactive Thermodynamics: IT* also provides values of the specific internal energy and enthalpy for a wide range of gases modeled as ideal gases. Let us consider the use of *IT*, first for air, and then for other gases.

**AIR.** For air, *IT* uses the same reference state and reference value as in Table A-22, and the values computed by *IT* agree closely with table data.

► **FOR EXAMPLE** let us use *IT* to evaluate the change in specific enthalpy of air from a state where  $T_1 = 400$  K to a state where  $T_2 = 900$  K. Selecting Air from the **Properties** menu, the following code would be used by *IT* to determine  $\Delta h$  (delh), in kJ/kg

```

h1 = h_T("Air",T1)
h2 = h_T("Air",T2)
T1 = 400//K
T2 = 900//K
delh = h2 - h1

```

Choosing K for the temperature unit and kg for the amount under the **Units** menu, the results returned by *IT* are  $h_1 = 400.8$ ,  $h_2 = 932.5$ , and  $\Delta h = 531.7$  kJ/kg, respectively. These values agree closely with those obtained from Table A-22:  $h_1 = 400.98$ ,  $h_2 = 932.93$ , and  $\Delta h = 531.95$  kJ/kg. ◀◀◀◀◀

**OTHER GASES.** *IT* also provides data for each of the gases included in Table A-23. For these gases, the values of specific internal energy  $\bar{u}$  and enthalpy  $\bar{h}$  returned by *IT* are determined relative to a *standard reference state* that differs from that used in Table A-23. This equips *IT* for use in combustion applications; see Sec. 13.2.1 for further discussion. Consequently, the values of  $\bar{u}$  and  $\bar{h}$  returned by *IT* for the gases of Table A-23 differ from those obtained directly from the table. Still, the property differences between two states remain the same, for datums cancel when differences are calculated.

► **FOR EXAMPLE** let us use *IT* to evaluate the change in specific enthalpy, in kJ/kmol, for carbon dioxide ( $\text{CO}_2$ ) as an ideal gas from a state where  $T_1 = 300$  K to a state where  $T_2 = 500$  K. Selecting  $\text{CO}_2$  from the **Properties** menu, the following code would be used by *IT*:

```

h1 = h_T("CO2",T1)
h2 = h_T("CO2",T2)
T1 = 300//K
T2 = 500//K
delh = h2 - h1

```

Choosing K for the temperature unit and moles for the amount under the **Units** menu, the results returned by *IT* are  $\bar{h}_1 = -3.935 \times 10^5$ ,  $\bar{h}_2 = -3.852 \times 10^5$ , and  $\Delta \bar{h} = 8238$  kJ/mol, respectively. The large negative values for  $\bar{h}_1$  and  $\bar{h}_2$  are a consequence of the reference state and reference value used by *IT* for  $\text{CO}_2$ . Although these values for specific enthalpy at states 1 and 2 differ from the corresponding values read from Table A-23:  $\bar{h}_1 = 9,431$  and  $\bar{h}_2 = 17,678$ , which give  $\Delta \bar{h} = 8247$  kJ/kmol, the *difference* in specific enthalpy determined with each set of data agree closely. ◀◀◀◀◀

The next example illustrates the use of software for problem solving with the ideal gas model. The results obtained are compared with those determined assuming the specific heat  $\bar{c}_v$  is constant.

**EXAMPLE 3.11****Using the Energy Balance and Software**

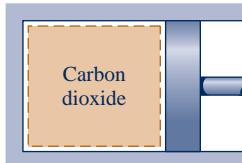
One kmol of carbon dioxide gas ( $\text{CO}_2$ ) in a piston–cylinder assembly undergoes a constant-pressure process at 1 bar from  $T_1 = 300 \text{ K}$  to  $T_2$ . Plot the heat transfer to the gas, in kJ, versus  $T_2$  ranging from 300 to 1500 K. Assume the ideal gas model, and determine the specific internal energy change of the gas using

- (a)  $\bar{u}$  data from *IT*.
- (b) a constant  $\bar{c}_v$  evaluated at  $T_1$  from *IT*.

**SOLUTION**

**Known:** One kmol of  $\text{CO}_2$  undergoes a constant-pressure process in a piston–cylinder assembly. The initial temperature,  $T_1$ , and the pressure are known.

**Find:** Plot the heat transfer versus the final temperature,  $T_2$ . Use the ideal gas model and evaluate  $\Delta\bar{u}$  using (a)  $\bar{u}$  data from *IT*, (b) constant  $\bar{c}_v$  evaluated at  $T_1$  from *IT*.

**Schematic and Given Data:**

$T_1 = 300 \text{ K}$   
 $n = 1 \text{ kmol}$   
 $p = 1 \text{ bar}$

**Fig. E3.11a**

**Engineering Model:**

1. The carbon dioxide is a closed system.
2. The piston is the only work mode, and the process occurs at constant pressure.
3. The carbon dioxide behaves as an ideal gas.
4. Kinetic and potential energy effects are negligible.

**Analysis:** The heat transfer is found using the closed system energy balance, which reduces to

$$U_2 - U_1 = Q - W$$

Using Eq. 2.17 at constant pressure (assumption 2)

$$W = p(V_2 - V_1) = pn(\bar{v}_2 - \bar{v}_1)$$

Then, with  $\Delta U = n(\bar{u}_2 - \bar{u}_1)$ , the energy balance becomes

$$n(\bar{u}_2 - \bar{u}_1) = Q - pn(\bar{v}_2 - \bar{v}_1)$$

Solving for  $Q$

$$\textcircled{1} \quad Q = n[(\bar{u}_2 - \bar{u}_1) + p(\bar{v}_2 - \bar{v}_1)]$$

With  $p\bar{v} = \bar{R}T$ , this becomes

$$Q = n[(\bar{u}_2 - \bar{u}_1) + \bar{R}(T_2 - T_1)]$$

The object is to plot  $Q$  versus  $T_2$  for each of the following cases: (a) values for  $\bar{u}_1$  and  $\bar{u}_2$  at  $T_1$  and  $T_2$ , respectively, are provided by *IT*, (b) Eq. 3.50 is used on a molar basis, namely

$$\bar{u}_2 - \bar{u}_1 = \bar{c}_v(T_2 - T_1)$$

where the value of  $\bar{c}_v$  is evaluated at  $T_1$  using *IT*.

The *IT* program follows, where  $\bar{R}$  denotes  $\overline{R}$ ,  $\bar{c}_v$  denotes  $\overline{c}_v$ , and  $\bar{u}_1$  and  $\bar{u}_2$  denote  $\overline{u}_1$  and  $\overline{u}_2$ , respectively.

```
// Using the Units menu, select "mole" for the substance amount.
//Given Data
T1 = 300//K
T2 = 1500//K
n = 1//kmol
Rbar = 8.314//kJ/kmol · K

// (a) Obtain molar specific internal energy data using IT.
ubar1 = u_T ("CO2", T1)
ubar2 = u_T ("CO2", T2)
Qa = n*(ubar2 - ubar1) + n*Rbar*(T2 - T1)

// (b) Use Eq. 3.50 with cv evaluated at T1.
cvb = cv_T ("CO2", T1)
Qb = n*cvb*(T2 - T1) + n*Rbar*(T2 - T1)
```

Use the **Solve** button to obtain the solution for the sample case of  $T_2 = 1500$  K. For part (a), the program returns  $Q_a = 6.16 \times 10^4$  kJ. The solution can be checked using  $\text{CO}_2$  data from Table A-23, as follows:

$$\begin{aligned} Q_a &= n[(\bar{u}_2 - \bar{u}_1) + \bar{R}(T_2 - T_1)] \\ &= (1 \text{ kmol})[(58,606 - 6939)\text{kJ/kmol} + (8.314 \text{ kJ/kmol} \cdot \text{K})(1500 - 300)\text{K}] \\ &= 61,644 \text{ kJ} \end{aligned}$$

Thus, the result obtained using  $\text{CO}_2$  data from Table A-23 is in close agreement with the computer solution for the sample case. For part (b), *IT* returns  $\bar{c}_v = 28.95 \text{ kJ/kmol} \cdot \text{K}$  at  $T_1$ , giving  $Q_b = 4.472 \times 10^4$  kJ when  $T_2 = 1500$  K. This value agrees with the result obtained using the specific heat  $c_v$  at 300 K from Table A-20, as can be verified.

Now that the computer program has been verified, use the **Explore** button to vary  $T_2$  from 300 to 1500 K in steps of 10. Construct the following graph using the **Graph** button:

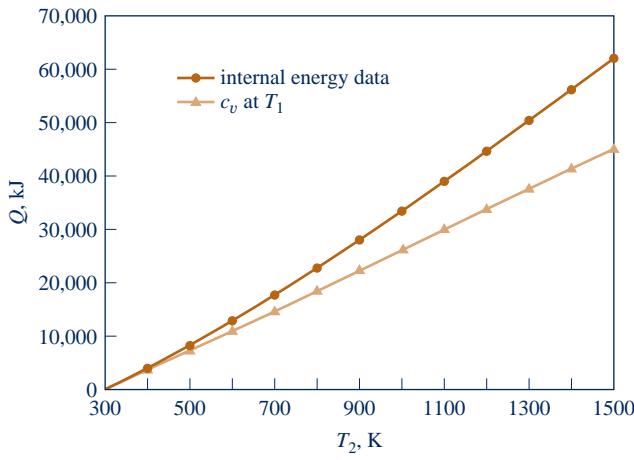


Fig. E3.11b

As expected, the heat transfer is seen to increase as the final temperature increases. From the plots, we also see that using constant  $\bar{c}_v$  evaluated at  $T_1$  for calculating  $\Delta\bar{u}$ , and hence  $Q$ , can lead to considerable error when compared to using  $\bar{u}$  data. The two solutions compare favorably up to about 500 K, but differ by approximately 27% when heating to a temperature of 1500 K.

### Skills Developed

Ability to...

- define a closed system and identify interactions on its boundary.
- apply the energy balance using the ideal gas model.
- use *IT* to retrieve property data for  $\text{CO}_2$  as an ideal gas and plot calculated data.

1 Alternatively, this expression for  $Q$  can be written as

$$Q = n[(\bar{u}_2 + p\bar{v}_2) - (\bar{u}_1 + p\bar{v}_1)]$$

Introducing  $\bar{h} = \bar{u} + p\bar{v}$ , the expression for  $Q$  becomes

$$Q = n(\bar{h}_2 - \bar{h}_1)$$

### QuickQUIZ

Repeat part (b) using  $\bar{c}_v$  evaluated at  $T_{\text{average}} = (T_1 + T_2)/2$ .

Which approach gives better agreement with the results of part (a): evaluating  $\bar{c}_v$  at  $T_1$  or at  $T_{\text{average}}$ ? Ans. At  $T_{\text{average}}$ .

## 3.15 Polytropic Process Relations

A *polytropic process* is a quasiequilibrium process (Sec. 2.2.5) described by

$$pV^n = \text{constant} \quad (3.52)$$

or, in terms of specific volumes, by  $pV^n = \text{constant}$ . In these expressions,  $n$  is a constant.

For a polytropic process between two states

$$p_1 V_1^n = p_2 V_2^n$$

or

$$\frac{p_2}{p_1} = \left( \frac{V_1}{V_2} \right)^n \quad (3.53)$$

The exponent  $n$  may take on any value from  $-\infty$  to  $+\infty$  depending on the particular process. When  $n = 0$ , the process is an isobaric (constant-pressure) process, and when  $n = \pm\infty$  the process is an isometric (constant-volume) process.

For a polytropic process

$$\int_1^2 p \, dV = \frac{p_2 V_2 - p_1 V_1}{1 - n} \quad (n \neq 1) \quad (3.54)$$

for any exponent  $n$  except  $n = 1$ . When  $n = 1$ ,

$$\int_1^2 p \, dV = p_1 V_1 \ln \frac{V_2}{V_1} \quad (n = 1) \quad (3.55)$$

Example 2.1 provides the details of these integrations.

Equations 3.52 through 3.55 apply to *any* gas (or liquid) undergoing a polytropic process. When the *additional* idealization of ideal gas behavior is appropriate, further relations can be derived. Thus, when the ideal gas equation of state is introduced into Eqs. 3.53, 3.54, and 3.55, the following expressions are obtained, respectively

$$\frac{T_2}{T_1} = \left( \frac{p_2}{p_1} \right)^{(n-1)/n} = \left( \frac{V_1}{V_2} \right)^{n-1} \quad (\text{ideal gas}) \quad (3.56)$$

$$\int_1^2 p \, dV = \frac{mR(T_2 - T_1)}{1 - n} \quad (\text{ideal gas, } n \neq 1) \quad (3.57)$$

$$\int_1^2 p \, dV = mRT \ln \frac{V_2}{V_1} \quad (\text{ideal gas, } n = 1) \quad (3.58)$$

For an ideal gas, the case  $n = 1$  corresponds to an isothermal (constant-temperature) process, as can readily be verified.

Example 3.12 illustrates the use of the closed system energy balance for a system consisting of an ideal gas undergoing a polytropic process.

### EXAMPLE 3.12

## Analyzing Polytropic Processes of Air as an Ideal Gas

Air undergoes a polytropic compression in a piston–cylinder assembly from  $p_1 = 1 \text{ atm}$ ,  $T_1 = 70^\circ\text{F}$  to  $p_2 = 5 \text{ atm}$ . Employing the ideal gas model with constant specific heat ratio  $k$ , determine the work and heat transfer per unit mass, in Btu/lb, if (a)  $n = 1.3$ , (b)  $n = k$ . Evaluate  $k$  at  $T_1$ .

### SOLUTION

**Known:** Air undergoes a polytropic compression process from a given initial state to a specified final pressure.

**Find:** Determine the work and heat transfer, each in Btu/lb.

### Schematic and Given Data:

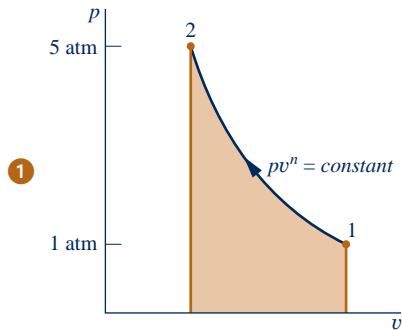
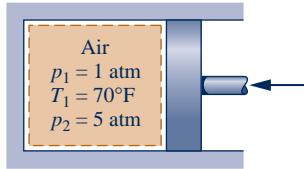


Fig. E3.12



### Engineering Model:

1. The air is a closed system.
2. The air behaves as an ideal gas with constant specific heat ratio  $k$  evaluated at the initial temperature.
3. The compression is polytropic and the piston is the only work mode.
4. There is no change in kinetic or potential energy.

**Analysis:** The work can be evaluated in this case from the expression

$$W = \int_1^2 p \, dV$$

With Eq. 3.57

$$\frac{W}{m} = \frac{R(T_2 - T_1)}{1 - n} \quad (a)$$

The heat transfer can be evaluated from an energy balance. Thus

$$\frac{Q}{m} = \frac{W}{m} + (u_2 - u_1)$$

Inspection of Eq. 3.47b shows that when the specific heat ratio  $k$  is constant,  $c_v$  is constant. Thus

$$\frac{Q}{m} = \frac{W}{m} + c_v(T_2 - T_1) \quad (b)$$

(a) For  $n = 1.3$ , the temperature at the final state,  $T_2$ , can be evaluated from Eq. 3.56 as follows

$$T_2 = T_1 \left( \frac{p_2}{p_1} \right)^{(n-1)/n} = 530^\circ\text{R} \left( \frac{5}{1} \right)^{(1.3-1)/1.3} = 768^\circ\text{R} (308^\circ\text{F})$$

Using Eq. (a), the work is then

$$\frac{W}{m} = \frac{R(T_2 - T_1)}{1 - n} = \left( \frac{1.986 \text{ Btu}}{28.97 \text{ lb} \cdot ^\circ\text{R}} \right) \left( \frac{768^\circ\text{R} - 530^\circ\text{R}}{1 - 1.3} \right) = -54.39 \text{ Btu/lb}$$

At 70°F, Table A-20E gives  $k = 1.401$  and  $c_v = 0.171 \text{ Btu/lb} \cdot ^\circ\text{R}$ . Alternatively,  $c_v$  can be found using Eq. 3.47b, as follows:

$$\begin{aligned} c_v &= \frac{R}{k - 1} \\ &= \frac{(1.986/28.97) \text{ Btu/lb} \cdot ^\circ\text{R}}{(1.401 - 1)} = 0.171 \frac{\text{Btu}}{\text{lb} \cdot ^\circ\text{R}} \end{aligned} \quad (\text{c})$$

Substituting values into Eq. (b), we get

$$\begin{aligned} \frac{Q}{m} &= -54.39 \frac{\text{Btu}}{\text{lb}} + \left( 0.171 \frac{\text{Btu}}{\text{lb} \cdot ^\circ\text{R}} \right) (768^\circ\text{R} - 530^\circ\text{R}) \\ &= -13.69 \frac{\text{Btu}}{\text{lb}} \end{aligned}$$

(b) For  $n = k$ , substituting Eqs. (a) and (c) into Eq. (b) gives

$$\frac{Q}{m} = \frac{R(T_2 - T_1)}{1 - k} + \frac{R(T_2 - T_1)}{k - 1} = 0$$

That is, no heat transfer occurs in the polytropic process of an ideal gas for which  $n = k$ .



### Skills Developed

*Ability to...*

- evaluate work using Eq. 2.17.
- apply the energy balance using the ideal gas model.
- apply the polytropic process concept.

- 1 The states visited in a polytropic compression process are shown by the curve on the accompanying  $p-v$  diagram. The magnitude of the work per unit of mass is represented by the shaded area *below* the curve.

#### QuickQUIZ

For  $n = k$ , evaluate the temperature at the final state, in  $^\circ\text{R}$  and  $^\circ\text{F}$ . Ans.  $840^\circ\text{R}$  ( $380^\circ\text{F}$ )

## ► CHAPTER SUMMARY AND STUDY GUIDE

In this chapter, we have considered property relations for a broad range of substances in tabular, graphical, and equation form. Primary emphasis has been placed on the use of tabular data, but computer retrieval also has been considered.

A key aspect of thermodynamic analysis is fixing states. This is guided by the state principle for pure, simple compressible systems, which indicates that the intensive state is fixed by the values of *any two* independent, intensive properties.

Another important aspect of thermodynamic analysis is locating principal states of processes on appropriate diagrams:  $p-v$ ,  $T-v$ , and  $p-T$  diagrams. The skills of fixing states and using property diagrams are particularly important when solving problems involving the energy balance.

The ideal gas model is introduced in the second part of this chapter, using the compressibility factor as a point of departure. This arrangement emphasizes the limitations of the ideal gas

model. When it is appropriate to use the ideal gas model, we stress that specific heats generally vary with temperature, and feature the use of the ideal gas tables in problem solving.

The following checklist provides a study guide for this chapter. When your study of the text and end-of-chapter exercises has been completed you should be able to

- write out the meanings of the terms listed in the margins throughout the chapter and understand each of the related concepts. The subset of key concepts listed on the next page is particularly important in subsequent chapters.
- retrieve property data from Tables A-1 through A-23, using the state principle to fix states and linear interpolation when required.
- sketch  $T-v$ ,  $p-v$ , and  $p-T$  diagrams, and locate principal states on such diagrams.

- apply the closed system energy balance with property data.
- evaluate the properties of two-phase, liquid–vapor mixtures using Eqs. 3.1, 3.2, 3.6, and 3.7.
- estimate the properties of liquids using Eqs. 3.11–3.14.
- apply the incompressible substance model.
- use the generalized compressibility chart to relate  $p$ – $v$ – $T$  data of gases.
- apply the ideal gas model for thermodynamic analysis, including determining when use of the ideal gas model is warranted, and appropriately using ideal gas table data or constant specific heat data to determine  $\Delta u$  and  $\Delta h$ .

## ► KEY ENGINEERING CONCEPTS

**phase** p. 92  
**pure substance** p. 92  
**state principle** p. 92  
**simple compressible system** p. 92  
 **$p$ – $v$ – $T$  surface** p. 94  
**phase diagram** p. 96  
**saturation temperature** p. 96

**saturation pressure** p. 96  
 **$p$ – $v$  diagram** p. 96  
 **$T$ – $v$  diagram** p. 96  
**compressed liquid** p. 97  
**two-phase, liquid–vapor mixture** p. 98  
**quality** p. 98  
**superheated vapor** p. 98

**enthalpy** p. 106  
**specific heats** p. 117  
**incompressible substance model** p. 119  
**universal gas constant** p. 122  
**compressibility factor** p. 122  
**ideal gas model** p. 128

## ► KEY EQUATIONS

$$x = \frac{m_{\text{vapor}}}{m_{\text{liquid}} + m_{\text{vapor}}}$$

(3.1) p. 98

**Quality,  $x$ , of a two-phase, liquid–vapor mixture.**

$$v = (1 - x)v_f + xv_g = v_f + x(v_g - v_f)$$

(3.2) p. 103

**Specific volume, internal energy and enthalpy of a two-phase, liquid–vapor mixture.**

$$u = (1 - x)u_f + xu_g = u_f + x(u_g - u_f)$$

(3.6) p. 107

$$h = (1 - x)h_f + xh_g = h_f + x(h_g - h_f)$$

(3.7) p. 107

$$v(T, p) \approx v_f(T)$$

(3.11) p. 118

$$u(T, p) \approx u_f(T)$$

(3.12) p. 118

$$h(T, p) \approx h_f(T)$$

(3.14) p. 119

**Specific volume, internal energy, and enthalpy of liquids, approximated by saturated liquid values, respectively.**

### Ideal Gas Model Relations

$$pv = RT$$

(3.32) p. 127

$$u = u(T)$$

(3.36) p. 128

$$h = h(T) = u(T) + RT$$

(3.37) p. 128

**Ideal gas model.**

$$u(T_2) - u(T_1) = \int_{T_1}^{T_2} c_v(T) dT$$

(3.40) p. 131

**Change in specific internal energy.**

$$u(T_2) - u(T_1) = c_v(T_2 - T_1)$$

(3.50) p. 135

**For constant  $c_v$ .**

$$h(T_2) - h(T_1) = \int_{T_1}^{T_2} c_p(T) dT$$

(3.43) p. 131

**Change in specific enthalpy.**

$$h(T_2) - h(T_1) = c_p(T_2 - T_1)$$

(3.51) p. 135

**For constant  $c_p$ .**

## ► EXERCISES: THINGS ENGINEERS THINK ABOUT

1. Why does popcorn *pop*?
2. A plastic milk jug filled with water and stored within a freezer ruptures. Why?
3. Apart from keeping food and beverages cool, what are other uses for *dry ice*?
4. What are several actions you can take to reduce *your CO<sub>2</sub>* emissions?
5. What is the price of tap water, per liter, where you live and how does this compare to the average price of tap water in the United States?
6. When should Table A-5 be used for liquid water *v*, *u*, and *h* values? When should Eqs. 3.11–3.14 be used?
7. A traffic sign states, “Bridge Ices Before Road.” Explain.
8. Home canning of fruits and vegetables can be accomplished with either a boiling water canner or a pressure canner. How does each type of canner operate?
9. An automobile’s radiator cap is labeled “Never open when hot.” Why not?
10. Why are the tires of airplanes and race cars inflated with nitrogen instead of air?
11. If pressure and specific internal energy are known at a state of water vapor, how is the specific volume at that state determined using *IT*? Using the *steam tables*? Repeat if temperature and specific internal energy are known.
12. What is a *molten salt*?
13. How many minutes do you have to exercise to *burn* the calories in a helping of your favorite dessert?

## ► PROBLEMS: DEVELOPING ENGINEERING SKILLS

### Exploring Concepts: Phase and Pure Substance

**3.1** A system consists of liquid water in equilibrium with a gaseous mixture of air and water vapor. How many phases are present? Does the system consist of a pure substance? Explain. Repeat for a system consisting of ice and liquid water in equilibrium with a gaseous mixture of air and water vapor.

**3.2** A system consists of liquid oxygen in equilibrium with oxygen vapor. How many phases are present? The system undergoes a process during which some of the liquid is vaporized. Can the system be viewed as being a pure substance during the process? Explain.

**3.3** A system consisting of liquid water undergoes a process. At the end of the process, some of the liquid water has frozen, and the system contains liquid water and ice. Can the system be viewed as being a pure substance during the process? Explain.

**3.4** A dish of liquid water is placed on a table in a room. After a while, all of the water evaporates. Taking the water and the air in the room to be a closed system, can the system be regarded as a pure substance *during* the process? *After* the process is completed? Discuss.

### Using *p-v-T* Data

**3.5** Determine the phase or phases in a system consisting of H<sub>2</sub>O at the following conditions and sketch *p-v* and *T-v* diagrams showing the location of each state.

- (a)  $p = 80 \text{ lbf/in.}^2$ ,  $T = 312.07^\circ\text{F}$ .
- (b)  $p = 80 \text{ lbf/in.}^2$ ,  $T = 400^\circ\text{F}$ .
- (c)  $T = 400^\circ\text{F}$ ,  $p = 360 \text{ lbf/in.}^2$ .
- (d)  $T = 320^\circ\text{F}$ ,  $p = 70 \text{ lbf/in.}^2$ .
- (e)  $T = 10^\circ\text{F}$ ,  $p = 14.7 \text{ lbf/in.}^2$ .

**3.6** Determine the phase or phases in a system consisting of H<sub>2</sub>O at the following conditions and sketch *p-v* and *T-v* diagrams showing the location of each state.

- (a)  $p = 5 \text{ bar}$ ,  $T = 151.9^\circ\text{C}$ .
- (b)  $p = 5 \text{ bar}$ ,  $T = 200^\circ\text{C}$ .
- (c)  $T = 200^\circ\text{C}$ ,  $p = 2.5 \text{ MPa}$ .
- (d)  $T = 160^\circ\text{C}$ ,  $p = 4.8 \text{ bar}$ .
- (e)  $T = -12^\circ\text{C}$ ,  $p = 1 \text{ bar}$ .

**3.7** The following table lists temperatures and specific volumes of water vapor at two pressures:

$p = 1.0 \text{ MPa}$		$p = 1.5 \text{ MPa}$	
$T (\text{°C})$	$v(\text{m}^3/\text{kg})$	$T (\text{°C})$	$v(\text{m}^3/\text{kg})$
200	0.2060	200	0.1325
240	0.2275	240	0.1483
280	0.2480	280	0.1627

Data encountered in solving problems often do not fall exactly on the grid of values provided by property tables, and *linear interpolation* between adjacent table entries becomes necessary. Using the data provided here, estimate

- (a) the specific volume at  $T = 240^\circ\text{C}$ ,  $p = 1.25 \text{ MPa}$ , in  $\text{m}^3/\text{kg}$ .
- (b) the temperature at  $p = 1.5 \text{ MPa}$ ,  $v = 0.1555 \text{ m}^3/\text{kg}$ , in  $^\circ\text{C}$ .
- (c) the specific volume at  $T = 220^\circ\text{C}$ ,  $p = 1.4 \text{ MPa}$ , in  $\text{m}^3/\text{kg}$ .

**3.8** The following table lists temperatures and specific volumes of ammonia vapor at two pressures:

$p = 50 \text{ lbf/in.}^2$		$p = 60 \text{ lbf/in.}^2$	
$T (\text{°F})$	$v(\text{ft}^3/\text{lb})$	$T (\text{°F})$	$v(\text{ft}^3/\text{lb})$
100	6.836	100	5.659
120	7.110	120	5.891
140	7.380	140	6.120

Data encountered in solving problems often do not fall exactly on the grid of values provided by property tables, and *linear interpolation* between adjacent table entries becomes necessary. Using the data provided here, estimate

- (a) the specific volume at  $T = 120^\circ\text{F}$ ,  $p = 54 \text{ lbf/in.}^2$ , in  $\text{ft}^3/\text{lb}$ .

- (b) the temperature at  $p = 60 \text{ lbf/in.}^2$ ,  $v = 5.982 \text{ ft}^3/\text{lb}$ , in  $^{\circ}\text{F}$ .  
 (c) the specific volume at  $T = 110^{\circ}\text{F}$ ,  $p = 58 \text{ lbf/in.}^2$ , in  $\text{ft}^3/\text{lb}$ .

**3.9** Determine the volume change, in  $\text{ft}^3$ , when 1 lb of water, initially saturated liquid, is heated to saturated vapor while pressure remains constant at 1.0, 14.7, 100, and 500, each in  $\text{lbf/in.}^2$ . Comment.

**3.10** For  $\text{H}_2\text{O}$ , determine the specified property at the indicated state. Locate the state on a sketch of the  $T-v$  diagram.

- (a)  $p = 300 \text{ kPa}$ ,  $v = 0.5 \text{ m}^3/\text{kg}$ . Find  $T$ , in  $^{\circ}\text{C}$ .  
 (b)  $p = 28 \text{ MPa}$ ,  $T = 200^{\circ}\text{C}$ . Find  $v$ , in  $\text{m}^3/\text{kg}$ .  
 (c)  $p = 1 \text{ MPa}$ ,  $T = 405^{\circ}\text{C}$ . Find  $v$ , in  $\text{m}^3/\text{kg}$ .  
 (d)  $T = 100^{\circ}\text{C}$ ,  $x = 60\%$ . Find  $v$ , in  $\text{m}^3/\text{kg}$ .

**3.11** For each case, determine the specific volume at the indicated state. Locate the state on a sketch of the  $T-v$  diagram.

- (a) Water at  $p = 14.7 \text{ lbf/in.}^2$ ,  $T = 100^{\circ}\text{F}$ . Find  $v$ , in  $\text{ft}^3/\text{lb}$ .  
 (b) Ammonia at  $T = -30^{\circ}\text{C}$ ,  $x = 50\%$ . Find  $v$ , in  $\text{m}^3/\text{kg}$ .  
 (c) Refrigerant 134a at  $p = 1.5 \text{ MPa}$ ,  $T = 100^{\circ}\text{C}$ . Find  $v$ , in  $\text{m}^3/\text{kg}$ .

**3.12** For each case, determine the specified property at the indicated state. Locate the state on a sketch of the  $T-v$  diagram.

- (a) Water at  $v = 0.5 \text{ m}^3/\text{kg}$ ,  $p = 3 \text{ bar}$ , determine  $T$ , in  $^{\circ}\text{C}$ .  
 (b) Ammonia at  $p = 11 \text{ lbf/in.}^2$ ,  $T = -20^{\circ}\text{F}$ , determine  $v$ , in  $\text{ft}^3/\text{lb}$ .  
 (c) Propane at  $p = 1 \text{ MPa}$ ,  $T = 85^{\circ}\text{C}$ , determine  $v$ , in  $\text{m}^3/\text{kg}$ .

**3.13** For  $\text{H}_2\text{O}$ , determine the specific volume at the indicated state, in  $\text{m}^3/\text{kg}$ . Locate the states on a sketch of the  $T-v$  diagram.

- (a)  $T = 400^{\circ}\text{C}$ ,  $p = 20 \text{ MPa}$ .  
 (b)  $T = 40^{\circ}\text{C}$ ,  $p = 20 \text{ MPa}$ .  
 (c)  $T = 40^{\circ}\text{C}$ ,  $p = 2 \text{ MPa}$ .

**3.14** For  $\text{H}_2\text{O}$ , locate each of the following states on sketches of the  $p-v$ ,  $T-v$ , and phase diagrams.

- (a)  $T = 120^{\circ}\text{C}$ ,  $p = 5 \text{ bar}$ .  
 (b)  $T = 120^{\circ}\text{C}$ ,  $v = 0.6 \text{ m}^3/\text{kg}$ .  
 (c)  $T = 120^{\circ}\text{C}$ ,  $p = 1 \text{ bar}$ .

**3.15** Complete the following exercises. In each case locate the state on sketches of the  $T-v$  and  $p-v$  diagrams.

- (a) Four kg of water at  $100^{\circ}\text{C}$  fill a closed container having a volume of  $1 \text{ m}^3$ . If the water at this state is a vapor, determine the pressure, in bar. If the water is a two-phase liquid-vapor mixture, determine the quality.  
 (b) Ammonia at a pressure of  $40 \text{ lbf/in.}^2$  has a specific internal energy of  $308.75 \text{ Btu/lb}$ . Determine the specific volume at the state, in  $\text{ft}^3/\text{lb}$ .

**3.16** Two kg of a two-phase, liquid-vapor mixture of carbon dioxide ( $\text{CO}_2$ ) exists at  $-40^{\circ}\text{C}$  in a  $0.05 \text{ m}^3$  tank. Determine the quality of the mixture, if the values of specific volume for saturated liquid and saturated vapor  $\text{CO}_2$  at  $-40^{\circ}\text{C}$  are  $v_f = 0.896 \times 10^{-3} \text{ m}^3/\text{kg}$  and  $v_g = 3.824 \times 10^{-2} \text{ m}^3/\text{kg}$ , respectively.

**3.17** Each of the following exercises requires evaluating the quality of a two-phase liquid-vapor mixture:

- (a) The quality of a two-phase liquid-vapor mixture of  $\text{H}_2\text{O}$  at  $40^{\circ}\text{C}$  with a specific volume of  $10 \text{ m}^3/\text{kg}$  is  
 (i) 0, (ii) 0.486, (iii) 0.512, (iv) 1.  
 (b) The quality of a two-phase liquid-vapor mixture of propane at 20 bar with a specific internal energy of  $300 \text{ kJ/kg}$  is  
 (i) 0.166, (ii) 0.214, (iii) 0.575, (iv) 0.627.  
 (c) The quality of a two-phase liquid-vapor mixture of Refrigerant 134a at  $90 \text{ lbf/in.}^2$  with a specific enthalpy of  $90 \text{ Btu/lb}$  is  
 (i) 0.387, (ii) 0.718, (iii) 0.806, (iv) 0.854.  
 (d) The quality of a two-phase liquid-vapor mixture of ammonia at  $-20^{\circ}\text{F}$  with a specific volume of  $11 \text{ ft}^3/\text{lb}$  is  
 (i) 0, (ii) 0.251, (iii) 0.537, (iv) 0.749.

**3.18** Determine the quality of a two-phase liquid-vapor mixture of

- (a)  $\text{H}_2\text{O}$  at  $10 \text{ lbf/in.}^2$  with a specific volume of  $15 \text{ ft}^3/\text{lb}$ .  
 (b) Refrigerant 134a at  $60^{\circ}\text{F}$  with a specific internal energy of  $50.5 \text{ Btu/lb}$ .  
 (c) ammonia at  $80 \text{ lbf/in.}^2$  with a specific enthalpy of  $350 \text{ Btu/lb}$ .  
 (d) propane at  $-20^{\circ}\text{F}$  with a specific volume of  $1 \text{ ft}^3/\text{lb}$ .

**3.19** A two-phase liquid-vapor mixture of ammonia has a specific volume of  $1.0 \text{ ft}^3/\text{lb}$ . Determine the quality if the temperature is (a)  $100^{\circ}\text{F}$ , (b)  $0^{\circ}\text{F}$ . Locate the states on a sketch of the  $T-v$  diagram.

**3.20** A two-phase liquid-vapor mixture of a substance has a pressure of 150 bar and occupies a volume of  $0.2 \text{ m}^3$ . The masses of saturated liquid and vapor present are 3.8 kg and 4.2 kg, respectively. Determine the specific volume of the mixture, in  $\text{m}^3/\text{kg}$ .

**3.21** As shown in Fig. P3.21, a closed, rigid cylinder contains different volumes of saturated liquid water and saturated water vapor at a temperature of  $150^{\circ}\text{C}$ . Determine the quality of the mixture, expressed as a percent.

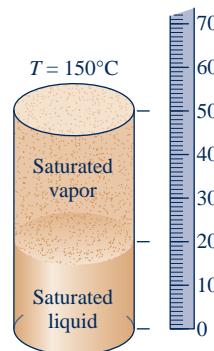


Fig. P3.21

**3.22** As shown in Fig. P3.22, 0.1 kg of water is contained within a piston-cylinder assembly at  $100^{\circ}\text{C}$ . The piston is free to move smoothly in the cylinder. The local atmospheric pressure and acceleration of gravity are  $100 \text{ kPa}$  and  $9.81 \text{ m/s}^2$ , respectively. For the water, determine the pressure, in kPa, and volume, in  $\text{cm}^3$ .

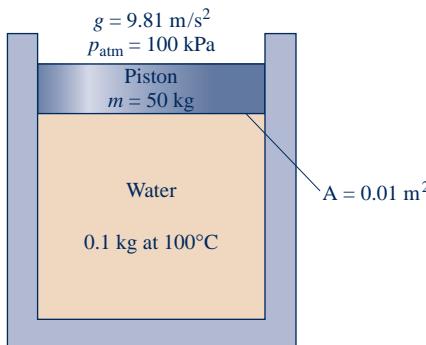


Fig. P3.22

**3.23** Ammonia, initially saturated vapor at  $-4^\circ\text{C}$ , undergoes a constant-specific volume process to 200 kPa. At the final state, determine the temperature, in  $^\circ\text{C}$ , and the quality. Locate each state on a sketch of the  $T$ - $v$  diagram.

**3.24** Water contained in a closed, rigid tank, initially saturated vapor at  $200^\circ\text{C}$ , is cooled to  $100^\circ\text{C}$ . Determine the initial and final pressures, each in bar. Locate the initial and final states on sketches of the  $p$ - $v$  and  $T$ - $v$  diagrams.

**3.25** A closed, rigid tank whose volume is  $1.5 \text{ m}^3$  contains Refrigerant 134a, initially a two-phase liquid-vapor mixture at  $10^\circ\text{C}$ . The refrigerant is heated to a final state where temperature is  $50^\circ\text{C}$  and quality is 100%. Locate the initial and final states on a sketch of the  $T$ - $v$  diagram. Determine the mass of vapor present at the initial and final states, each in kg.

**3.26** In each of the following cases, ammonia contained in a closed, rigid tank is heated from an initial saturated vapor state at temperature  $T_1$  to the final temperature,  $T_2$ :

- (a)  $T_1 = 20^\circ\text{C}$ ,  $T_2 = 40^\circ\text{C}$ . Using IT, determine the final pressure, in bar.
- (b)  $T_1 = 70^\circ\text{F}$ ,  $T_2 = 120^\circ\text{F}$ . Using IT, determine the final pressure, in lbf/in.<sup>2</sup>.

Compare the pressure values determined using IT with those obtained using the appropriate Appendix tables for ammonia.

**3.27** Propane is contained in a closed, rigid container with a volume of  $10 \text{ m}^3$ . Initially the pressure and temperature of the propane are 8 bar and  $80^\circ\text{C}$ , respectively. The temperature drops as a result of energy rejected by heat transfer to the surroundings. Determine the temperature at which condensation first occurs, in  $^\circ\text{C}$ , and the fraction of the total mass that has condensed when the pressure reaches 5 bar. What is the volume, in  $\text{m}^3$ , occupied by saturated liquid at the final state?

**3.28** Water vapor is cooled in a closed, rigid tank from  $520^\circ\text{C}$  and 100 bar to a final temperature of  $270^\circ\text{C}$ . Determine the final pressure, in bar, and sketch the process on  $T$ - $v$  and  $p$ - $v$  diagrams.

**3.29** Ammonia contained in a piston-cylinder assembly, initially saturated vapor at  $0^\circ\text{F}$ , undergoes an isothermal process during which its volume (a) doubles, (b) reduces by a half. For each case, fix the final state by giving the quality or pressure, in lbf/in.<sup>2</sup>, as appropriate. Locate the initial and final states on sketches of the  $p$ - $v$  and  $T$ - $v$  diagrams.

**3.30** One kg of water initially is at the critical point.

- (a) If the water is cooled at constant-specific volume to a pressure of 30 bar, determine the quality at the final state.
- (b) If the water undergoes a constant-temperature expansion to a pressure of 30 bar, determine the specific volume at the final state, in  $\text{m}^3/\text{kg}$ .

Show each process on a sketch of the  $T$ - $v$  diagram.

**3.31** As shown in Fig. P3.31, a cylinder fitted with a piston is filled with 600 lb of saturated liquid ammonia at  $45^\circ\text{F}$ . The piston weighs 1 ton and has a diameter of 2.5 ft. What is the volume occupied by the ammonia, in  $\text{ft}^3$ ? Ignoring friction, is it necessary to provide mechanical attachments, such as stops, to hold the piston in place? Explain.

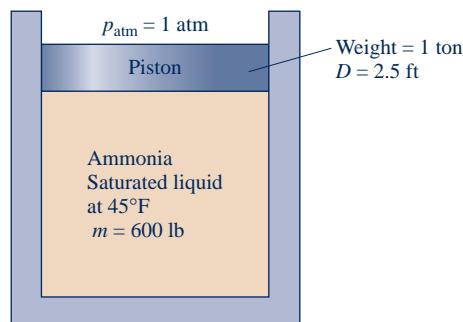


Fig. P3.31

**3.32** Two lb of water vapor in a piston-cylinder assembly is compressed at a constant pressure of  $250 \text{ lbf/in.}^2$  from a volume of  $6.88 \text{ ft}^3$  to a saturated vapor state. Determine the temperatures at the initial and final states, each in  $^\circ\text{F}$ , and the work for the process, in Btu.

**3.33** Seven lb of propane in a piston-cylinder assembly, initially at  $p_1 = 200 \text{ lbf/in.}^2$  and  $T_1 = 200^\circ\text{F}$ , undergoes a constant-pressure process to a final state. The work for the process is  $-88.84 \text{ Btu}$ . At the final state, determine the temperature, in  $^\circ\text{F}$ , if superheated, or the quality if saturated.

**3.34** Ammonia in a piston-cylinder assembly undergoes a constant-pressure process at 2.5 bar from  $T_1 = 30^\circ\text{C}$  to saturated vapor. Determine the work for the process, in kJ per kg of refrigerant.

**3.35** From an initial state where the pressure is  $p_1$ , the temperature is  $T_1$ , and the volume is  $V_1$ , water vapor contained in a piston-cylinder assembly undergoes each of the following processes:

**Process 1-2:** Constant-temperature to  $p_2 = 2p_1$ .

**Process 1-3:** Constant-volume to  $p_3 = 2p_1$ .

**Process 1-4:** Constant-pressure to  $V_4 = 2V_1$ .

**Process 1-5:** Constant-temperature to  $V_5 = 2V_1$

On a  $p$ - $V$  diagram, sketch each process, identify the work by an area on the diagram, and indicate whether the work is done by, or on, the water vapor.

**3.36** Three kilograms of Refrigerant 22 undergo a process for which the pressure-specific volume relation is  $pv^{-0.8} = \text{constant}$ . The initial state of the refrigerant is 12 bar and  $60^\circ\text{C}$ , and the

final pressure is 8 bar. Kinetic and potential energy effects are negligible. Determine the work, in kJ, for the process.

- 3.37** As shown in Fig. P3.37, Refrigerant 134a is contained in a piston–cylinder assembly, initially as saturated vapor. The refrigerant is slowly heated until its temperature is 160°C. During the process, the piston moves smoothly in the cylinder. For the refrigerant, evaluate the work, in kJ/kg.

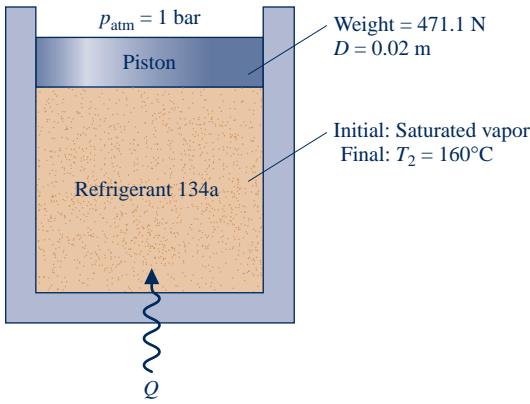


Fig. P3.37

- 3.38** A piston–cylinder assembly contains 0.1 lb of propane. The propane expands from an initial state where  $p_1 = 60 \text{ lbf/in.}^2$  and  $T_1 = 30^\circ\text{F}$  to a final state where  $p_2 = 10 \text{ lbf/in.}^2$ . During the process, the pressure and specific volume are related by  $pv^2 = \text{constant}$ . Determine the energy transfer by work, in Btu.

#### Using $u$ - $h$ Data

- 3.39** Determine the values of the specified properties at each of the following conditions.

- (a) For Refrigerant 134a at  $T = 60^\circ\text{C}$  and  $v = 0.072 \text{ m}^3/\text{kg}$ , determine  $p$  in kPa and  $h$  in kJ/kg.
- (b) For ammonia at  $p = 8 \text{ bar}$  and  $v = 0.005 \text{ m}^3/\text{kg}$ , determine  $T$  in  $^\circ\text{C}$  and  $u$  in kJ/kg.
- (c) For Refrigerant 22 at  $T = -10^\circ\text{C}$  and  $u = 200 \text{ kJ/kg}$ , determine  $p$  in bar and  $v$  in  $\text{m}^3/\text{kg}$ .

- 3.40** Determine the values of the specified properties at each of the following conditions.

- (a) For Refrigerant 134a at  $p = 140 \text{ lbf/in.}^2$  and  $h = 100 \text{ Btu/lb}$ , determine  $T$  in  $^\circ\text{F}$  and  $v$  in  $\text{ft}^3/\text{lb}$ .
- (b) For ammonia at  $T = 0^\circ\text{F}$  and  $v = 15 \text{ ft}^3/\text{lb}$ , determine  $p$  in  $\text{lbf/in.}^2$  and  $h$  in  $\text{Btu/lb}$ .
- (c) For Refrigerant 22 at  $T = 30^\circ\text{F}$  and  $v = 1.2 \text{ ft}^3/\text{lb}$ , determine  $p$  in  $\text{lbf/in.}^2$  and  $h$  in  $\text{Btu/lb}$ .

- 3.41** Using  $IT$ , determine the specified property data at the indicated states. Compare with results from the appropriate table.



- (a) Cases (a), (b), and (c) of Problem 3.39.
- (b) Cases (a), (b), and (c) of Problem 3.40.

- 3.42** Using the tables for water, determine the specified property data at the indicated states. In each case, locate the state by hand on sketches of the  $p$ - $v$  and  $T$ - $v$  diagrams.

- (a) At  $p = 2 \text{ MPa}$ ,  $T = 300^\circ\text{C}$ . Find  $u$ , in kJ/kg.
- (b) At  $p = 2.5 \text{ MPa}$ ,  $T = 200^\circ\text{C}$ . Find  $u$ , in kJ/kg.
- (c) At  $T = 170^\circ\text{F}$ ,  $x = 50\%$ . Find  $u$ , in Btu/lb.
- (d) At  $p = 100 \text{ lbf/in.}^2$ ,  $T = 300^\circ\text{F}$ . Find  $h$ , in Btu/lb
- (e) At  $p = 1.5 \text{ MPa}$ ,  $v = 0.2095 \text{ m}^3/\text{kg}$ . Find  $h$ , in kJ/kg.

- 3.43** For each case, determine the specified property value and locate the state by hand on sketches of the  $p$ - $v$  and  $T$ - $v$  diagrams.

- (a) For Refrigerant 134a at  $T = 160^\circ\text{F}$ ,  $h = 127.7 \text{ Btu/lb}$ . Find  $v$ , in  $\text{ft}^3/\text{lb}$ .
- (b) For Refrigerant 134a at  $T = 90^\circ\text{F}$ ,  $u = 72.71 \text{ Btu/lb}$ . Find  $h$ , in Btu/lb.
- (c) For ammonia at  $T = 160^\circ\text{F}$ ,  $p = 60 \text{ lbf/in.}^2$ . Find  $u$ , in Btu/lb.
- (d) For ammonia at  $T = 0^\circ\text{F}$ ,  $p = 35 \text{ lbf/in.}^2$ . Find  $u$ , in Btu/lb.
- (e) For Refrigerant 22 at  $p = 350 \text{ lbf/in.}^2$ ,  $T = 350^\circ\text{F}$ . Find  $u$ , in Btu/lb.

- 3.44** Using the tables for water, determine the specified property data at the indicated states. In each case, locate the state by hand on sketches of the  $p$ - $v$  and  $T$ - $v$  diagrams.

- (a) At  $p = 3 \text{ bar}$ ,  $v = 0.5 \text{ m}^3/\text{kg}$ , find  $T$  in  $^\circ\text{C}$  and  $u$  in kJ/kg.
- (b) At  $T = 320^\circ\text{C}$ ,  $v = 0.03 \text{ m}^3/\text{kg}$ , find  $p$  in MPa and  $u$  in kJ/kg.
- (c) At  $p = 28 \text{ MPa}$ ,  $T = 520^\circ\text{C}$ , find  $v$  in  $\text{m}^3/\text{kg}$  and  $h$  in kJ/kg.
- (d) At  $T = 10^\circ\text{C}$ ,  $v = 100 \text{ m}^3/\text{kg}$ , find  $p$  in kPa and  $h$  in kJ/kg.
- (e) At  $p = 4 \text{ MPa}$ ,  $T = 160^\circ\text{C}$ , find  $v$  in  $\text{m}^3/\text{kg}$  and  $u$  in kJ/kg.

- 3.45** Using the tables for water, determine the specified property data at the indicated states. In each case, locate the state by hand on sketches of the  $p$ - $v$  and  $T$ - $v$  diagrams.

- (a) At  $p = 20 \text{ lbf/in.}^2$ ,  $v = 16 \text{ ft}^3/\text{lb}$ , find  $T$  in  $^\circ\text{F}$  and  $u$  in Btu/lb.
- (b) At  $T = 900^\circ\text{F}$ ,  $p = 170 \text{ lbf/in.}^2$ , find  $v$  in  $\text{ft}^3/\text{lb}$  and  $h$  in Btu/lb.
- (c) At  $T = 600^\circ\text{F}$ ,  $v = 0.6 \text{ ft}^3/\text{lb}$ , find  $p$  in  $\text{lbf/in.}^2$  and  $u$  in Btu/lb.
- (d) At  $T = 40^\circ\text{F}$ ,  $v = 1950 \text{ ft}^3/\text{lb}$ , find  $p$  in  $\text{lbf/in.}^2$  and  $h$  in Btu/lb.
- (e) At  $p = 600 \text{ lbf/in.}^2$ ,  $T = 320^\circ\text{F}$ , find  $v$  in  $\text{ft}^3/\text{lb}$  and  $u$  in Btu/lb.

- 3.46** For each case, determine the specified property data and locate the state by hand on a sketch of the  $T$ - $v$  diagram.

- (a) Evaluate the specific volume, in  $\text{ft}^3/\text{lb}$ , and the specific enthalpy, in  $\text{Btu/lb}$ , of water at  $400^\circ\text{F}$  and a pressure of  $3000 \text{ lbf/in.}^2$ .
- (b) Evaluate the specific volume, in  $\text{ft}^3/\text{lb}$ , and the specific enthalpy, in  $\text{Btu/lb}$ , of Refrigerant 134a at  $95^\circ\text{F}$  and  $150 \text{ lbf/in.}^2$ .
- (c) Evaluate the specific volume, in  $\text{m}^3/\text{kg}$ , and the specific enthalpy, in  $\text{kJ/kg}$ , of ammonia at  $20^\circ\text{C}$  and  $1.0 \text{ MPa}$ .
- (d) Evaluate the specific volume, in  $\text{m}^3/\text{kg}$ , and the specific enthalpy, in  $\text{kJ/kg}$ , of propane at  $800 \text{ kPa}$  and  $0^\circ\text{C}$ .

#### Applying the Energy Balance

- 3.47** Water, initially saturated vapor at 4 bar, fills a closed, rigid container. The water is heated until its temperature is  $400^\circ\text{C}$ . For the water, determine the heat transfer, in  $\text{kJ/kg}$ . Kinetic and potential energy effects can be ignored.

**3.48** A closed, rigid tank contains Refrigerant 134a, initially at 100°C. The refrigerant is cooled until it becomes saturated vapor at 20°C. For the refrigerant, determine the initial and final pressures, each in bar, and the heat transfer, in kJ/kg. Kinetic and potential energy effects can be ignored.

**3.49** A closed, rigid tank is filled with water. Initially, the tank holds 9.9 ft<sup>3</sup> saturated vapor and 0.1 ft<sup>3</sup> saturated liquid, each at 212°F. The water is heated until the tank contains only saturated vapor. For the water, determine (a) the quality at the initial state, (b) the temperature at the final state, in °F, and (c) the heat transfer, in Btu. Kinetic and potential energy effects can be ignored.

**3.50** A closed, rigid tank is filled with water, initially at the critical point. The water is cooled until it attains a temperature of 400°F. For the water, show the process on a sketch of the *T-v* diagram and determine the heat transfer, in Btu/lb.

**3.51** Propane within a piston–cylinder assembly undergoes a constant-pressure process from saturated vapor at 400 kPa to a temperature of 40°C. Kinetic and potential energy effects are negligible. For the propane, (a) show the process on a *p-v* diagram, (b) evaluate the work, in kJ/kg, and (c) evaluate the heat transfer, in kJ/kg.

**3.52** Refrigerant 134a expands in a piston–cylinder assembly from 180 lbf/in.<sup>2</sup> and 140°F to 30 lbf/in.<sup>2</sup> The mass of refrigerant is 0.5 lb. During the process, heat transfer to the refrigerant from its surroundings is 1.2 Btu while the work done by the refrigerant is 4.32 Btu. Determine the final temperature of the refrigerant, in °F. Kinetic and potential energy effects are negligible.

**3.53** Ammonia vapor in a piston–cylinder assembly undergoes a constant-pressure process from saturated vapor at 10 bar. The work is +16.5 kJ/kg. Changes in kinetic and potential energy are negligible. Determine (a) the final temperature of the ammonia, in °C, and (b) the heat transfer, in kJ/kg.

**3.54** Water in a piston–cylinder assembly, initially at a temperature of 99.63°C and a quality of 65%, is heated at constant pressure to a temperature of 200°C. If the work during the process is +300 kJ, determine (a) the mass of water, in kg, and (b) the heat transfer, in kJ. Changes in kinetic and potential energy are negligible.

**3.55** A piston–cylinder assembly containing water, initially a liquid at 50°F, undergoes a process at a constant pressure of 20 lbf/in.<sup>2</sup> to a final state where the water is a vapor at 300°F. Kinetic and potential energy effects are negligible. Determine the work and heat transfer, in Btu per lb, for each of three parts of the overall process: (a) from the initial liquid state to the saturated liquid state, (b) from saturated liquid to saturated vapor, and (c) from saturated vapor to the final vapor state, all at 20 lbf/in.<sup>2</sup>

**3.56** As shown in Fig. P3.56, 0.1 kg of propane is contained within a piston–cylinder assembly at a constant pressure of 0.2 MPa. Energy transfer by heat occurs slowly to the propane, and the volume of the propane increases from 0.0277 m<sup>3</sup> to 0.0307 m<sup>3</sup>. Friction between the piston and cylinder is negligible. The local atmospheric pressure and acceleration of gravity are 100 kPa and 9.81 m/s<sup>2</sup>, respectively. The propane experiences no significant kinetic and potential energy effects. For the propane, determine (a) the initial and

final temperatures, in °C, (b) the work, in kJ, and (c) the heat transfer, in kJ.

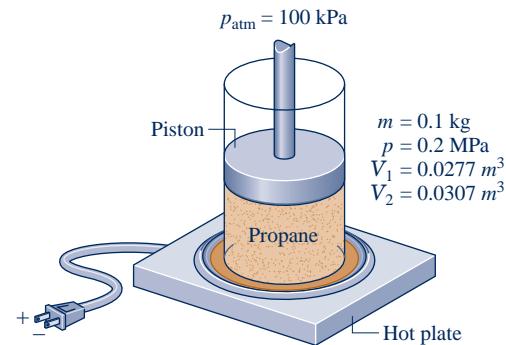


Fig. P3.56

**3.57** A piston–cylinder assembly contains water, initially saturated liquid at 150°C. The water is heated at constant temperature to saturated vapor.

(a) If the rate of heat transfer to the water is 2.28 kW, determine the rate at which work is done by the water on the piston, in kW.

(b) If in addition to the heat transfer rate given in part (a) the total mass of water is 0.1 kg, determine the time, in s, required to execute the process.

**3.58** A closed, rigid tank contains 2 kg of water, initially a two-phase liquid–vapor mixture at 80°C. Heat transfer occurs until the tank contains only saturated vapor with  $v = 2.045 \text{ m}^3/\text{kg}$ . For the water, locate the initial and final states on a sketch of the *T-v* diagram and determine the heat transfer, in kJ.

**3.59** As shown in Fig. P3.59, a rigid, closed tank having a volume of 20 ft<sup>3</sup> and filled with 75 lb of Refrigerant 134a is exposed to the sun. At 9:00 a.m., the refrigerant is at a pressure of 100 lbf/in.<sup>2</sup> By 3:00 p.m., owing to solar radiation, the refrigerant is a saturated vapor at a pressure greater than 100 lbf/in.<sup>2</sup> For the refrigerant, determine (a) the initial

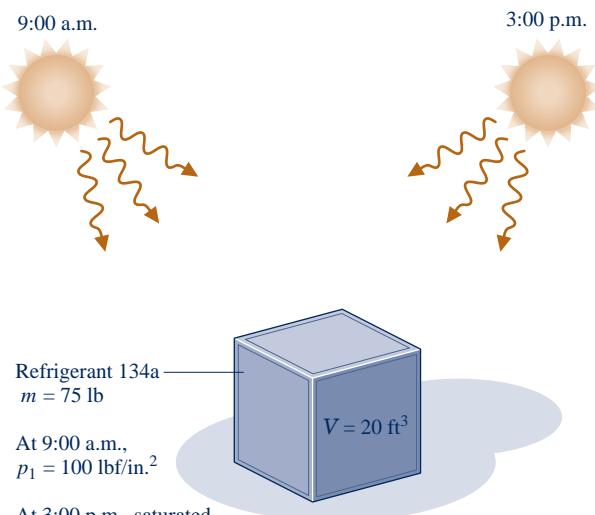


Fig. P3.59

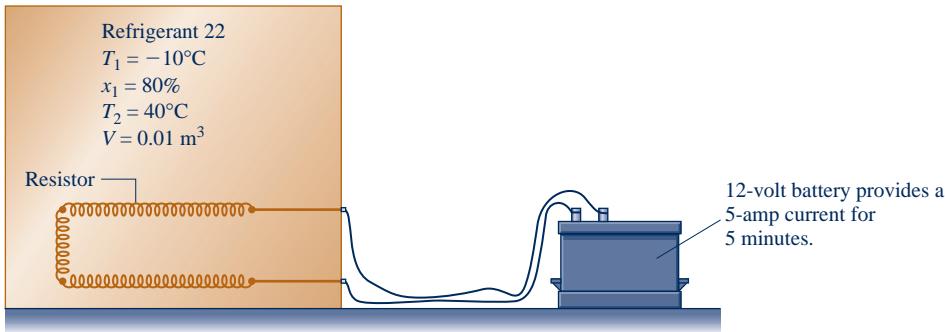


Fig. P3.63

temperature, in  $^\circ\text{F}$ , (b) the final pressure, in  $\text{lbf/in.}^2$ , and (c) the heat transfer, in Btu.

- 3.60** A rigid, insulated tank fitted with a paddle wheel is filled with water, initially a two-phase liquid–vapor mixture at  $20 \text{ lbf/in.}^2$ , consisting of 0.07 lb of saturated liquid and 0.07 lb of saturated vapor. The tank contents are stirred by the paddle wheel until all of the water is saturated vapor at a pressure greater than  $20 \text{ lbf/in.}^2$ . Kinetic and potential energy effects are negligible. For the water, determine the

- volume occupied, in  $\text{ft}^3$ .
- initial temperature, in  $^\circ\text{F}$ .
- final pressure, in  $\text{lbf/in.}^2$ .
- work, in Btu.

- 3.61** If the hot plate of Example 3.2 transfers energy at a rate of 0.1 kW to the two-phase mixture, determine the time required, in h, to bring the mixture from (a) state 1 to state 2, (b) state 1 to state 3.

- 3.62** A closed, rigid tank filled with water, initially at 20 bar, a quality of 80%, and a volume of  $0.5 \text{ m}^3$ , is cooled until the pressure is 4 bar. Show the process of the water on a sketch of the  $T$ – $v$  diagram and evaluate the heat transfer, in kJ.

- 3.63** As shown in Fig. P3.63, a closed, rigid tank fitted with a fine-wire electric resistor is filled with Refrigerant 22, initially at  $-10^\circ\text{C}$ , a quality of 80%, and a volume of  $0.01 \text{ m}^3$ . A 12-volt battery provides a 5-amp current to the resistor for 5 minutes. If the final temperature of the refrigerant is  $40^\circ\text{C}$ , determine the heat transfer, in kJ, from the refrigerant.

- 3.64** A rigid, well-insulated tank contains a two-phase mixture of ammonia with  $0.0025 \text{ ft}^3$  of saturated liquid and  $1.5 \text{ ft}^3$  of saturated vapor, initially at  $40 \text{ lbf/in.}^2$ . A paddle wheel stirs the mixture until only saturated vapor at higher pressure remains in the tank. Kinetic and potential energy effects are negligible. For the ammonia, determine the amount of energy transfer by work, in Btu.

- 3.65** A closed, rigid tank is filled with 0.02 lb of water, initially at  $120^\circ\text{F}$  and a quality of 50%. The water receives 8 Btu by heat transfer. Determine the temperature, in  $^\circ\text{F}$ , pressure, in  $\text{lbf/in.}^2$ , and quality of the water at its final state.

- 3.66** A piston–cylinder assembly contains ammonia, initially at a temperature of  $-20^\circ\text{C}$  and a quality of 50%. The ammonia is slowly heated to a final state where the pressure is 6 bar and the temperature is  $180^\circ\text{C}$ . While the ammonia is heated,

its pressure varies linearly with specific volume. Show the process of the ammonia on a sketch of the  $p$ – $v$  diagram. For the ammonia, determine the work and heat transfer, each in  $\text{kJ/kg}$ .

- 3.67** A rigid, well-insulated container with a volume of  $2 \text{ ft}^3$  holds 0.12 lb of ammonia initially at a pressure of  $20 \text{ lbf/in.}^2$ . The ammonia is stirred by a paddle wheel, resulting in an energy transfer to the ammonia with a magnitude of 1 Btu. For the ammonia, determine the initial and final temperatures, each in  $^\circ\text{R}$ , and the final pressure, in  $\text{lbf/in.}^2$ . Neglect kinetic and potential energy effects.

- 3.68** Water contained in a piston–cylinder assembly, initially at  $300^\circ\text{F}$ , a quality of 90%, and a volume of  $6 \text{ ft}^3$ , is heated at constant temperature to saturated vapor. If the rate of heat transfer is 0.3 Btu/s, determine the time, in min, for this process of the water to occur. Kinetic and potential energy effects are negligible.

- 3.69** Five kg of water is contained in a piston–cylinder assembly, initially at 5 bar and  $240^\circ\text{C}$ . The water is slowly heated at constant pressure to a final state. If the heat transfer for the process is 2960 kJ, determine the temperature at the final state, in  $^\circ\text{C}$ , and the work, in kJ. Kinetic and potential energy effects are negligible.

- 3.70** Referring to Fig. P3.70, water contained in a piston–cylinder assembly, initially at 1.5 bar and a quality of 20%, is heated at constant pressure until the piston hits the stops. Heating then continues until the water is saturated vapor. Show the processes of the water in series on a sketch of the  $T$ – $v$  diagram. For the overall process of the water, evaluate the work and heat transfer, each in  $\text{kJ/kg}$ . Kinetic and potential effects are negligible.

- 3.71** A piston–cylinder assembly contains 2 lb of water, initially at  $300^\circ\text{F}$ . The water undergoes two processes in series: constant-volume heating followed by a constant-pressure process. At the end of the constant-volume process, the pressure is  $100 \text{ lbf/in.}^2$  and the water is a two-phase, liquid–vapor mixture with a quality of 80%. At the end of the constant-pressure process, the temperature is  $400^\circ\text{F}$ . Neglect kinetic and potential energy effects.

- Sketch  $T$ – $v$  and  $p$ – $v$  diagrams showing key states and the processes.
- Determine the work and heat transfer for each of the two processes, all in Btu.

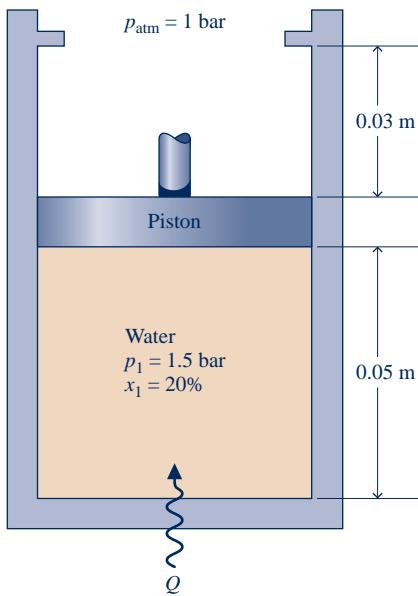


Fig. P3.70

**3.72** A system consisting of 3 lb of water vapor in a piston–cylinder assembly, initially at 350°F and a volume of 71.7 ft<sup>3</sup>, is expanded in a constant-pressure process to a volume of 85.38 ft<sup>3</sup>. The system then is compressed isothermally to a final volume of 28.2 ft<sup>3</sup>. During the isothermal compression, energy transfer by work into the system is 72 Btu. Kinetic and potential energy effects are negligible. Determine the heat transfer, in Btu, for each process.

**3.73** Ammonia in a piston–cylinder assembly undergoes two processes in series. Initially, the ammonia is saturated vapor at  $p_1 = 100 \text{ lbf/in}^2$ . Process 1–2 involves cooling at constant pressure until  $x_2 = 75\%$ . The second process, from state 2 to state 3, involves heating at constant volume until  $x_3 = 100\%$ . Kinetic and potential energy effects are negligible. For 1.2 lb of ammonia, determine (a) the heat transfer and work for Process 1–2 and (b) the heat transfer for Process 2–3, all in Btu.

**3.74** Three lb of water is contained in a piston–cylinder assembly, initially occupying a volume  $V_1 = 30 \text{ ft}^3$  at  $T_1 = 300^\circ\text{F}$ . The water undergoes two processes in series:

**Process 1–2:** Constant-temperature compression to  $V_2 = 11.19 \text{ ft}^3$ , during which there is an energy transfer by heat *from* the water of 1275 Btu.

**Process 2–3:** Constant-volume heating to  $p_3 = 120 \text{ lbf/in}^2$

Sketch the two processes in series on a  $T$ – $v$  diagram. Neglecting kinetic and potential energy effects, determine the work in Process 1–2 and the heat transfer in Process 2–3, each in Btu.

**3.75** As shown in Fig. P3.75, a piston–cylinder assembly fitted with stops contains 0.1 kg of water, initially at 1 MPa, 500°C. The water undergoes two processes in series:

**Process 1–2:** Constant-pressure cooling until the piston face rests against the stops. The volume occupied by the water is then one-half its initial volume.

**Process 2–3:** With the piston face resting against the stops, the water cools to 25°C.

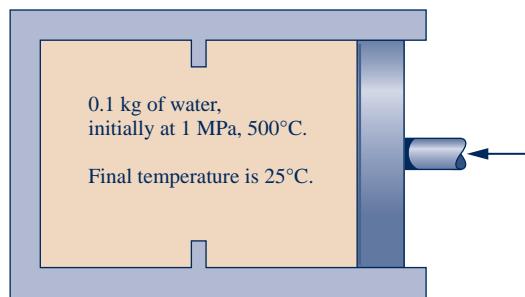


Fig. P3.75

Sketch the two processes in series on a  $p$ – $v$  diagram. Neglecting kinetic and potential energy effects, evaluate for each process the work and heat transfer, each in kJ.

**3.76** A two-phase, liquid–vapor mixture of H<sub>2</sub>O, initially at  $x = 30\%$  and a pressure of 100 kPa, is contained in a piston–cylinder assembly, as shown in Fig P3.76. The mass of the piston is 10 kg, and its diameter is 15 cm. The pressure of the surroundings is 100 kPa. As the water is heated, the pressure inside the cylinder remains constant until the piston hits the stops. Heat transfer to the water continues at constant volume until the pressure is 150 kPa. Friction between the piston and the cylinder wall and kinetic and potential energy effects are negligible. For the overall process of the water, determine the work and heat transfer, each in kJ.

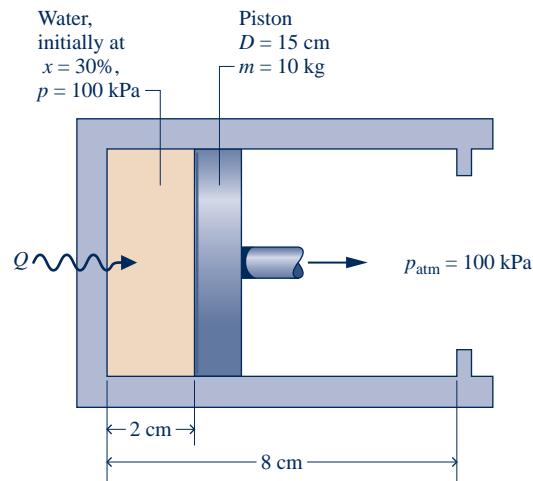


Fig. P3.76

**3.77** A system consisting of 1 kg of H<sub>2</sub>O undergoes a power cycle composed of the following processes:

**Process 1–2:** Constant-pressure heating at 10 bar from saturated vapor.

**Process 2–3:** Constant-volume cooling to  $p_3 = 5 \text{ bar}$ ,  $T_3 = 160^\circ\text{C}$ .

**Process 3–4:** Isothermal compression with  $Q_{34} = -815.8 \text{ kJ}$ .

**Process 4–1:** Constant-volume heating.

Sketch the cycle on  $T$ – $v$  and  $p$ – $v$  diagrams. Neglecting kinetic and potential energy effects, determine the thermal efficiency.

**3.78** One lb of water contained in a piston–cylinder assembly undergoes the power cycle shown in Fig. P3.78. For each of the four processes, evaluate the work and heat transfer, each in Btu. For the overall cycle, evaluate the thermal efficiency.

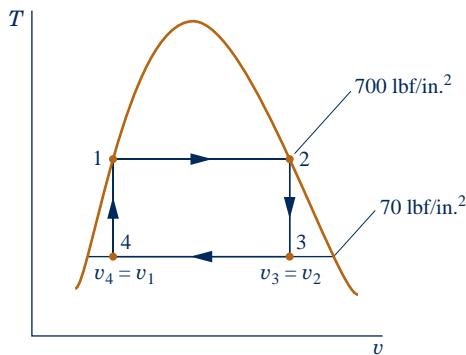


Fig. P3.78

**3.79** One-half kg of Refrigerant-22 is contained in a piston–cylinder assembly, initially saturated vapor at 5 bar. The refrigerant undergoes a process for which the pressure–specific volume relation is  $pv = \text{constant}$  to a final pressure of 20 bar. Kinetic and potential energy effects can be neglected. Determine the work and heat transfer for the process, each in kJ.

**3.80** Ten kilograms of Refrigerant 22 contained in a piston–cylinder assembly undergoes a process for which the pressure–specific volume relationship is  $pv^n = \text{constant}$ . The initial and final states of the refrigerant are fixed by  $p_1 = 400 \text{ kPa}$ ,  $T_1 = -5^\circ\text{C}$ , and  $p_2 = 2000 \text{ kPa}$ ,  $T_2 = 70^\circ\text{C}$ , respectively. Determine the work and heat transfer for the process, each in kJ.

**3.81** A piston–cylinder assembly contains ammonia, initially at 0.8 bar and  $-10^\circ\text{C}$ . The ammonia is compressed to a pressure of 5.5 bar. During the process, the pressure and specific volume are related by  $pv = \text{constant}$ . For 20 kg of ammonia, determine the work and heat transfer, each in kJ.

**3.82** A piston–cylinder assembly contains propane, initially at  $27^\circ\text{C}$ , 1 bar, and a volume of  $0.2 \text{ m}^3$ . The propane undergoes a process to a final pressure of 4 bar, during which the pressure–volume relationship is  $pV^{1.1} = \text{constant}$ . For the propane, evaluate the work and heat transfer, each in kJ. Kinetic and potential energy effects can be ignored.

**3.83** Figure P3.83 shows a piston–cylinder assembly fitted with a spring. The cylinder contains water, initially at  $1000^\circ\text{F}$ , and the spring is in a vacuum. The piston face, which has an area of  $20 \text{ in.}^2$ , is initially at  $x_1 = 20 \text{ in.}$ . The water is cooled until the piston face is at  $x_2 = 16 \text{ in.}$ . The force exerted by the spring varies linearly with  $x$  according to  $F_{\text{spring}} = kx$ , where  $k = 200 \text{ lbf/in.}$ . Friction between the piston and cylinder is negligible. For the water, determine

- the initial and final pressures, each in  $\text{lbf/in.}^2$ .
- the amount of water present, in lb.
- the work, in Btu.
- the heat transfer, in Btu.

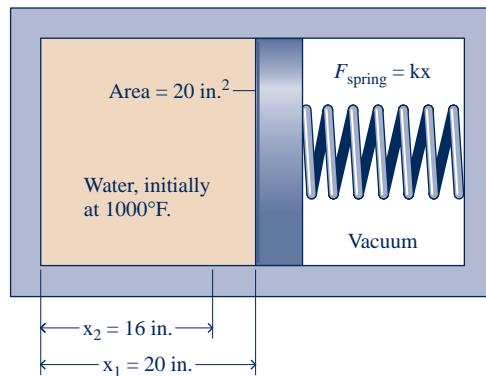


Fig. P3.83

**3.84** As shown in Fig. P3.84, 0.5 kg of ammonia is contained in a piston–cylinder assembly, initially at  $T_1 = -20^\circ\text{C}$  and a quality of 25%. As the ammonia is slowly heated to a final state, where  $T_2 = 20^\circ\text{C}$ ,  $p_2 = 0.6 \text{ MPa}$ , its pressure varies linearly with specific volume. There are no significant kinetic and potential energy effects. For the ammonia, (a) show the process on a sketch of the  $p$ – $v$  diagram and (b) evaluate the work and heat transfer, each in kJ.

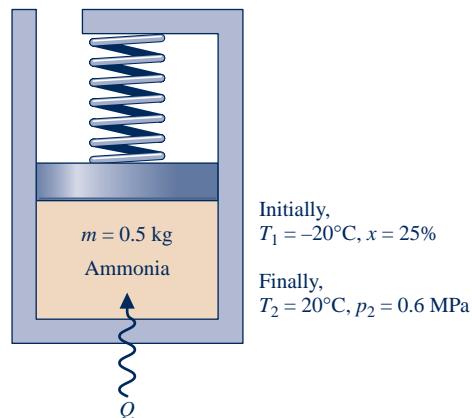


Fig. P3.84

**3.85** A gallon of milk at  $68^\circ\text{F}$  is placed in a refrigerator. If energy is removed from the milk by heat transfer at a constant rate of 0.08 Btu/s, how long would it take, in minutes, for the milk to cool to  $40^\circ\text{F}$ ? The specific heat and density of the milk are  $0.94 \text{ Btu/lb} \cdot ^\circ\text{R}$  and  $64 \text{ lb/ft}^3$ , respectively.

**3.86** Shown in Fig. P3.86 is an insulated copper block that receives energy at a rate of 100 W from an embedded resistor. If the block has a volume of  $10^{-3} \text{ m}^3$  and an initial temperature of  $20^\circ\text{C}$ , how long would it take, in minutes, for the temperature to reach  $60^\circ\text{C}$ ? Data for copper are provided in Table A-19.

**3.87** In a heat-treating process, a 1-kg metal part, initially at  $1075 \text{ K}$ , is quenched in a closed tank containing 100 kg of water, initially at  $295 \text{ K}$ . There is negligible heat transfer between the contents of the tank and their surroundings. Modeling the metal part and water as incompressible with constant specific heats  $0.5 \text{ kJ/kg} \cdot \text{K}$  and  $4.4 \text{ kJ/kg} \cdot \text{K}$ , respectively, determine the final equilibrium temperature after quenching, in K.

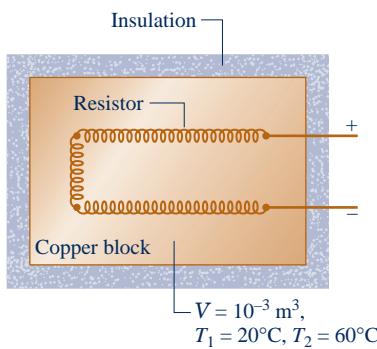


Fig. P3.86

**3.88** As shown in Fig. P3.88, a tank open to the atmosphere initially contains 2 lb of liquid water at 80°F and 0.4 lb of ice at 32°F. All of the ice melts as the tank contents attain equilibrium. If no significant heat transfer occurs between the tank contents and their surroundings, determine the final equilibrium temperature, in °F. For water, the specific enthalpy change for a phase change from solid to liquid at 32°F and 1 atm is 144 Btu/lb.

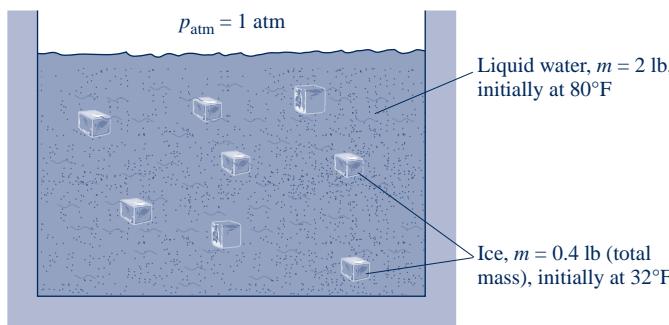


Fig. P3.88

**3.89** As shown in Fig. P3.89, a system consists of a copper tank whose mass is 13 kg, 4 kg of liquid water, and an electrical resistor of negligible mass. The system is insulated on its outer surface. Initially, the temperature of the copper is 27°C and the temperature of the water is 50°C. The electrical resistor transfers 100 kJ of energy to the system. Eventually the system comes to equilibrium. Determine the final equilibrium temperature, in °C.

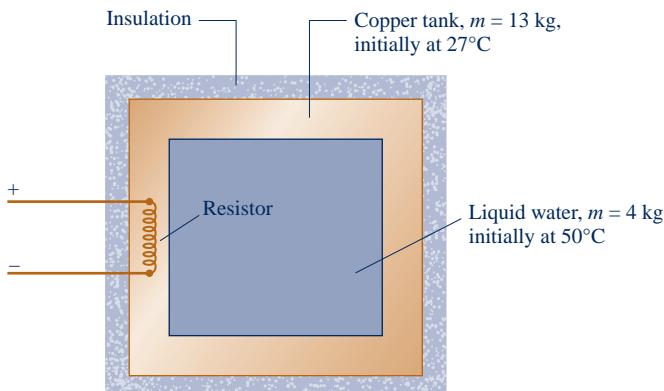


Fig. P3.89

**3.90** As shown in Fig. P3.90, a closed, insulated tank contains 0.15 kg of liquid water and has a 0.25-kg copper base. The thin walls of the container have negligible mass. Initially, the tank and its contents are all at 30°C. A heating element embedded in the copper base is energized with an electrical current of 10 amps at 12 volts for 100 seconds. Determine the final temperature, in °C, of the tank and its contents. Data for copper and liquid water are provided in Table A-19.

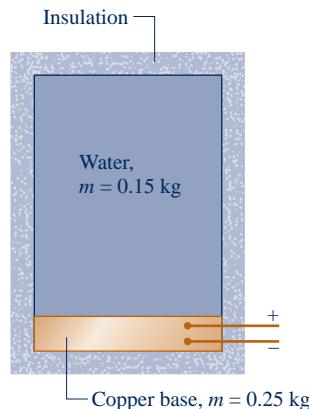


Fig. P3.90

#### Using Generalized Compressibility Data

**3.91** Determine the compressibility factor for water vapor at 120 bar and 520°C using

- data from the compressibility chart.
- data from the steam tables.

Compare the values obtained in parts (a) and (b) and comment.

**3.92** Determine the volume, in  $\text{m}^3$ , occupied by 20 kg of hydrogen ( $\text{H}_2$ ) at 1170 kPa, -220°C.

**3.93** Carbon monoxide (CO) with mass of 150 lb occupies a volume at 500°R and 3500 lbf/in.<sup>2</sup> Determine the volume, in ft<sup>3</sup>.

**3.94** Determine the temperature, in °F, of ethane ( $\text{C}_2\text{H}_6$ ) at 500 lbf/in.<sup>2</sup> and a specific volume of 0.4 ft<sup>3</sup>/lb.

**3.95** A tank contains 2 m<sup>3</sup> of air at -93°C and a gage pressure of 1.4 MPa. Determine the mass of air, in kg. The local atmospheric pressure is 1 atm.

**3.96** Butane ( $\text{C}_4\text{H}_{10}$ ) in a piston-cylinder assembly undergoes an isothermal compression at 173°C from  $p_1 = 1.9 \text{ MPa}$  to  $p_2 = 2.5 \text{ MPa}$ . Determine the work, in kJ/kg.

**3.97** Five kg of butane ( $\text{C}_4\text{H}_{10}$ ) in a piston-cylinder assembly undergo a process from  $p_1 = 5 \text{ MPa}$ ,  $T_1 = 500 \text{ K}$  to  $p_2 = 3 \text{ MPa}$ ,  $T_2 = 450 \text{ K}$  during which the relationship between pressure and specific volume is  $pv^n = \text{constant}$ . Determine the work, in kJ.

**3.98** Five lbmol of carbon dioxide ( $\text{CO}_2$ ), initially at 320 lbf/in.<sup>2</sup>, 660°R, is compressed at constant pressure in a piston-cylinder assembly. For the gas,  $W = -2000 \text{ Btu}$ . Determine the final temperature, in °R.

**3.99** For what ranges of pressure and temperature can air be considered an ideal gas? Explain your reasoning.

**Working with the Ideal Gas Model**

**3.100** A tank contains  $0.5 \text{ m}^3$  of nitrogen ( $\text{N}_2$ ) at  $-71^\circ\text{C}$  and  $1356 \text{ kPa}$ . Determine the mass of nitrogen, in kg, using

- (a) the ideal gas model.
- (b) data from the compressibility chart.

Comment on the applicability of the ideal gas model for nitrogen at this state.

**3.101** Determine the percent error in using the ideal gas model to determine the specific volume of

- (a) water vapor at  $4000 \text{ lbf/in.}^2$ ,  $1000^\circ\text{F}$ .
- (b) water vapor at  $5 \text{ lbf/in.}^2$ ,  $250^\circ\text{F}$ .
- (c) ammonia at  $40 \text{ lbf/in.}^2$ ,  $60^\circ\text{F}$ .
- (d) air at  $1 \text{ atm}$ ,  $560^\circ\text{R}$ .
- (e) Refrigerant 134a at  $300 \text{ lbf/in.}^2$ ,  $180^\circ\text{F}$ .

**3.102** Check the applicability of the ideal gas model

- (a) for water at  $700^\circ\text{F}$  and pressures of  $1600 \text{ lbf/in.}^2$  and  $160 \text{ lbf/in.}^2$ .
- (b) for carbon dioxide at  $865 \text{ K}$  and pressures of  $75 \text{ bar}$  and  $3 \text{ bar}$ .

**3.103** Determine the specific volume, in  $\text{m}^3/\text{kg}$ , of Refrigerant 134a at  $16 \text{ bar}$ ,  $100^\circ\text{C}$ , using

- (a) Table A-12.
- (b) Figure A-1.
- (c) the ideal gas equation of state.

Compare the values obtained in parts (b) and (c) with that of part (a).

**3.104** Determine the specific volume, in  $\text{m}^3/\text{kg}$ , of ammonia at  $50^\circ\text{C}$ ,  $10 \text{ bar}$ , using

- (a) Table A-15.
- (b) Figure A-1.
- (c) the ideal gas equation of state.

Compare the values obtained in parts (b) and (c) with that of part (a).

**3.105** A closed, rigid tank is filled with a gas modeled as an ideal gas, initially at  $27^\circ\text{C}$  and a gage pressure of  $300 \text{ kPa}$ . If the gas is heated to  $77^\circ\text{C}$ , determine the final pressure, expressed as a gage pressure, in kPa. The local atmospheric pressure is  $1 \text{ atm}$ .

**3.106** The air in a room measuring  $8 \text{ ft} \times 9 \text{ ft} \times 12 \text{ ft}$  is at  $80^\circ\text{F}$  and  $1 \text{ atm}$ . Determine the mass of the air, in lb, and its weight, in lbf, if  $g = 32.0 \text{ ft/s}^2$ .

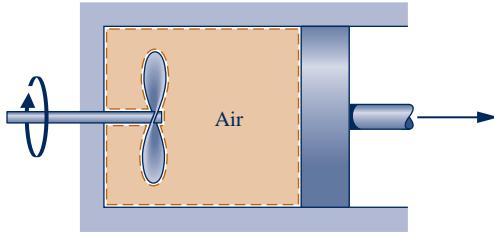
**3.107** Determine the total mass of nitrogen ( $\text{N}_2$ ), in kg, required to inflate all four tires of a vehicle, each to a gage pressure of  $180 \text{ kPa}$  at a temperature of  $25^\circ\text{C}$ . The volume of each tire is  $0.6 \text{ m}^3$ , and the atmospheric pressure is  $1 \text{ atm}$ .

**3.108** Using Table A-18, determine the temperature, in K and  $^\circ\text{C}$ , of propane at a state where the pressure is  $2 \text{ bar}$  and the specific volume is  $0.307 \text{ m}^3/\text{kg}$ . Compare with the temperature, in K and  $^\circ\text{C}$ , respectively, obtained using Fig. A-1. Comment.

**3.109** A balloon filled with helium, initially at  $27^\circ\text{C}$ ,  $1 \text{ bar}$ , is released and rises in the atmosphere until the helium is at  $17^\circ\text{C}$ ,  $0.9 \text{ bar}$ . Determine, as a percent, the change in volume of the helium from its initial volume.

**Using Energy Concepts and the Ideal Gas Model**

**3.110** As shown in Fig. P3.110, a piston–cylinder assembly fitted with a paddle wheel contains air, initially at  $p_1 = 30 \text{ lbf/in.}^2$ ,  $T_1 = 540^\circ\text{F}$ , and  $V_1 = 4 \text{ ft}^3$ . The air undergoes a process to a final state where  $p_2 = 20 \text{ lbf/in.}^2$ ,  $V_2 = 4.5 \text{ ft}^3$ . During the process, the paddle wheel transfers energy to the air by work in the amount  $1 \text{ Btu}$ , while the air transfers energy by work to the piston in the amount  $3.31 \text{ Btu}$ . Assuming ideal gas behavior, determine for the air (a) the temperature at state 2, in  $^\circ\text{R}$ , and (b) the heat transfer, in Btu.



Initially,  $p_1 = 30 \text{ lbf/in.}^2$ ,  $T_1 = 540^\circ\text{F}$ ,  $V_1 = 4 \text{ ft}^3$ .  
Finally,  $p_2 = 20 \text{ lbf/in.}^2$ ,  $V_2 = 4.5 \text{ ft}^3$ .

**Fig. P3.110**

**3.111** A piston–cylinder assembly contains air, initially at  $2 \text{ bar}$ ,  $300 \text{ K}$ , and a volume of  $2 \text{ m}^3$ . The air undergoes a process to a state where the pressure is  $1 \text{ bar}$ , during which the pressure–volume relationship is  $pV = \text{constant}$ . Assuming ideal gas behavior for the air, determine the mass of the air, in kg, and the work and heat transfer, each in kJ.

**3.112** Air contained in a piston–cylinder assembly, initially at  $2 \text{ bar}$ ,  $200 \text{ K}$ , and a volume of  $1 \text{ L}$ , undergoes a process to a final state where the pressure is  $8 \text{ bar}$  and the volume is  $2 \text{ L}$ . During the process, the pressure–volume relationship is linear. Assuming the ideal gas model for the air, determine the work and heat transfer, each in kJ.

**3.113** Carbon dioxide ( $\text{CO}_2$ ) contained in a piston–cylinder arrangement, initially at  $6 \text{ bar}$  and  $400 \text{ K}$ , undergoes an expansion to a final temperature of  $298 \text{ K}$ , during which the pressure–volume relationship is  $pV^{1.2} = \text{constant}$ . Assuming the ideal gas model for the  $\text{CO}_2$ , determine the final pressure, in bar, and the work and heat transfer, each in  $\text{kJ/kg}$ .

**3.114** Water vapor contained in a piston–cylinder assembly undergoes an isothermal expansion at  $240^\circ\text{C}$  from a pressure of  $7 \text{ bar}$  to a pressure of  $3 \text{ bar}$ . Evaluate the work, in  $\text{kJ/kg}$ . Solve two ways: using (a) the ideal gas model, (b)  $IT$  with water/steam data. Comment.

**3.115** One kilogram of nitrogen fills the cylinder of a piston–cylinder assembly, as shown in Fig. P3.115. There is no friction between the piston and the cylinder walls, and the surroundings are at  $1 \text{ atm}$ . The initial volume and pressure in the cylinder are  $1 \text{ m}^3$  and  $1 \text{ atm}$ , respectively. Heat transfer to the nitrogen occurs until the volume is doubled. Determine the heat transfer for the process, in kJ, assuming the specific heat ratio is constant,  $k = 1.4$ .

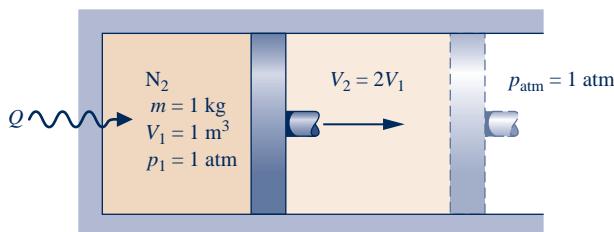


Fig. P3.115

**3.116** A piston–cylinder assembly contains air at a pressure of  $30 \text{ lbf/in.}^2$  and a volume of  $0.75 \text{ ft}^3$ . The air is heated at constant pressure until its volume is doubled. Assuming the ideal gas model with constant specific heat ratio,  $k = 1.4$ , for the air, determine the work and heat transfer, each in Btu.

**3.117** As shown in Fig. P3.117, a fan drawing electricity at a rate of  $1.5 \text{ kW}$  is located within a rigid enclosure, measuring  $3 \text{ m} \times 4 \text{ m} \times 5 \text{ m}$ . The enclosure is filled with air, initially at  $27^\circ\text{C}$ ,  $0.1 \text{ MPa}$ . The fan operates steadily for 30 minutes. Assuming the ideal gas model, determine for the air (a) the mass, in kg, (b) the final temperature, in  $^\circ\text{C}$ , and (c) the final pressure, in MPa. There is no heat transfer between the enclosure and the surroundings. Ignore the volume occupied by the fan itself and assume there is no overall change in internal energy for the fan.

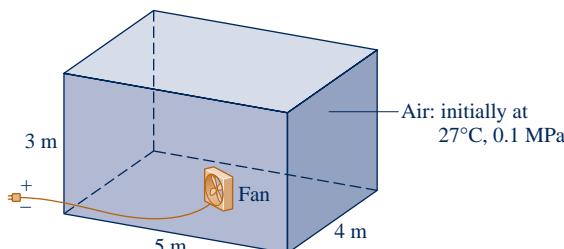


Fig. P3.117

**3.118** Nitrogen ( $N_2$ ) fills a closed, rigid tank fitted with a paddle wheel, initially at  $540^\circ\text{R}$ ,  $20 \text{ lbf/in.}^2$ , and a volume of  $2 \text{ ft}^3$ . The gas is stirred until its temperature is  $760^\circ\text{R}$ . During this process heat transfer from the gas to its surroundings occurs in an amount  $1.6 \text{ Btu}$ . Assuming ideal gas behavior, determine the mass of the nitrogen, in lb, and the work, in Btu. Kinetic and potential energy effects can be ignored.

**3.119** Four-tenth lb of air, initially at  $540^\circ\text{R}$ , is contained in a closed, rigid tank fitted with a paddle wheel that stirs the air until its temperature is  $740^\circ\text{R}$ . The driveshaft of the paddle wheel rotates for 60 seconds at 100 RPM with an applied torque of  $20 \text{ ft} \cdot \text{lbf}$ . Assuming ideal gas behavior for the air, determine the work and heat transfer, each in Btu. There are no overall changes in kinetic or potential energy.

**3.120** Argon contained in a closed, rigid tank, initially at  $50^\circ\text{C}$ ,  $2 \text{ bar}$ , and a volume of  $2 \text{ m}^3$ , is heated to a final pressure of  $8 \text{ bar}$ . Assuming the ideal gas model with  $k = 1.67$  for the argon, determine the final temperature, in  $^\circ\text{C}$ , and the heat transfer, in kJ.

**3.121** Ten kg of hydrogen ( $H_2$ ), initially at  $20^\circ\text{C}$ , fills a closed, rigid tank. Heat transfer to the hydrogen occurs at the rate

$400 \text{ W}$  for one hour. Assuming the ideal gas model with  $k = 1.405$  for the hydrogen, determine its final temperature, in  $^\circ\text{C}$ .

**3.122** As shown in Fig. P3.122, a piston–cylinder assembly whose piston is resting on a set of stops contains  $0.5 \text{ kg}$  of helium gas, initially at  $100 \text{ kPa}$  and  $25^\circ\text{C}$ . The mass of the piston and the effect of the atmospheric pressure acting on the piston are such that a gas pressure of  $500 \text{ kPa}$  is required to raise it. How much energy must be transferred by heat to the helium, in kJ, before the piston starts rising? For the helium, assume ideal gas behavior with  $c_p = \frac{5}{2} R$ .

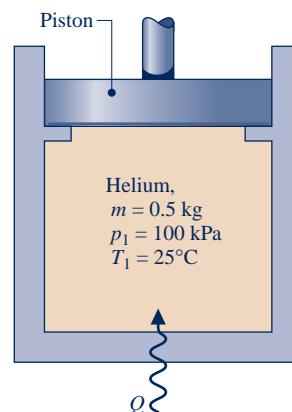


Fig. P3.122

**3.123** A piston–cylinder assembly fitted with a slowly rotating paddle wheel contains  $0.13 \text{ kg}$  of air, initially at  $300 \text{ K}$ . The air undergoes a constant-pressure process to a final temperature of  $400 \text{ K}$ . During the process, energy is gradually transferred to the air by heat transfer in the amount  $12 \text{ kJ}$ . Assuming the ideal gas model with  $k = 1.4$  and negligible changes in kinetic and potential energy for the air, determine the work done (a) by the paddle wheel on the air and (b) by the air to displace the piston, each in kJ.

**3.124** A piston–cylinder assembly contains air. The air undergoes a constant-pressure process, during which the rate of heat transfer to the air is  $0.7 \text{ kW}$ . Assuming ideal gas behavior with  $k = 1.4$  and negligible effects of kinetic and potential energy for the air, determine the rate at which work is done by the air on the piston, in kW.

**3.125** As shown in Fig. P3.125, a tank fitted with an electrical resistor of negligible mass holds  $2 \text{ kg}$  of nitrogen ( $N_2$ ), initially at  $27^\circ\text{C}$ ,  $0.1 \text{ MPa}$ . Over a period of 10 minutes, electricity is provided to the resistor at a rate of  $0.12 \text{ kW}$ . During this same period, a heat transfer of magnitude  $12.59 \text{ kJ}$

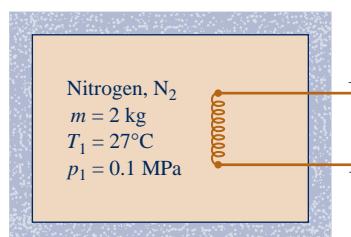


Fig. P3.125

occurs from the nitrogen to its surroundings. Assuming ideal gas behavior, determine the nitrogen's final temperature, in °C, and final pressure, in MPa.

- 3.126** A closed, rigid tank fitted with a paddle wheel contains 0.1 kg of air, initially at 300 K, 0.1 MPa. The paddle wheel stirs the air for 20 minutes, with the power input varying with time according to  $\dot{W} = -10t$ , where  $\dot{W}$  is in watts and  $t$  is time, in minutes. The final temperature of the air is 1060 K. Assuming ideal gas behavior and no change in kinetic or potential energy, determine for the air (a) the final pressure, in MPa, (b) the work, in kJ, and (c) the heat transfer, in kJ.

- 3.127** As shown in Fig. P3.127, one side of a rigid, insulated container initially holds  $2 \text{ m}^3$  of air at  $27^\circ\text{C}$ , 0.3 MPa. The air is separated by a thin membrane from an evacuated volume of  $3 \text{ m}^3$ . Owing to the pressure of the air, the membrane stretches and eventually bursts, allowing the air to occupy the full volume. Assuming the ideal gas model for the air, determine (a) the mass of the air, in kg, (b) the final temperature of the air, in K, and (c) the final pressure of the air, in MPa.

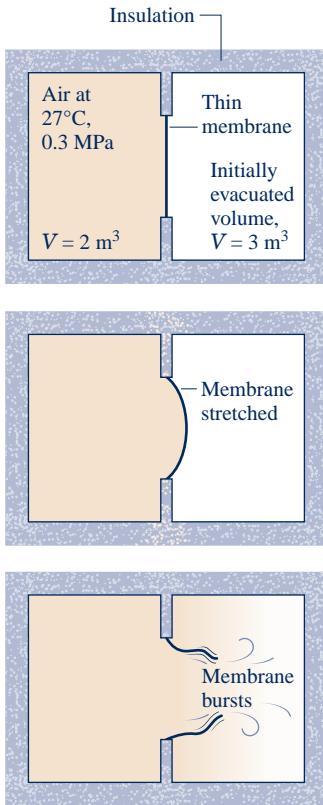


Fig. P3.127

- 3.128** Air is confined to one side of a rigid container divided by a partition, as shown in Fig. P3.128. The other side is initially evacuated. The air is initially at  $p_1 = 5 \text{ bar}$ ,  $T_1 = 500 \text{ K}$ , and  $V_1 = 0.2 \text{ m}^3$ . When the partition is removed, the air expands to fill the entire chamber. Measurements show that  $V_2 = 2 V_1$  and  $p_2 = p_1/4$ . Assuming the air behaves as an ideal gas, determine (a) the final temperature, in K, and (b) the heat transfer, kJ.

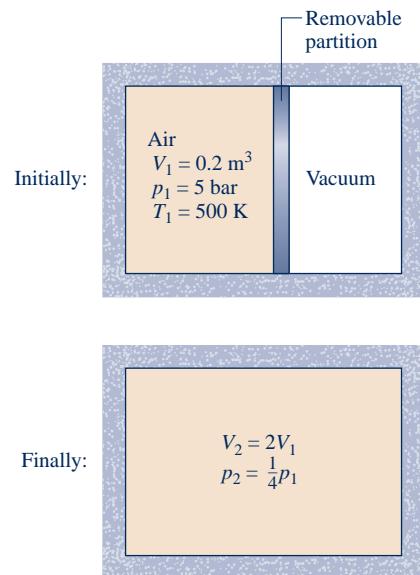


Fig. P3.128

- 3.129** Two kilograms of air, initially at 5 bar, 350 K and 4 kg of carbon monoxide (CO) initially at 2 bar, 450 K are confined to opposite sides of a rigid, well-insulated container by a partition, as shown in Fig. P3.129. The partition is free to move and allows conduction from one gas to the other without energy storage in the partition itself. The air and CO each behave as ideal gases with constant specific heat ratio,  $k = 1.395$ . Determine at equilibrium (a) the temperature, in K, (b) the pressure, in bar, and (c) the volume occupied by each gas, in  $\text{m}^3$ .

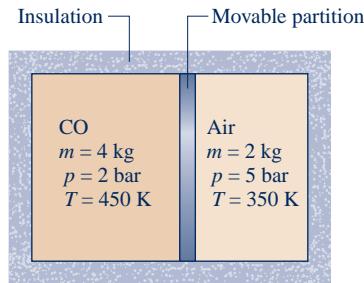


Fig. P3.129

- 3.130** As shown in Fig. P3.130, a piston–cylinder assembly contains 5 g of air holding the piston against the stops. The air, initially at 3 bar, 600 K, is slowly cooled until the piston just begins to move downward in the cylinder. The air behaves as an ideal gas,  $g = 9.81 \text{ m/s}^2$ , and friction is negligible. Sketch the process of the air on a  $p$ - $V$  diagram labeled with the temperature and pressure at the end states. Also determine the heat transfer, in kJ, between the air and its surroundings.

- 3.131** Five kilograms of a gas with molecular weight of 32 kg/kmol and a temperature of  $110^\circ\text{C}$  is contained in a closed, rigid tank fitted with an electric resistor whose mass is negligible. The resistor draws a constant current of 12 amps

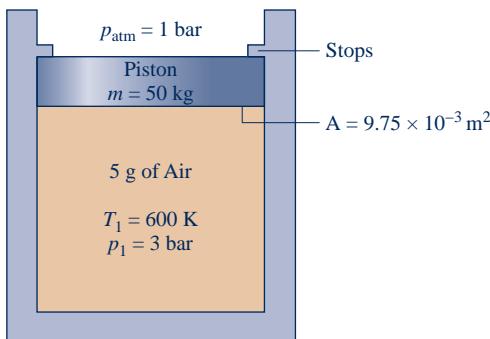


Fig. P3.130

at a voltage of 125 V for 5 minutes. Measurements indicate that when equilibrium is reached, the temperature of the gas has increased by  $44.1^\circ\text{C}$ . Heat transfer from the gas is estimated to occur at a constant rate of 1 kW. Assuming ideal gas behavior and negligible kinetic and potential energy effects, determine an average value of the specific heat,  $c_p$ , in  $\text{kJ/kg} \cdot \text{K}$ , of the gas in this temperature interval based on the measured data.

**3.132** As shown in Fig. P3.132, a rigid tank initially contains 3 kg of carbon dioxide ( $\text{CO}_2$ ) at 500 kPa. The tank is connected by a valve to a piston-cylinder assembly located vertically above, initially containing  $0.05 \text{ m}^3$  of  $\text{CO}_2$ . Although the valve is closed, a slow leak allows  $\text{CO}_2$  to flow into the cylinder from the tank until the tank pressure falls to 200 kPa. The weight of the piston and the pressure of the atmosphere maintain a constant pressure of 200 kPa in the cylinder. Owing to heat transfer, the temperature of the  $\text{CO}_2$  throughout the tank and cylinder stays constant at 290 K. Assuming ideal gas behavior, determine for the  $\text{CO}_2$  the work and heat transfer, each in kJ.

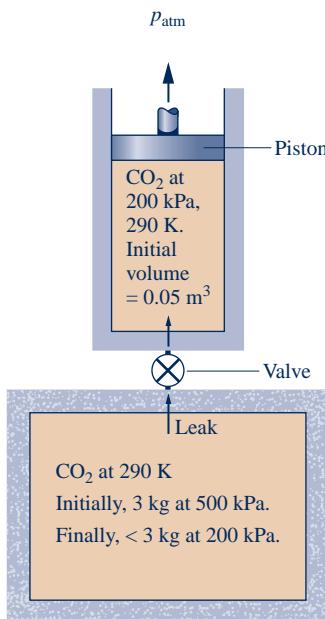


Fig. P3.132

**3.133** A closed, rigid tank fitted with a paddle wheel contains 2 kg of air, initially at 300 K. During an interval of 5 minutes, the paddle wheel transfers energy to the air at a rate of 1 kW. During this interval, the air also receives energy by heat transfer at a rate of 0.5 kW. These are the only energy transfers. Assuming the ideal gas model for the air, and no overall changes in kinetic or potential energy, determine the final temperature of the air, in K.

**3.134** As shown in Fig. P3.134, a piston-cylinder assembly fitted with a paddle wheel contains air, initially at  $560^\circ\text{R}$ ,  $18 \text{ lbf/in.}^2$ , and a volume of  $0.29 \text{ ft}^3$ . Energy in the amount of 1.7 Btu is transferred to the air by the paddle wheel. The piston moves smoothly in the cylinder, and heat transfer between the air and its surroundings can be ignored. Assuming ideal gas behavior by the air, determine its final temperature, in  $^\circ\text{R}$ .

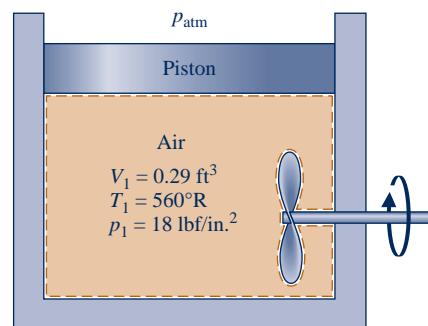


Fig. P3.134

**3.135** Air is compressed in a piston-cylinder assembly from  $p_1 = 10 \text{ lbf/in.}^2$ ,  $T_1 = 500^\circ\text{R}$  to a final volume of  $V_2 = 1 \text{ ft}^3$  in a process described by  $pv^{1.25} = \text{constant}$ . The mass of air is 0.5 lb. Assuming ideal gas behavior and neglecting kinetic and potential energy effects, determine the work and the heat transfer, each in Btu, using (a) constant specific heats evaluated at  $500^\circ\text{R}$ , and (b) data from Table A-22E. Compare the results and discuss.

**3.136** A piston-cylinder assembly contains carbon monoxide modeled as an ideal gas with constant specific heat ratio,  $k = 1.4$ . The carbon monoxide undergoes a polytropic expansion with  $n = k$  from an initial state, where  $T_1 = 200^\circ\text{F}$  and  $p_1 = 40 \text{ lbf/in.}^2$ , to a final state, where the volume is twice the initial volume. Determine (a) the final temperature, in  $^\circ\text{F}$ , and final pressure, in  $\text{lbf/in.}^2$ , and (b) the work and heat transfer, each in  $\text{Btu/lb}$ .

**3.137** Air contained in a piston-cylinder assembly undergoes two processes in series, as shown in Fig. P3.137. Assuming ideal gas behavior for the air, determine the work and heat transfer for the overall process, each in kJ/kg.

**3.138** Two-tenths kmol of nitrogen ( $\text{N}_2$ ) in a piston-cylinder assembly undergoes two processes in series as follows:

**Process 1–2:** Constant pressure at 5 bar from  $V_1 = 1.33 \text{ m}^3$  to  $V_2 = 1 \text{ m}^3$ .

**Process 2–3:** Constant volume to  $p_3 = 4 \text{ bar}$ .

Assuming ideal gas behavior and neglecting kinetic and potential energy effects, determine the work and heat transfer for each process, in kJ.

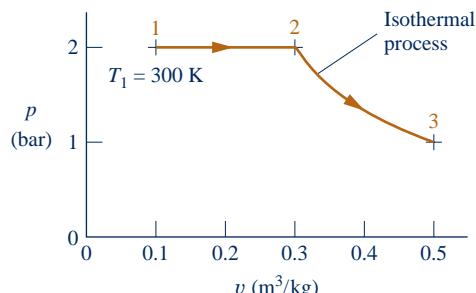


Fig. P3.137

**3.139** One kilogram of air in a piston–cylinder assembly undergoes two processes in series from an initial state where  $p_1 = 0.5 \text{ MPa}$ ,  $T_1 = 227^\circ\text{C}$ :

**Process 1–2:** Constant-temperature expansion until the volume is twice the initial volume.

**Process 2–3:** Constant-volume heating until the pressure is again 0.5 MPa.

Sketch the two processes in series on a  $p$ – $v$  diagram. Assuming ideal gas behavior, determine (a) the pressure at state 2, in MPa, (b) the temperature at state 3, in  $^\circ\text{C}$ , and for each of the processes (c) the work and heat transfer, each in kJ.

**3.140** Air contained in a piston–cylinder assembly undergoes the power cycle shown in Fig. P3.140. Assuming ideal gas behavior for the air, evaluate the thermal efficiency of the cycle.

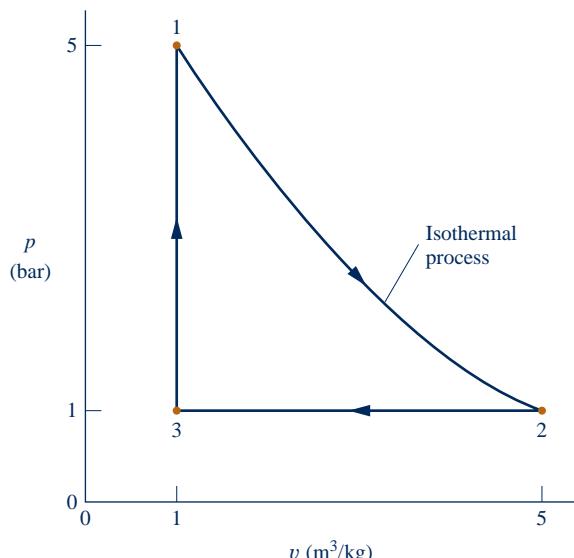


Fig. P3.140

**3.141** A piston–cylinder assembly contains air modeled as an ideal gas with a constant specific heat ratio,  $k = 1.4$ . The air undergoes a power cycle consisting of four processes in series:

**Process 1–2:** Constant-temperature expansion at 600 K from  $p_1 = 0.5 \text{ MPa}$  to  $p_2 = 0.4 \text{ MPa}$ .

**Process 2–3:** Polytropic expansion with  $n = k$  to  $p_3 = 0.3 \text{ MPa}$ .

**Process 3–4:** Constant-pressure compression to  $V_4 = V_1$ .

**Process 4–1:** Constant-volume heating.

Sketch the cycle on a  $p$ – $v$  diagram. Determine (a) the work and heat transfer for each process, in kJ/kg, and (d) the thermal efficiency.

**3.142** One lb of oxygen,  $\text{O}_2$ , undergoes a power cycle consisting of the following processes:

**Process 1–2:** Constant-volume from  $p_1 = 20 \text{ lbf/in.}^2$ ,  $T_1 = 500^\circ\text{R}$  to  $T_2 = 820^\circ\text{R}$ .

**Process 2–3:** Adiabatic expansion to  $v_3 = 1.432v_2$ .

**Process 3–1:** Constant-pressure compression to state 1.

Sketch the cycle on a  $p$ – $v$  diagram. Assuming ideal gas behavior, determine

- (a) the pressure at state 2, in  $\text{lbf/in.}^2$ .
- (b) the temperature at state 3, in  $^\circ\text{R}$ .
- (c) the heat transfer and work, each in Btu, for all processes.
- (d) the thermal efficiency of the cycle.

**3.143** A system consists of 2 kg of carbon dioxide gas initially at state 1, where  $p_1 = 1 \text{ bar}$ ,  $T_1 = 300 \text{ K}$ . The system undergoes a power cycle consisting of the following processes:

**Process 1–2:** Constant volume to  $p_2, p_2 > p_1$

**Process 2–3:** Expansion with  $pv^{1.28} = \text{constant}$

**Process 3–1:** Constant-pressure compression

Assuming the ideal gas model and neglecting kinetic and potential energy effects,

- (a) sketch the cycle on a  $p$ – $v$  diagram.
- (b) plot the thermal efficiency versus  $p_2/p_1$  ranging from 1.05 to 4.

**3.144** Air undergoes a polytropic process in a piston–cylinder assembly from  $p_1 = 14.7 \text{ lbf/in.}^2$ ,  $T_1 = 70^\circ\text{F}$  to  $p_2 = 100 \text{ lbf/in.}^2$ . Using  $IT$ , plot the work and heat transfer, each in Btu per lb of air, for polytropic exponents ranging from 1.0 to 1.6. Investigate the error in the heat transfer introduced by assuming constant  $c_v$  evaluated at  $70^\circ\text{F}$ . Discuss.

**3.145** Steam, initially at 5 MPa,  $280^\circ\text{C}$  undergoes a polytropic process in a piston–cylinder assembly to a final pressure of 20 MPa. Using  $IT$ , plot the heat transfer, in kJ per kg of steam, for polytropic exponents ranging from 1.0 to 1.6. Investigate the error in the heat transfer introduced by assuming ideal gas behavior for the steam. Discuss.

### Reviewing Concepts

**3.146** Answer the following true or false. Explain.

- (a) For a gas modeled as an ideal gas,  $c_p = c_v + R$ , where  $R$  is the gas constant for the gas.
- (b) Air always can be regarded as a *pure substance*.
- (c) Water at  $p = 100 \text{ lbf/in.}^2$  and  $v = 0.0169 \text{ ft}^3/\text{lb}$  is a *compressed liquid*.
- (d) Atmospheric air is normally not modeled as an ideal gas.
- (e) For liquid water, the following approximation is reasonable for many engineering calculations:  $v(T, p) = v_f(T)$ .

**3.147** Answer the following true or false. Explain.

- (a) If water, initially a superheated vapor at 30 MPa, is cooled at *constant pressure*, the water eventually will become saturated vapor, and then with sufficient additional cooling condensation to saturated liquid will occur.
- (b) A quasiequilibrium process for which the pressure-volume relation is described by  $p/V^n = \text{constant}$ , where  $n$  is a constant, is called a *polytropic process*.
- (c) For *simple compressible systems*, the state principle indicates that the number of independent intensive thermodynamic properties required to fix an intensive state is two.
- (d) For ammonia at 0.45 MPa and 50°C, the specific enthalpy is 1564.32 kJ/kg.
- (e) For gases modeled as ideal gases, the value of the specific heat ratio  $c_v/c_p$  is greater than 1.

**3.148** Answer the following true or false. Explain

- (a) The change in specific volume from saturated liquid to saturated vapor, ( $v_g - v_f$ ), at a specified saturation pressure increases as the pressure decreases.
- (b) A two-phase liquid-vapor mixture with equal volumes of saturated liquid and saturated vapor has a quality of 50%.
- (c) The following assumptions apply for a liquid modeled as *incompressible*: The specific volume (density) is constant and the specific internal energy is a function only of temperature.
- (d) Carbon dioxide (CO<sub>2</sub>) at 320 K and 55 bar can be modeled as an ideal gas.
- (e) When an ideal gas undergoes a *polytropic* process with  $n = 1$ , the gas temperature remains constant.

**► DESIGN & OPEN-ENDED PROBLEMS: EXPLORING ENGINEERING PRACTICE**

**3.1D** Dermatologists remove skin blemishes from patients by applying sprays from canisters filled with liquid nitrogen (N<sub>2</sub>). Investigate how liquid nitrogen is produced and delivered to physicians, and how physicians manage liquid nitrogen in their practices. Also investigate the advantages and disadvantages of this approach for removing blemishes compared to alternative approaches used today. Write a report including at least three references.

**3.2D** The EPA (Environmental Protection Agency) has developed an online *Personal Emissions Calculator* that helps individuals and families reduce greenhouse emissions. Use the EPA calculator to estimate, in the home and on the road, your personal greenhouse emissions or your family's greenhouse emissions. Also use the calculator to explore steps you as an individual or your family can take to cut emissions by at least 20%. In a memorandum, summarize your findings and present your program for lowering emissions.

**3.3D** Methane-laden gas generated by the decomposition of landfill trash has economic value. Research literature on the possible uses of landfill gas. Contact the manager of a large landfill in your locale concerning the capture and use, if any, of landfill gas generated by the facility. Write a report including at least three references.

**3.4D** Use of the *constant-volume* calorimeter to measure the calorie value of foods and other substances, as illustrated in Example 3.6, is one of three general types of biological calorimetry. Two others are *differential scanning calorimetry* and *isothermal titration calorimetry*. For these two, investigate the objectives and instrumentation of each. Present your findings in a memorandum, including sketches of the respective instrumentation together with summaries of how the instrumentation is used in the laboratory.

**3.5D** A newspaper article reports that on a day when an airline cancelled eleven flights from Las Vegas because the local

temperature was approaching the 117°F operating limit for its jets, another airline canceled seven flights from Denver because the local temperature there was above the 104°F operating level for its propeller planes. Prepare a 30-min. presentation suitable for a middle school science class explaining the technical considerations behind these cancellations.

**3.6D** Due to their zero ozone depletion and low global warming potential *natural refrigerants* are actively under consideration for commercial refrigeration applications (see box in Sec. 3.4). Investigate the viability of natural refrigerants in systems to improve human comfort and safeguard food. Consider performance benefits, safety, and cost. On the basis of your study, recommend especially promising natural refrigerants and areas of application where each is particularly well suited. Report your findings in a PowerPoint presentation.

**3.7D** According to the New York City Transit Authority, the operation of subways raises tunnel and station temperatures as much as 14 to 20°F above ambient temperature. Principal contributors to the temperature rise include train motor operation, lighting, and energy from the passengers themselves. Passenger discomfort can increase significantly in hot-weather periods if air conditioning is not provided. Still, because on-board air-conditioning units discharge energy by heat transfer to their surroundings, such units contribute to the overall tunnel and station energy management problem. Investigate the application to subways of *alternative* cooling strategies that provide substantial cooling with a minimal power requirement, including but not limited to thermal storage and nighttime ventilation. Write a report with at least three references.

**3.8D** Some oil and gas companies use *hydraulic fracturing* to access oil and natural gas trapped in deep rock formations. Investigate the process of hydraulic fracturing, its benefits, and environmental impacts. On this basis, write a three-page brief for submission to a congressional committee considering

whether hydraulic fracturing should continue to be exempt from regulation under the *Safe Drinking Water Act*. The brief can provide either objective technical background to inform committee members or take a position in favor of, or against, continuing the exemption.

**3.9D** Water is one of our most important resources, yet one of the most poorly managed—it is too often wasted and polluted. Investigate ways we can improve water use as a society in industry, businesses, and households. Record your daily water use for at least three days and compare it to that of those living in the poorest parts of the globe: about one gallon per day. Write a report including at least three references.

**3.10D** Passive solar heating may become more effective in coming years through incorporating *phase-change materials* (PCMs) into building materials. Investigate incorporation of phase-change materials into products used by the building industry to enhance passive solar heating. For each product, determine the PCM type, melting point, and accompanying phase-change enthalpy. Discuss how the PCM affects performance of the building material and how this benefits space heating. Prepare a 25-minute PowerPoint presentation suitable for a high school chemistry class based on your findings. Include at least two instructional aides to enhance your presentation.





**Pumps**, considered in Sec. 4.8, have long played a crucial role in providing clean water worldwide. © Liba Taylor Robert Harding Picture Library/Age Fotostock America, Inc.

**ENGINEERING CONTEXT** The **objective** of this chapter is to develop and illustrate the use of the control volume forms of the conservation of mass and conservation of energy principles. Mass and energy balances for control volumes are introduced in Secs. 4.1 and 4.4, respectively. These balances are applied in Secs. 4.5–4.11 to control volumes at steady state and in Sec. 4.12 for time-dependent (transient) applications.

Although devices such as turbines, pumps, and compressors through which mass flows can be analyzed in principle by studying a particular quantity of matter (a closed system) as it passes through the device, it is normally preferable to think of a region of space through which mass flows (a control volume). As in the case of a closed system, energy transfer across the boundary of a control volume can occur by means of work and heat. In addition, another type of energy transfer must be accounted for—the energy accompanying mass as it enters or exits.

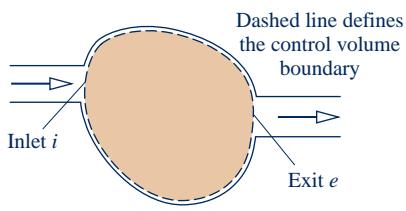
# 4

# Control Volume Analysis Using Energy

## ► LEARNING OUTCOMES

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

- ▶ demonstrate understanding of key concepts related to control volume analysis, including distinguishing between steady-state and transient analysis, distinguishing between mass flow rate and volumetric flow rate, and the meanings of one-dimensional flow and flow work.
- ▶ apply mass and energy balances to control volumes.
- ▶ develop appropriate engineering models for control volumes, with particular attention to analyzing components commonly encountered in engineering practice such as nozzles, diffusers, turbines, compressors, heat exchangers, throttling devices, and integrated systems that incorporate two or more components.
- ▶ use property data in control volume analysis appropriately.



**Fig. 4.1** One-inlet, one-exit control volume.

### conservation of mass

### mass flow rates

### mass rate balance

## 4.1 Conservation of Mass for a Control Volume

In this section an expression of the conservation of mass principle for control volumes is developed and illustrated. As a part of the presentation, the one-dimensional flow model is introduced.

### 4.1.1 Developing the Mass Rate Balance

The mass rate balance for control volumes is introduced by reference to Fig. 4.1, which shows a control volume with mass flowing in at *i* and flowing out at *e*, respectively. When applied to such a control volume, the **conservation of mass** principle states

$$\left[ \begin{array}{l} \text{time rate of change of} \\ \text{mass contained within the} \\ \text{control volume at time } t \end{array} \right] = \left[ \begin{array}{l} \text{time rate of flow of} \\ \text{mass in across} \\ \text{inlet } i \text{ at time } t \end{array} \right] - \left[ \begin{array}{l} \text{time rate of flow} \\ \text{of mass out across} \\ \text{exit } e \text{ at time } t \end{array} \right]$$

Denoting the mass contained within the control volume at time *t* by  $m_{cv}(t)$ , this statement of the conservation of mass principle can be expressed in symbols as

$$\frac{dm_{cv}}{dt} = \dot{m}_i - \dot{m}_e \quad (4.1)$$

where  $dm_{cv}/dt$  is the time rate of change of mass within the control volume, and  $\dot{m}_i$  and  $\dot{m}_e$  are the instantaneous **mass flow rates** at the inlet and exit, respectively. As for the symbols  $\dot{W}$  and  $\dot{Q}$ , the dots in the quantities  $\dot{m}_i$  and  $\dot{m}_e$  denote time rates of transfer. In SI, all terms in Eq. 4.1 are expressed in kg/s. In English units, they are expressed in lb/s. For a discussion of the development of Eq. 4.1, see the box.

In general, there may be several locations on the boundary through which mass enters or exits. This can be accounted for by summing, as follows

$$\frac{dm_{cv}}{dt} = \sum_i \dot{m}_i - \sum_e \dot{m}_e \quad (4.2)$$

Equation 4.2 is the **mass rate balance** for control volumes with several inlets and exits. It is a form of the conservation of mass principle commonly employed in engineering. Other forms of the mass rate balance are considered in discussions to follow.

#### Developing the Control Volume Mass Balance

For each of the extensive properties mass, energy, and entropy (Chap. 6), the control volume form of the property balance can be obtained by transforming the corresponding closed system form. Let us consider this for mass, recalling that the mass of a closed system is constant.

The figures in the margin at the top of the next page show a system consisting of a fixed quantity of matter  $m$  that occupies different regions at time *t* and a later time  $t + \Delta t$ . The mass under consideration is shown in color on the figures. At time *t*, the mass is the sum  $m = m_{cv}(t) + m_i$ , where  $m_{cv}(t)$  is the mass contained within the control volume, and  $m_i$  is the mass within the small region labeled *i* adjacent to the control volume. Let us study the fixed quantity of matter  $m$  as time elapses.

In a time interval  $\Delta t$  all the mass in region  $i$  crosses the control volume boundary, while some of the mass, call it  $m_e$ , initially contained within the control volume exits to fill the region labeled  $e$  adjacent to the control volume. Although the mass in regions  $i$  and  $e$  as well as in the control volume differ from time  $t$  to  $t + \Delta t$ , the *total* amount of mass is constant. Accordingly

$$m_{cv}(t) + m_i = m_{cv}(t + \Delta t) + m_e \quad (a)$$

or on rearrangement

$$m_{cv}(t + \Delta t) - m_{cv}(t) = m_i - m_e \quad (b)$$

Equation (b) is an *accounting balance* for mass. It states that the change in mass of the control volume during time interval  $\Delta t$  equals the amount of mass that enters less the amount of mass that exits.

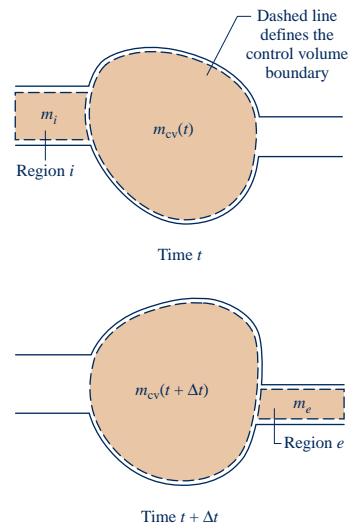
Equation (b) can be expressed on a time rate basis. First, divide by  $\Delta t$  to obtain

$$\frac{m_{cv}(t + \Delta t) - m_{cv}(t)}{\Delta t} = \frac{m_i}{\Delta t} - \frac{m_e}{\Delta t} \quad (c)$$

Then, in the limit as  $\Delta t$  goes to zero, Eq. (c) becomes Eq. 4.1, the instantaneous *control volume rate equation* for mass

$$\frac{dm_{cv}}{dt} = \dot{m}_i - \dot{m}_e \quad (4.1)$$

where  $dm_{cv}/dt$  denotes the time rate of change of mass within the control volume, and  $\dot{m}_i$  and  $\dot{m}_e$  are the inlet and exit mass flow rates, respectively, all at time  $t$ .

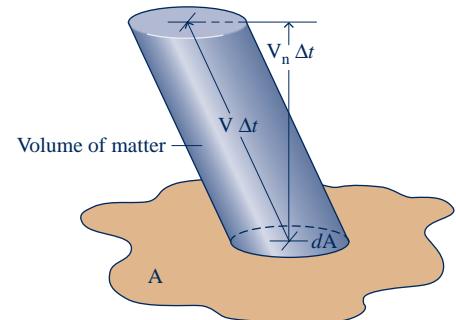


## 4.1.2 Evaluating the Mass Flow Rate

An expression for the mass flow rate  $\dot{m}$  of the matter entering or exiting a control volume can be obtained in terms of local properties by considering a small quantity of matter flowing with velocity  $V$  across an incremental area  $dA$  in a time interval  $\Delta t$ , as shown in Fig. 4.2. Since the portion of the control volume boundary through which mass flows is not necessarily at rest, the velocity shown in the figure is understood to be the velocity *relative* to the area  $dA$ . The velocity can be resolved into components normal and tangent to the plane containing  $dA$ . In the following development  $V_n$  denotes the component of the relative velocity normal to  $dA$  in the direction of flow.

The *volume* of the matter crossing  $dA$  during the time interval  $\Delta t$  shown in Fig. 4.2 is an oblique cylinder with a volume equal to the product of the area of its base  $dA$  and its altitude  $V_n \Delta t$ . Multiplying by the density  $\rho$  gives the amount of mass that crosses  $dA$  in time  $\Delta t$

$$\left[ \begin{array}{l} \text{amount of mass} \\ \text{crossing } dA \text{ during} \\ \text{the time interval } \Delta t \end{array} \right] = \rho(V_n \Delta t) dA$$



**Fig. 4.2** Illustration used to develop an expression for mass flow rate in terms of local fluid properties.

Dividing both sides of this equation by  $\Delta t$  and taking the limit as  $\Delta t$  goes to zero, the instantaneous mass flow rate across incremental area  $dA$  is

$$\left[ \begin{array}{l} \text{instantaneous rate} \\ \text{of mass flow} \\ \text{across } dA \end{array} \right] = \rho V_n dA$$

When this is integrated over the area A through which mass passes, an expression for the mass flow rate is obtained

$$\dot{m} = \int_A \rho V_n dA \quad (4.3)$$

Equation 4.3 can be applied at the inlets and exits to account for the rates of mass flow into and out of the control volume.

## 4.2 Forms of the Mass Rate Balance

The mass rate balance, Eq. 4.2, is a form that is important for control volume analysis. In many cases, however, it is convenient to apply the mass balance in forms suited to particular objectives. Some alternative forms are considered in this section.

### 4.2.1 One-Dimensional Flow Form of the Mass Rate Balance

#### one-dimensional flow

##### TAKE NOTE...

In subsequent control volume analyses, we routinely assume that the idealizations of one-dimensional flow are appropriate. Accordingly the assumption of one-dimensional flow is not listed explicitly in solved examples.

When a flowing stream of matter entering or exiting a control volume adheres to the following idealizations, the flow is said to be **one-dimensional**:

- The flow is normal to the boundary at locations where mass enters or exits the control volume.
- All intensive properties, including velocity and density, are *uniform with position* (bulk average values) over each inlet or exit area through which matter flows.

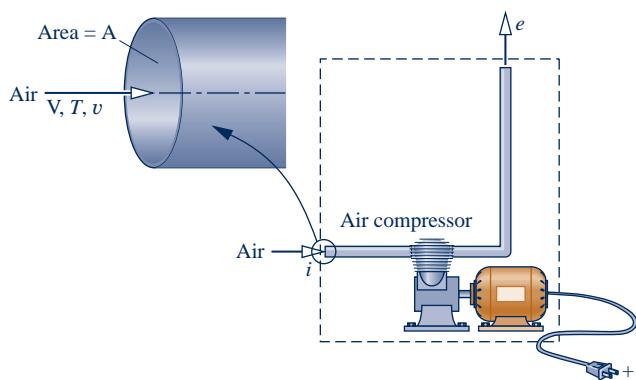
**► FOR EXAMPLE** Figure 4.3 illustrates the meaning of one-dimensional flow. The area through which mass flows is denoted by A. The symbol V denotes a single value that represents the velocity of the flowing air. Similarly T and v are single values that represent the temperature and specific volume, respectively, of the flowing air. ▲▲▲▲▲

When the flow is one-dimensional, Eq. 4.3 for the mass flow rate becomes

$$\dot{m} = \rho AV \quad (\text{one-dimensional flow}) \quad (4.4a)$$

or in terms of specific volume

$$\dot{m} = \frac{AV}{v} \quad (\text{one-dimensional flow}) \quad (4.4b)$$



**Fig. 4.3** Figure illustrating the one-dimensional flow model.

When area is in m<sup>2</sup>, velocity is in m/s, and specific volume is in m<sup>3</sup>/kg, the mass flow rate found from Eq. 4.4b is in kg/s, as can be verified. The product AV in Eqs. 4.4 is the **volumetric flow rate**. The volumetric flow rate is expressed in units of m<sup>3</sup>/s or ft<sup>3</sup>/s.

**volumetric flow rate**

Substituting Eq. 4.4b into Eq. 4.2 results in an expression for the conservation of mass principle for control volumes limited to the case of one-dimensional flow at the inlets and exits

$$\frac{dm_{cv}}{dt} = \sum_i \frac{A_i V_i}{v_i} - \sum_e \frac{A_e V_e}{v_e} \quad (\text{one-dimensional flow}) \quad (4.5)$$

Note that Eq. 4.5 involves summations over the inlets and exits of the control volume. Each individual term in these sums applies to a particular inlet or exit. The area, velocity, and specific volume appearing in each term refers only to the corresponding inlet or exit.

## 4.2.2 Steady-State Form of the Mass Rate Balance

Many engineering systems can be idealized as being at **steady state**, meaning that *all* properties are unchanging in time. For a control volume at steady state, the identity of the matter within the control volume changes continuously, but the total amount present at any instant remains constant, so  $dm_{cv}/dt = 0$  and Eq. 4.2 reduces to

**steady state**

$$\sum_i \dot{m}_i = \sum_e \dot{m}_e \quad (\text{mass rate in} \quad \text{mass rate out}) \quad (4.6)$$

That is, the total incoming and outgoing rates of mass flow are equal.

Note that equality of total incoming and outgoing rates of mass flow does not necessarily imply that a control volume is at steady state. Although the total amount of mass within the control volume at any instant would be constant, other properties such as temperature and pressure might be varying with time. When a control volume is at steady state, *every* property is independent of time. Also note that the steady-state assumption and the one-dimensional flow assumption are independent idealizations. One does not imply the other.

## 4.2.3 Integral Form of the Mass Rate Balance

We consider next the mass rate balance expressed in terms of local properties. The total mass contained within the control volume at an instant  $t$  can be related to the local density as follows

$$m_{cv}(t) = \int_V \rho dV \quad (4.7)$$

where the integration is over the volume at time  $t$ .

With Eqs. 4.3 and 4.7, the mass rate balance Eq. 4.2 can be written as

$$\frac{d}{dt} \int_V \rho dV = \sum_i \left( \int_A \rho V_n dA \right)_i - \sum_e \left( \int_A \rho V_n dA \right)_e \quad (4.8)$$

where the area integrals are over the areas through which mass enters and exits the control volume, respectively. The product  $\rho V_n$  appearing in this equation, known as the **mass flux**, gives the time rate of mass flow per unit of area. To evaluate the terms of the right side of Eq. 4.8 requires information about the variation of the mass flux

**mass flux**

over the flow areas. The form of the conservation of mass principle given by Eq. 4.8 is usually considered in detail in fluid mechanics.

## 4.3 Applications of the Mass Rate Balance

### 4.3.1 Steady-State Application

For a control volume at steady state, the conditions of the mass within the control volume and at the boundary do not vary with time. The mass flow rates also are constant with time.

Example 4.1 illustrates an application of the steady-state form of the mass rate balance to a control volume enclosing a mixing chamber called a *feedwater heater*. Feedwater heaters are components of the vapor power systems considered in Chap. 8.

#### EXAMPLE 4.1

### Applying the Mass Rate Balance to a Feedwater Heater at Steady State

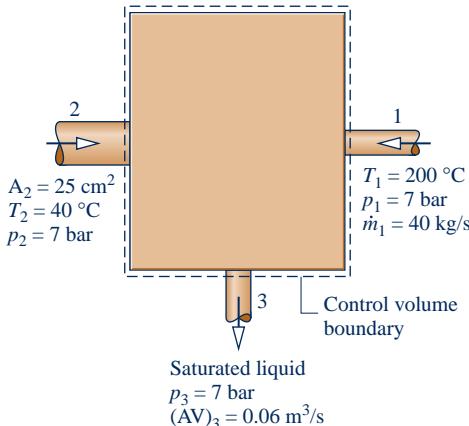
A feedwater heater operating at steady state has two inlets and one exit. At inlet 1, water vapor enters at  $p_1 = 7 \text{ bar}$ ,  $T_1 = 200^\circ\text{C}$  with a mass flow rate of  $40 \text{ kg/s}$ . At inlet 2, liquid water at  $p_2 = 7 \text{ bar}$ ,  $T_2 = 40^\circ\text{C}$  enters through an area  $A_2 = 25 \text{ cm}^2$ . Saturated liquid at 7 bar exits at 3 with a volumetric flow rate of  $0.06 \text{ m}^3/\text{s}$ . Determine the mass flow rates at inlet 2 and at the exit, in kg/s, and the velocity at inlet 2, in m/s.

#### SOLUTION

**Known:** A stream of water vapor mixes with a liquid water stream to produce a saturated liquid stream at the exit. The states at the inlets and exit are specified. Mass flow rate and volumetric flow rate data are given at one inlet and at the exit, respectively.

**Find:** Determine the mass flow rates at inlet 2 and at the exit, and the velocity  $V_2$ .

#### Schematic and Given Data:



**Engineering Model:** The control volume shown on the accompanying figure is at steady state.

Fig. E4.1

**Analysis:** The principal relations to be employed are the mass rate balance (Eq. 4.2) and the expression  $\dot{m} = AV/v$  (Eq. 4.4b). At steady state the mass rate balance becomes

①

$$\cancel{\frac{d\dot{m}_{cv}}{dt}}^0 = \dot{m}_1 + \dot{m}_2 - \dot{m}_3$$

Solving for  $\dot{m}_2$ ,

$$\dot{m}_2 = \dot{m}_3 - \dot{m}_1$$

The mass flow rate  $\dot{m}_1$  is given. The mass flow rate at the exit can be evaluated from the given volumetric flow rate

$$\dot{m}_3 = \frac{(AV)_3}{v_3}$$

where  $v_3$  is the specific volume at the exit. In writing this expression, one-dimensional flow is assumed. From Table A-3,  $v_3 = 1.108 \times 10^{-3} \text{ m}^3/\text{kg}$ . Hence,

$$\dot{m}_3 = \frac{0.06 \text{ m}^3/\text{s}}{(1.108 \times 10^{-3} \text{ m}^3/\text{kg})} = 54.15 \text{ kg/s}$$

The mass flow rate at inlet 2 is then

$$\dot{m}_2 = \dot{m}_3 - \dot{m}_1 = 54.15 - 40 = 14.15 \text{ kg/s}$$

For one-dimensional flow at 2,  $\dot{m}_2 = A_2 V_2 / v_2$ , so

$$V_2 = \dot{m}_2 v_2 / A_2$$

State 2 is a compressed liquid. The specific volume at this state can be approximated by  $v_2 \approx v_f(T_2)$  (Eq. 3.11). From Table A-2 at 40°C,  $v_2 = 1.0078 \times 10^{-3} \text{ m}^3/\text{kg}$ . So,

$$V_2 = \frac{(14.15 \text{ kg/s})(1.0078 \times 10^{-3} \text{ m}^3/\text{kg})}{25 \text{ cm}^2} \left| \frac{10^4 \text{ cm}^2}{1 \text{ m}^2} \right| = 5.7 \text{ m/s}$$

- In accord with Eq. 4.6, the mass flow rate at the exit equals the sum of the mass flow rates at the inlets. It is left as an exercise to show that the volumetric flow rate at the exit *does not equal* the sum of the volumetric flow rates at the inlets.

### QuickQUIZ

Evaluate the volumetric flow rate, in  $\text{m}^3/\text{s}$ , at each inlet.

**Ans.**  $(AV)_1 = 12 \text{ m}^3/\text{s}$ ,  $(AV)_2 = 0.01 \text{ m}^3/\text{s}$



### Skills Developed

Ability to...

- apply the steady-state mass rate balance.
- apply the mass flow rate expression, Eq. 4.4b.
- retrieve property data for water.

## 4.3.2 Time-Dependent (Transient) Application

Many devices undergo periods of operation during which the state changes with time—for example, the startup and shutdown of motors. Other examples include containers being filled or emptied and applications to biological systems. The steady-state model is not appropriate when analyzing time-dependent (transient) cases.

Example 4.2 illustrates a time-dependent, or transient, application of the mass rate balance. In this case, a barrel is filled with water.

### EXAMPLE 4.2

#### Applying the Mass Rate Balance to a Barrel Filling with Water

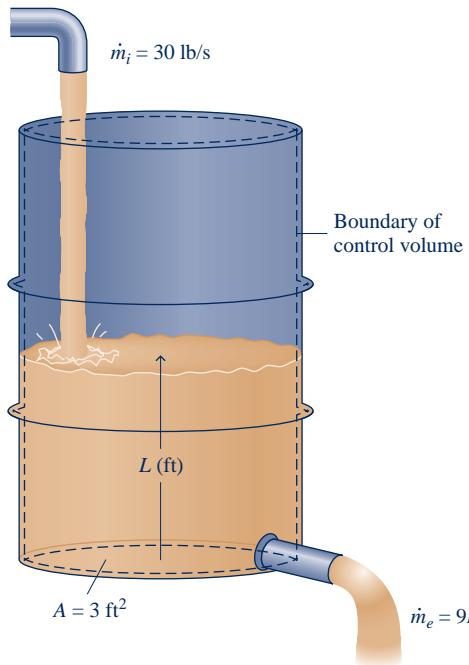
Water flows into the top of an open barrel at a constant mass flow rate of 30 lb/s. Water exits through a pipe near the base with a mass flow rate proportional to the height of liquid inside:  $\dot{m}_e = 9 L$ , where  $L$  is the instantaneous liquid height, in ft. The area of the base is  $3 \text{ ft}^2$ , and the density of water is  $62.4 \text{ lb}/\text{ft}^3$ . If the barrel is initially empty, plot the variation of liquid height with time and comment on the result.

### SOLUTION

**Known:** Water enters and exits an initially empty barrel. The mass flow rate at the inlet is constant. At the exit, the mass flow rate is proportional to the height of the liquid in the barrel.

**Find:** Plot the variation of liquid height with time and comment.

**Schematic and Given Data:**



**Engineering Model:**

1. The control volume is defined by the dashed line on the accompanying diagram.
2. The water density is constant.

Fig. E4.2a

**Analysis:** For the one-inlet, one-exit control volume, Eq. 4.2 reduces to

$$\frac{dm_{cv}}{dt} = \dot{m}_i - \dot{m}_e$$

The mass of water contained within the barrel at time  $t$  is given by

$$m_{cv}(t) = \rho AL(t)$$

where  $\rho$  is density,  $A$  is the area of the base, and  $L(t)$  is the instantaneous liquid height. Substituting this into the mass rate balance together with the given mass flow rates

$$\frac{d(\rho AL)}{dt} = 30 - 9L$$

Since density and area are constant, this equation can be written as

$$\frac{dL}{dt} + \left(\frac{9}{\rho A}\right)L = \frac{30}{\rho A}$$

which is a first-order, ordinary differential equation with constant coefficients. The solution is

$$1 \quad L = 3.33 + C \exp\left(-\frac{9t}{\rho A}\right)$$

where  $C$  is a constant of integration. The solution can be verified by substitution into the differential equation.

To evaluate  $C$ , use the initial condition: at  $t = 0$ ,  $L = 0$ . Thus,  $C = -3.33$ , and the solution can be written as

$$L = 3.33[1 - \exp(-9t/\rho A)]$$

Substituting  $\rho = 62.4 \text{ lb}/\text{ft}^3$  and  $A = 3 \text{ ft}^2$  results in

$$L = 3.33[1 - \exp(-0.048t)]$$

This relation can be plotted by hand or using appropriate software. The result is

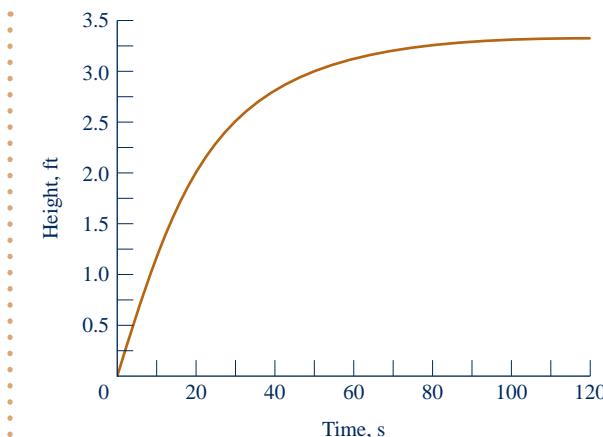


Fig. E4.2b

From the graph, we see that initially the liquid height increases rapidly and then levels out as steady-state operation is approached. After about 100 s, the height stays constant with time. At this point, the rate of water flow into the barrel equals the rate of flow out of the barrel. From the graph, the limiting value of  $L$  is 3.33 ft, which also can be verified by taking the limit of the analytical solution as  $t \rightarrow \infty$ .

- 1 Alternatively, this differential equation can be solved using *Interactive Thermodynamics: IT*. The differential equation can be expressed as

$$\text{der}(L, t) + (g * L) / (\rho * A) = \dot{m} / (\rho * A)$$

$$\rho = 62.4 \text{ lb/ft}^3$$

$$A = 3 \text{ ft}^2$$

where  $\text{der}(L, t)$  is  $dL/dt$ ,  $\rho$  is density  $\rho$ , and  $A$  is area. Using the **Explore** button, set the initial condition at  $L = 0$ , and sweep  $t$  from 0 to 200 in steps of 0.5. Then, the plot can be constructed using the **Graph** button.

### QuickQUIZ

If the mass flow rate of the water flowing into the barrel were 27 lb/s while all other data remains the same, what is the limiting value of the liquid height,  $L$ , in ft? **Ans.** 3.0 ft



### Skills Developed

Ability to...

- apply the time-dependent mass rate balance.
- solve an ordinary differential equation and plot the solution.



### BIO CONNECTIONS

The human heart provides a good example of how biological systems can be modeled as control volumes. Figure 4.4 shows the cross-section of a human heart. The flow is controlled by valves that intermittently allow blood to enter from veins and exit through arteries as the heart muscles pump. Work is done to increase the pressure of the blood leaving the heart to a level that will propel it through the cardiovascular system of the body. Observe that the boundary of the control volume enclosing the heart is not fixed but moves with time as the heart pulses.

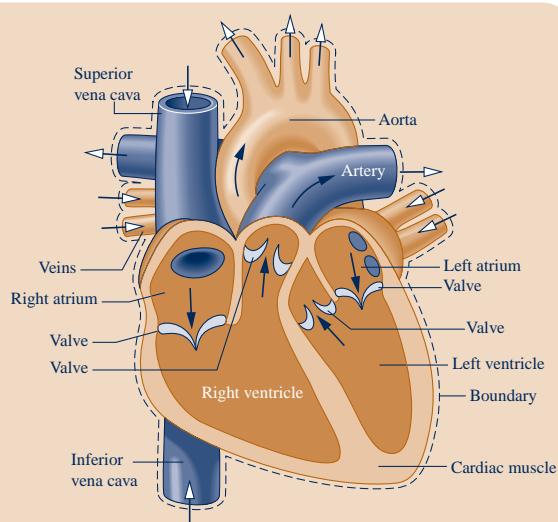


Fig. 4.4 Control volume enclosing the heart.

Understanding the medical condition known as *arrhythmia* requires consideration of the time-dependent behavior of the heart. An arrhythmia is a change in the regular beat of the heart. This can take several forms. The heart may beat irregularly, skip a beat, or beat very fast or slowly. An arrhythmia may be detectable by listening to the heart with a stethoscope, but an electrocardiogram offers a more precise approach. Although arrhythmia does occur in people without underlying heart disease, patients having serious symptoms may require treatment to keep their heartbeats regular. Many patients with arrhythmia may require no medical intervention at all.

## 4.4 Conservation of Energy for a Control Volume

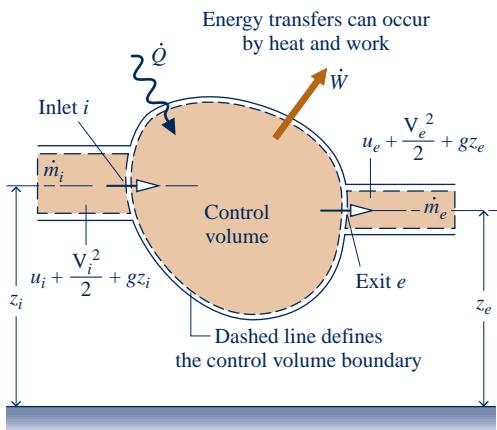
In this section, the rate form of the energy balance for control volumes is obtained. The energy rate balance plays an important role in subsequent sections of this book.

### 4.4.1 • Developing the Energy Rate Balance for a Control Volume

We begin by noting that the control volume form of the energy rate balance can be derived by an approach closely paralleling that considered in the box of Sec. 4.1.1, where the control volume mass rate balance is obtained by transforming the closed system form. The present development proceeds less formally by arguing that, like mass, energy is an extensive property, so it too can be transferred into or out of a control volume as a result of mass crossing the boundary. Since this is the principal difference between the closed system and control volume forms, the control volume energy rate balance can be obtained by modifying the closed system energy rate balance to account for these energy transfers.

Accordingly, the *conservation of energy* principle applied to a control volume states:

$$\left[ \begin{array}{l} \text{time rate of change} \\ \text{of the energy} \\ \text{contained within} \\ \text{the control volume} \\ \text{at time } t \end{array} \right] = \left[ \begin{array}{l} \text{net rate at which} \\ \text{energy is being} \\ \text{transferred in} \\ \text{by heat transfer} \\ \text{at time } t \end{array} \right] - \left[ \begin{array}{l} \text{net rate at which} \\ \text{energy is being} \\ \text{transferred out} \\ \text{by work at} \\ \text{time } t \end{array} \right] + \left[ \begin{array}{l} \text{net rate of energy} \\ \text{transfer into the} \\ \text{control volume} \\ \text{accompanying} \\ \text{mass flow} \end{array} \right]$$



For the one-inlet one-exit control volume with one-dimensional flow shown in Fig. 4.5 the energy rate balance is

$$\underline{\frac{dE_{cv}}{dt}} = \underline{\dot{Q}} - \underline{\dot{W}} + \underline{\dot{m}_i \left( u_i + \frac{V_i^2}{2} + gz_i \right)} - \underline{\dot{m}_e \left( u_e + \frac{V_e^2}{2} + gz_e \right)} \quad (4.9)$$

where  $E_{cv}$  denotes the energy of the control volume at time  $t$ . The terms  $\dot{Q}$  and  $\dot{W}$  account, respectively, for the net rate of energy transfer by heat and work across the boundary of the control volume at  $t$ . The underlined terms account for the rates of transfer of internal, kinetic, and potential energy of the entering and exiting streams. If there is no mass flow in or out, the respective mass flow rates vanish and the underlined terms of Eq. 4.9 drop out. The equation then reduces to the rate form of the energy balance for closed systems: Eq. 2.37.

Next, we will place Eq. 4.9 in an alternative form that is more convenient for subsequent applications. This will be accomplished primarily

**Fig. 4.5** Figure used to develop Eq. 4.9.

by recasting the work term  $\dot{W}$ , which represents the net rate of energy transfer by work across *all* portions of the boundary of the control volume.



#### 4.4.2 • Evaluating Work for a Control Volume

Because work is always done on or by a control volume where matter flows across the boundary, it is convenient to separate the work term  $\dot{W}$  of Eq. 4.9 into *two contributions*: One contribution is the work associated with the fluid pressure as mass is introduced at inlets and removed at exits. The other contribution, denoted by  $\dot{W}_{cv}$ , includes *all other* work effects, such as those associated with rotating shafts, displacement of the boundary, and electrical effects.

Consider the work at an exit  $e$  associated with the pressure of the flowing matter. Recall from Eq. 2.13 that the rate of energy transfer by work can be expressed as the product of a force and the velocity at the point of application of the force. Accordingly, the *rate* at which work is done at the exit by the normal force (normal to the exit area in the direction of flow) due to pressure is the product of the normal force,  $p_e A_e$ , and the fluid velocity,  $V_e$ . That is

$$\left[ \begin{array}{l} \text{time rate of energy transfer} \\ \text{by work from the control} \\ \text{volume at exit } e \end{array} \right] = (p_e A_e) V_e \quad (4.10)$$

where  $p_e$  is the pressure,  $A_e$  is the area, and  $V_e$  is the velocity at exit  $e$ , respectively. A similar expression can be written for the rate of energy transfer by work into the control volume at inlet  $i$ .

With these considerations, the work term  $\dot{W}$  of the energy rate equation, Eq. 4.9, can be written as

$$\dot{W} = \dot{W}_{cv} + (p_e A_e) V_e - (p_i A_i) V_i \quad (4.11)$$

where, in accordance with the sign convention for work, the term at the inlet has a negative sign because energy is transferred into the control volume there. A positive sign precedes the work term at the exit because energy is transferred out of the control volume there. With  $AV = \dot{m}v$  from Eq. 4.4b, the above expression for work can be written as

$$\dot{W} = \dot{W}_{cv} + \dot{m}_e(p_e v_e) - \dot{m}_i(p_i v_i) \quad (4.12)$$

where  $\dot{m}_i$  and  $\dot{m}_e$  are the mass flow rates and  $v_i$  and  $v_e$  are the specific volumes evaluated at the inlet and exit, respectively. In Eq. 4.12, the terms  $\dot{m}_i(p_i v_i)$  and  $\dot{m}_e(p_e v_e)$  account for the work associated with the pressure at the inlet and exit, respectively. They are commonly referred to as **flow work**. The term  $\dot{W}_{cv}$  accounts for *all other* energy transfers by work across the boundary of the control volume.

**flow work**

#### 4.4.3 • One-Dimensional Flow Form of the Control Volume Energy Rate Balance

Substituting Eq. 4.12 in Eq. 4.9 and collecting all terms referring to the inlet and the exit into separate expressions, the following form of the control volume energy rate balance results

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}_i \left( u_i + p_i v_i + \frac{V_i^2}{2} + g z_i \right) - \dot{m}_e \left( u_e + p_e v_e + \frac{V_e^2}{2} + g z_e \right) \quad (4.13)$$

The subscript “cv” has been added to  $\dot{Q}$  to emphasize that this is the heat transfer rate over the boundary (control surface) of the *control volume*.

The last two terms of Eq. 4.13 can be rewritten using the specific enthalpy  $h$  introduced in Sec. 3.6.1. With  $h = u + pv$ , the energy rate balance becomes

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}_i \left( h_i + \frac{V_i^2}{2} + gz_i \right) - \dot{m}_e \left( h_e + \frac{V_e^2}{2} + gz_e \right) \quad (4.14)$$

The appearance of the sum  $u + pv$  in the control volume energy equation is the principal reason for introducing enthalpy previously. It is brought in solely as a *convenience*: The algebraic form of the energy rate balance is simplified by the use of enthalpy and, as we have seen, enthalpy is normally tabulated along with other properties.

In practice there may be several locations on the boundary through which mass enters or exits. This can be accounted for by introducing summations as in the mass balance. Accordingly, the **energy rate balance** is

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i \left( h_i + \frac{V_i^2}{2} + gz_i \right) - \sum_e \dot{m}_e \left( h_e + \frac{V_e^2}{2} + gz_e \right) \quad (4.15)$$

### energy rate balance

#### TAKE NOTE...

Equation 4.15 is the most general form of the conservation of energy principle for control volumes used in this book. It serves as the starting point for applying the conservation of energy principle to control volumes in problem solving.

In writing Eq. 4.15, the one-dimensional flow model is assumed where mass enters and exits the control volume.

Equation 4.15 is an *accounting* balance for the energy of the control volume. It states that the rate of energy increase or decrease within the control volume equals the difference between the rates of energy transfer in and out across the boundary. The mechanisms of energy transfer are heat and work, as for closed systems, and the energy that accompanies the mass entering and exiting.

#### 4.4.4 • Integral Form of the Control Volume Energy Rate Balance

As for the case of the mass rate balance, the energy rate balance can be expressed in terms of local properties to obtain forms that are more generally applicable. Thus, the term  $E_{cv}(t)$ , representing the total energy associated with the control volume at time  $t$ , can be written as a volume integral

$$E_{cv}(t) = \int_V \rho e \, dV = \int_V \rho \left( u + \frac{V^2}{2} + gz \right) \, dV \quad (4.16)$$

Similarly, the terms accounting for the energy transfers accompanying mass flow and flow work at inlets and exits can be expressed as shown in the following form of the energy rate balance

$$\begin{aligned} \frac{d}{dt} \int_V \rho e \, dV &= \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \left[ \int_A \left( h + \frac{V^2}{2} + gz \right) \rho V_n \, dA \right]_i \\ &\quad - \sum_e \left[ \int_A \left( h + \frac{V^2}{2} + gz \right) \rho V_n \, dA \right]_e \end{aligned} \quad (4.17)$$

Additional forms of the energy rate balance can be obtained by expressing the heat transfer rate  $\dot{Q}_{cv}$  as the integral of the *heat flux* over the boundary of the control volume, and the work  $\dot{W}_{cv}$  in terms of normal and shear stresses at the moving portions of the boundary.

In principle, the change in the energy of a control volume over a time period can be obtained by integration of the energy rate balance with respect to time. Such integrations require information about the time dependences of the work and heat transfer rates, the various mass flow rates, and the states at which mass enters and leaves the control volume. Examples of this type of analysis are presented in Sec. 4.12.



**Energy\_Rate\_Bal\_CV**  
A.16 – Tab b

## 4.5 Analyzing Control Volumes at Steady State

In this section we consider steady-state forms of the mass and energy rate balances. These balances are applied to a variety of devices of engineering interest in Secs. 4.6–4.11. The steady-state forms considered here do not apply to the transient startup or shutdown periods of operation of such devices, but only to periods of steady operation. This situation is commonly encountered in engineering.

**System Types**  
A.1 – Tab e

A

### 4.5.1 Steady-State Forms of the Mass and Energy Rate Balances

For a control volume at steady state, the conditions of the mass within the control volume and at the boundary do not vary with time. The mass flow rates and the rates of energy transfer by heat and work are also constant with time. There can be no accumulation of mass within the control volume, so  $dm_{cv}/dt = 0$  and the mass rate balance, Eq. 4.2, takes the form

$$\sum_i \dot{m}_i = \sum_e \dot{m}_e \quad (4.6)$$

(mass rate in)      (mass rate out)

Furthermore, at steady state  $dE_{cv}/dt = 0$ , so Eq. 4.15 can be written as

$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i \left( h_i + \frac{V_i^2}{2} + gz_i \right) - \sum_e \dot{m}_e \left( h_e + \frac{V_e^2}{2} + gz_e \right) \quad (4.18)$$

Alternatively

$$\dot{Q}_{cv} + \sum_i \dot{m}_i \left( h_i + \frac{V_i^2}{2} + gz_i \right) = \dot{W}_{cv} + \sum_e \dot{m}_e \left( h_e + \frac{V_e^2}{2} + gz_e \right) \quad (4.19)$$

(energy rate in)      (energy rate out)

Equation 4.6 asserts that at steady state the total rate at which mass enters the control volume equals the total rate at which mass exits. Similarly, Eq. 4.19 asserts that the total rate at which energy is transferred into the control volume equals the total rate at which energy is transferred out.

Many important applications involve one-inlet, one-exit control volumes at steady state. It is instructive to apply the mass and energy rate balances to this special case. The mass rate balance reduces simply to  $\dot{m}_1 = \dot{m}_2$ . That is, the mass flow rate must be the same at the exit, 2, as it is at the inlet, 1. The common mass flow rate is designated simply by  $\dot{m}$ . Next, applying the energy rate balance and factoring the mass flow rate gives

$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m} \left[ (h_1 - h_2) + \frac{(V_1^2 - V_2^2)}{2} + g(z_1 - z_2) \right] \quad (4.20a)$$

**Energy\_Rate\_Bal\_CV**  
A.16 – Tab c

A

Or, dividing by the mass flow rate

$$0 = \frac{\dot{Q}_{cv}}{\dot{m}} - \frac{\dot{W}_{cv}}{\dot{m}} + (h_1 - h_2) + \frac{(V_1^2 - V_2^2)}{2} + g(z_1 - z_2) \quad (4.20b)$$

The enthalpy, kinetic energy, and potential energy terms all appear in Eqs. 4.20 as differences between their values at the inlet and exit. This illustrates that the datums

used to assign values to specific enthalpy, velocity, and elevation cancel. In Eq. 4.20b, the ratios  $\dot{Q}_{cv}/\dot{m}$  and  $\dot{W}_{cv}/\dot{m}$  are rates of energy transfer *per unit mass flowing through the control volume*.

The foregoing steady-state forms of the energy rate balance relate only energy transfer quantities evaluated at the *boundary* of the control volume. No details concerning properties *within* the control volume are required by, or can be determined with, these equations. When applying the energy rate balance in any of its forms, it is necessary to use the same units for all terms in the equation. For instance, *every* term in Eq. 4.20b must have a unit such as kJ/kg or Btu/lb. Appropriate unit conversions are emphasized in examples to follow.

### 4.5.2 Modeling Considerations for Control Volumes at Steady State

In this section, we provide the basis for subsequent applications by considering the modeling of control volumes *at steady state*. In particular, several applications are given in Secs. 4.6–4.11 showing the use of the principles of conservation of mass and energy, together with relationships among properties for the analysis of control volumes at steady state. The examples are drawn from applications of general interest to engineers and are chosen to illustrate points common to all such analyses. Before studying them, it is recommended that you review the methodology for problem solving outlined in Sec. 1.9. As problems become more complicated, the use of a systematic problem-solving approach becomes increasingly important.

When the mass and energy rate balances are applied to a control volume, simplifications are normally needed to make the analysis manageable. That is, the control volume of interest is *modeled* by making assumptions. The *careful* and *conscious* step of listing assumptions is necessary in every engineering analysis. Therefore, an important part of this section is devoted to considering various assumptions that are commonly made when applying the conservation principles to different types of devices. As you study the examples presented in Secs. 4.6–4.11, it is important to recognize the role played by careful assumption making in arriving at solutions. In each case considered, steady-state operation is assumed. The flow is regarded as one-dimensional at places where mass enters and exits the control volume. Also, at each of these locations equilibrium property relations are assumed to apply.

#### Horizons

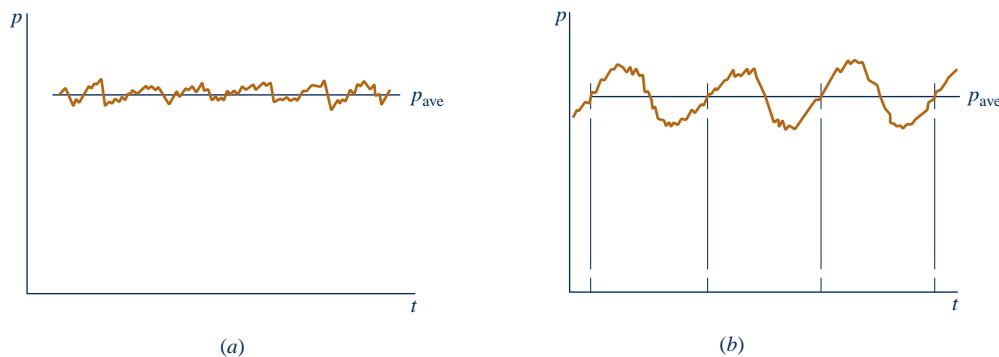
### Smaller Can Be Better .....

Engineers are developing miniature systems for use where weight, portability, and/or compactness are critically important. Some of these applications involve tiny *micro systems* with dimensions in the micrometer to millimeter range. Other somewhat larger *meso-scale* systems can measure up to a few centimeters.

*Microelectromechanical systems (MEMS)* combining electrical and mechanical features are now widely used for sensing and control. Medical applications of MEMS include pressure sensors that monitor pressure within the balloon inserted into a blood vessel during angioplasty. Air bags are triggered in an automobile crash by tiny acceleration sensors. MEMS are also found in computer hard drives and printers.

Miniature versions of other technologies are being investigated. One study aims at developing an entire gas turbine power plant the size of a shirt button. Another involves micromotors with shafts the diameter of a human hair. Emergency workers wearing fire-, chemical-, or biological-protection suits might in the future be kept cool by tiny heat pumps imbedded in the suit material.

As designers aim at smaller sizes, frictional effects and heat transfers pose special challenges. Fabrication of miniature systems is also demanding. Taking a design from the concept stage to high-volume production can be both expensive and risky, industry representatives say.



**Fig. 4.6** Pressure variations about an average. (a) Fluctuation. (b) Periodic.

In several of the examples to follow, the heat transfer term  $\dot{Q}_{cv}$  is set to zero in the energy rate balance because it is small relative to other energy transfers across the boundary. This may be the result of one or more of the following factors:

- ▶ The outer surface of the control volume is well insulated.
- ▶ The outer surface area is too small for there to be effective heat transfer.
- ▶ The temperature difference between the control volume and its surroundings is so small that the heat transfer can be ignored.
- ▶ The gas or liquid passes through the control volume so quickly that there is not enough time for significant heat transfer to occur.

The work term  $\dot{W}_{cv}$  drops out of the energy rate balance when there are no rotating shafts, displacements of the boundary, electrical effects, or other work mechanisms associated with the control volume being considered. The kinetic and potential energies of the matter entering and exiting the control volume are neglected when they are small relative to other energy transfers.

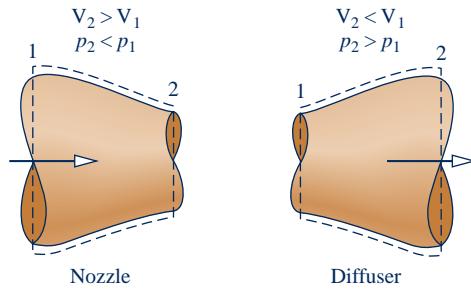
In practice, the properties of control volumes considered to be at steady state *do* vary with time. The steady-state assumption would still apply, however, when properties fluctuate only slightly about their averages, as for pressure in Fig. 4.6a. Steady state also might be assumed in cases where *periodic* time variations are observed, as in Fig. 4.6b. For example, in reciprocating engines and compressors, the entering and exiting flows pulsate as valves open and close. Other parameters also might be time varying. However, the steady-state assumption can apply to control volumes enclosing these devices if the following are satisfied for each successive period of operation: (1) There is no *net* change in the total energy and the total mass within the control volume. (2) The *time-averaged* mass flow rates, heat transfer rates, work rates, and properties of the substances crossing the control surface all remain constant.

Next, we present brief discussions and examples illustrating the analysis of several devices of interest in engineering, including nozzles and diffusers, turbines, compressors and pumps, heat exchangers, and throttling devices. The discussions highlight some common applications of each device and the modeling typically used in thermodynamic analysis.

## 4.6 Nozzles and Diffusers

A **nozzle** is a flow passage of varying cross-sectional area in which the velocity of a gas or liquid increases in the direction of flow. In a **diffuser**, the gas or liquid decelerates in the direction of flow. Figure 4.7 shows a nozzle in which the cross-sectional area decreases in the direction of flow and a diffuser in which the walls of the flow passage diverge. Observe that as velocity increases pressure decreases, and conversely.

nozzle  
diffuser



**Fig. 4.7** Illustration of a nozzle and a diffuser.

For many readers the most familiar application of a nozzle is its use with a garden hose. But nozzles and diffusers have several important engineering applications. In Fig. 4.8, a nozzle and diffuser are combined in a wind-tunnel test facility. Ducts with converging and diverging passages are commonly used in distributing cool and warm air in building air-conditioning systems. Nozzles and diffusers also are key components of turbojet engines (Sec. 9.11).

### 4.6.1 Nozzle and Diffuser Modeling Considerations

For a control volume enclosing a nozzle or diffuser, the only work is *flow work* at locations where mass enters and exits the control volume, so the term  $\dot{W}_{cv}$  drops out of the energy rate balance. The change in potential energy from inlet to exit is negligible under most conditions. Thus, the underlined terms of Eq. 4.20a (repeated below) drop out, leaving the enthalpy, kinetic energy, and heat transfer terms, as shown by Eq. (a)

$$\begin{aligned} 0 &= \dot{Q}_{cv} - \underline{\dot{W}_{cv}} + \dot{m} \left[ (h_1 - h_2) + \frac{(V_1^2 - V_2^2)}{2} + g(z_1 - z_2) \right] \\ 0 &= \dot{Q}_{cv} + \dot{m} \left[ (h_1 - h_2) + \frac{(V_1^2 - V_2^2)}{2} \right] \end{aligned} \quad (\text{a})$$

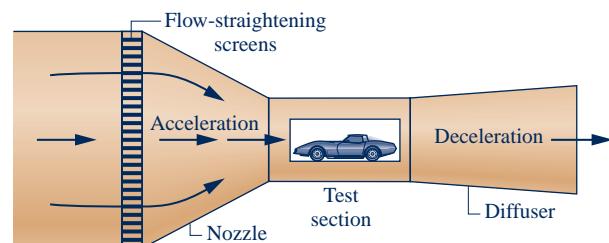
where  $\dot{m}$  is the mass flow rate. The term  $\dot{Q}_{cv}$  representing heat transfer with the surroundings normally would be unavoidable (or stray) heat transfer, and this is often small enough relative to the enthalpy and kinetic energy terms that it also can be neglected, giving simply

$$0 = (h_1 - h_2) + \left( \frac{V_1^2 - V_2^2}{2} \right) \quad (4.21)$$



### 4.6.2 Application to a Steam Nozzle

The modeling introduced in Sec. 4.6.1 is illustrated in the next example involving a steam nozzle. Particularly note the use of unit conversion factors in this application.



**Fig. 4.8** Wind-tunnel test facility.

▶▶▶▶ **EXAMPLE 4.3 ▶**

## Calculating Exit Area of a Steam Nozzle

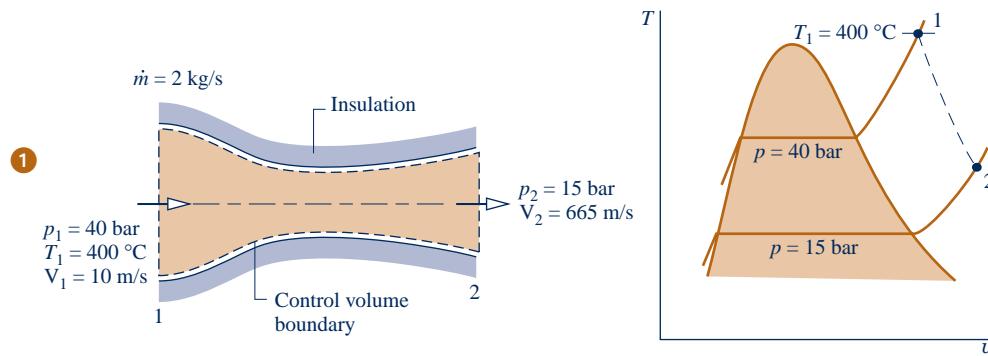
Steam enters a converging-diverging nozzle operating at steady state with  $p_1 = 40$  bar,  $T_1 = 400^\circ\text{C}$ , and a velocity of 10 m/s. The steam flows through the nozzle with negligible heat transfer and no significant change in potential energy. At the exit,  $p_2 = 15$  bar, and the velocity is 665 m/s. The mass flow rate is 2 kg/s. Determine the exit area of the nozzle, in  $\text{m}^2$ .

### SOLUTION

**Known:** Steam flows through a nozzle at steady state with known properties at the inlet and exit, a known mass flow rate, and negligible effects of heat transfer and potential energy.

**Find:** Determine the exit area.

### Schematic and Given Data:



**Fig. E4-3**

**Analysis:** The exit area can be determined from the mass flow rate  $\dot{m}$  and Eq. 4.4b, which can be arranged to read

$$A_2 = \frac{\dot{m}v_2}{V_2}$$

To evaluate  $A_2$  from this equation requires the specific volume  $v_2$  at the exit, and this requires that the exit state be fixed.

The state at the exit is fixed by the values of two independent intensive properties. One is the pressure  $p_2$ , which is known. The other is the specific enthalpy  $h_2$ , determined from the steady-state energy rate balance Eq. 4.20a, as follows

$$0 = \dot{Q}_{cv}^0 - \dot{W}_{cv}^0 + \dot{m} \left[ (h_1 - h_2) + \frac{(V_1^2 - V_2^2)}{2} + g(z_1 - z_2) \right]$$

The terms  $\dot{Q}_{cv}$  and  $\dot{W}_{cv}$  are deleted by assumption 2. The change in specific potential energy drops out in accordance with assumption 3 and  $\dot{m}$  cancels, leaving

$$0 = (h_1 - h_2) + \left( \frac{V_1^2 - V_2^2}{2} \right)$$

Solving for  $h_2$

$$h_2 = h_1 + \left( \frac{V_1^2 - V_2^2}{2} \right)$$

### Engineering Model:

1. The control volume shown on the accompanying figure is at steady state.
2. Heat transfer is negligible and  $\dot{W}_{cv} = 0$ .
3. The change in potential energy from inlet to exit can be neglected.

From Table A-4,  $h_1 = 3213.6 \text{ kJ/kg}$ . The velocities  $V_1$  and  $V_2$  are given. Inserting values and converting the units of the kinetic energy terms to  $\text{kJ/kg}$  results in

$$\begin{aligned} ② \quad h_2 &= 3213.6 \text{ kJ/kg} + \left[ \frac{(10)^2 - (665)^2}{2} \right] \left( \frac{\text{m}^2}{\text{s}^2} \right) \left| \frac{1 \text{ N}}{1 \text{ kg} \cdot \text{m/s}^2} \right| \left| \frac{1 \text{ kJ}}{10^3 \text{ N} \cdot \text{m}} \right| \\ &= 3213.6 - 221.1 = 2992.5 \text{ kJ/kg} \end{aligned}$$

Finally, referring to Table A-4 at  $p_2 = 15 \text{ bar}$  with  $h_2 = 2992.5 \text{ kJ/kg}$ , the specific volume at the exit is  $v_2 = 0.1627 \text{ m}^3/\text{kg}$ . The exit area is then

$$A_2 = \frac{(2 \text{ kg/s})(0.1627 \text{ m}^3/\text{kg})}{665 \text{ m/s}} = 4.89 \times 10^{-4} \text{ m}^2$$

- ① Although equilibrium property relations apply at the inlet and exit of the control volume, the intervening states of the steam are not necessarily equilibrium states. Accordingly, the expansion through the nozzle is represented on the  $T-v$  diagram as a dashed line.
- ② Care must be taken in converting the units for specific kinetic energy to  $\text{kJ/kg}$ .

### Skills Developed

Ability to...

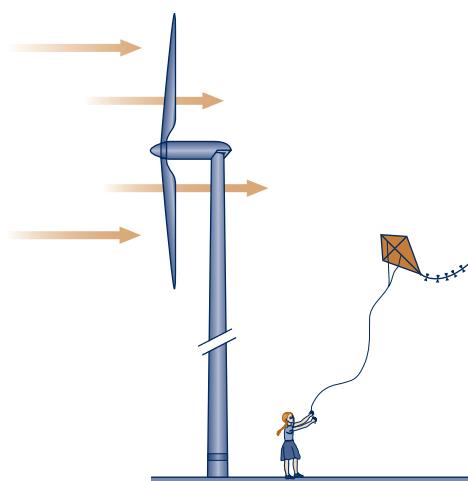
- apply the steady-state energy rate balance to a control volume.
- apply the mass flow rate expression, Eq. 4.4b.
- develop an engineering model.
- retrieve property data for water.

### QuickQUIZ

Evaluate the nozzle inlet area, in  $\text{m}^2$ . Ans.  $1.47 \times 10^{-2} \text{ m}^2$ .

## 4.7 Turbines

### turbine

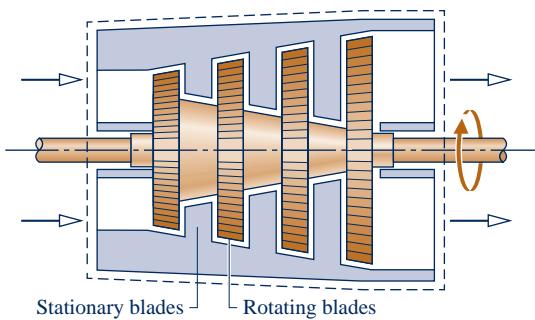


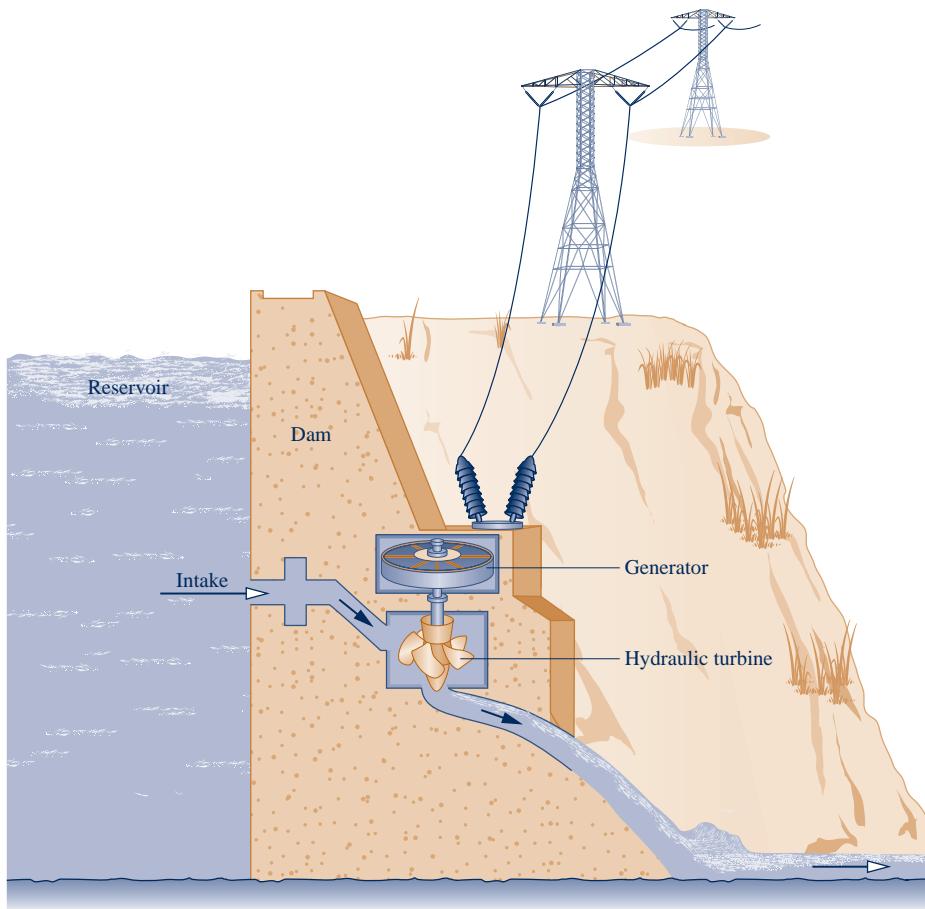
A **turbine** is a device in which power is developed as a result of a gas or liquid passing through a set of blades attached to a shaft free to rotate. A schematic of an axial-flow steam or gas turbine is shown in Fig. 4.9. Such turbines are widely used for power generation in vapor power plants, gas turbine power plants, and aircraft engines (see Chaps. 8 and 9). In these applications, superheated steam or a gas enters the turbine and expands to a lower pressure as power is generated.

A **hydraulic** turbine coupled to a generator installed in a dam is shown in Fig. 4.10. As water flows from higher to lower elevation through the turbine, the turbine provides shaft power to the generator. The generator converts shaft power to electricity. This type of generation is called *hydropower*. Today, hydropower is a leading *renewable* means for producing electricity, and it is one of the least expensive ways to do so. Electricity can also be produced from flowing water by using turbines to tap into currents in oceans and rivers.

Turbines are also key components of wind-turbine power plants that, like hydropower plants, are renewable means for generating electricity.

Fig. 4.9 Schematic of an axial-flow steam or gas turbine.





**Fig. 4.10** Hydraulic turbine installed in a dam.



**ENERGY & ENVIRONMENT** Industrial-scale wind turbines can stand as tall as a 30-story building and produce electricity at a rate meeting the needs of hundreds of typical U.S. homes. The three-bladed rotors of these wind turbines have a diameter nearly the length of a football field and can operate in winds up to 55 miles per hour. They feature microprocessor control of all functions, ensuring each blade is pitched at the correct angle for current wind conditions. Wind farms consisting of dozens of such turbines increasingly dot the landscape over the globe.

In the United States, wind farms at favorable sites in several Great Plains states alone could supply much of the nation's electricity needs—provided the electrical grid is upgraded and expanded (see *Horizons* on p. 430). Offshore wind farms along the U.S. coastline could also contribute significantly to meeting national needs. Experts say wind variability can be managed by producing maximum power when winds are strong and storing some, or all, of the power by various means, including *pumped-hydro* storage and *compressed-air* storage, for distribution when consumer demand is highest and electricity has its greatest economic value (see box in Sec. 4.8.3).

Wind power can produce electricity today at costs competitive with all alternative means and within a few years is expected to be among the least costly ways to do it. Wind energy plants take less time to build than conventional power plants and are modular, allowing additional units to be added as warranted. While generating electricity, wind-turbine plants produce no global warming gases or other emissions.

The industrial-scale wind turbines considered thus far are not the only ones available. Companies manufacture smaller, relatively inexpensive wind turbines that can generate electricity with wind speeds as low as 3 or 4 miles per hour. These *low-wind* turbines are suitable for small businesses, farms, groups of neighbors, or individual users.

### 4.7.1 • Steam and Gas Turbine Modeling Considerations

With a proper selection of the control volume enclosing a steam or gas turbine, the net kinetic energy of the matter flowing across the boundary is usually small enough to be neglected. The net potential energy of the flowing matter also is typically negligible. Thus, the underlined terms of Eq. 4.20a (repeated below) drop out, leaving the power, enthalpy, and heat transfer terms, as shown by Eq. (a)

$$\begin{aligned} 0 &= \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m} \left[ (h_1 - h_2) + \frac{(V_1^2 - V_2^2)}{2} + g(z_1 - z_2) \right] \\ 0 &= \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}(h_1 - h_2) \end{aligned} \quad (\text{a})$$

where  $\dot{m}$  is the mass flow rate. The only heat transfer between the turbine and surroundings normally would be unavoidable (or stray) heat transfer, and this is often small enough relative to the power and enthalpy terms that it also can be neglected, giving simply

$$\dot{W}_{cv} = \dot{m}(h_1 - h_2) \quad (\text{b})$$



### 4.7.2 • Application to a Steam Turbine

In this section, modeling considerations for turbines are illustrated by application to a case involving the practically important steam turbine. Objectives in this example include assessing the significance of the heat transfer and kinetic energy terms of the energy balance and illustrating the appropriate use of unit conversion factors.

#### EXAMPLE 4.4

#### Calculating Heat Transfer from a Steam Turbine

Steam enters a turbine operating at steady state with a mass flow rate of 4600 kg/h. The turbine develops a power output of 1000 kW. At the inlet, the pressure is 60 bar, the temperature is 400°C, and the velocity is 10 m/s. At the exit, the pressure is 0.1 bar, the quality is 0.9 (90%), and the velocity is 30 m/s. Calculate the rate of heat transfer between the turbine and surroundings, in kW.

#### SOLUTION

**Known:** A steam turbine operates at steady state. The mass flow rate, power output, and states of the steam at the inlet and exit are known.

**Find:** Calculate the rate of heat transfer.

#### Schematic and Given Data:

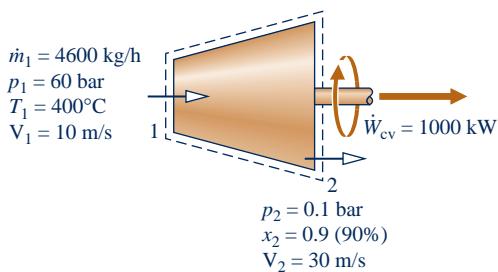
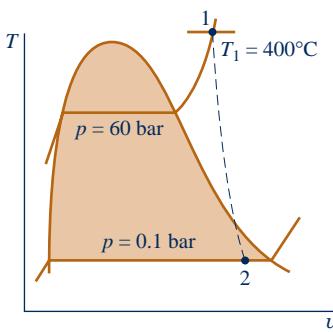


Fig. E4.4



#### Engineering Model:

1. The control volume shown on the accompanying figure is at steady state.
2. The change in potential energy from inlet to exit can be neglected.

**Analysis:** To calculate the heat transfer rate, begin with the one-inlet, one-exit form of the energy rate balance for a control volume at steady state, Eq. 4.20a. That is

$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m} \left[ (h_1 - h_2) + \frac{(V_1^2 - V_2^2)}{2} + g(z_1 - z_2) \right]$$

where  $\dot{m}$  is the mass flow rate. Solving for  $\dot{Q}_{cv}$  and dropping the potential energy change from inlet to exit

$$\dot{Q}_{cv} = \dot{W}_{cv} + \dot{m} \left[ (h_2 - h_1) + \frac{(V_2^2 - V_1^2)}{2} \right] \quad (a)$$

To compare the magnitudes of the enthalpy and kinetic energy terms, and stress the unit conversions needed, each of these terms is evaluated separately.

First, the specific *enthalpy difference*  $h_2 - h_1$  is found. Using Table A-4,  $h_1 = 3177.2$  kJ/kg. State 2 is a two-phase liquid-vapor mixture, so with data from Table A-3 and the given quality

$$\begin{aligned} h_2 &= h_{f2} + x_2(h_{g2} - h_{f2}) \\ &= 191.83 + (0.9)(2392.8) = 2345.4 \text{ kJ/kg} \end{aligned}$$

Hence

$$h_2 - h_1 = 2345.4 - 3177.2 = -831.8 \text{ kJ/kg}$$

Consider next the specific *kinetic energy difference*. Using the given values for the velocities

$$\begin{aligned} ① \quad \left( \frac{V_2^2 - V_1^2}{2} \right) &= \left[ \frac{(30)^2 - (10)^2}{2} \right] \left( \frac{\text{m}^2}{\text{s}^2} \right) \left| \frac{1 \text{ N}}{1 \text{ kg} \cdot \text{m/s}^2} \right| \left| \frac{1 \text{ kJ}}{10^3 \text{ N} \cdot \text{m}} \right| \\ &= 0.4 \text{ kJ/kg} \end{aligned}$$

Calculating  $\dot{Q}_{cv}$  from Eq. (a)

$$\begin{aligned} ② \quad \dot{Q}_{cv} &= (1000 \text{ kW}) + \left( 4600 \frac{\text{kg}}{\text{h}} \right) (-831.8 + 0.4) \left( \frac{\text{kJ}}{\text{kg}} \right) \left| \frac{1 \text{ h}}{3600 \text{ s}} \right| \left| \frac{1 \text{ kW}}{1 \text{ kJ/s}} \right| \\ &= -62.3 \text{ kW} \end{aligned}$$

- ① The magnitude of the change in specific kinetic energy from inlet to exit is much smaller than the specific enthalpy change. Note the use of unit conversion factors here and in the calculation of  $\dot{Q}_{cv}$  to follow.
- ② The negative value of  $\dot{Q}_{cv}$  means that there is heat transfer from the turbine to its surroundings, as would be expected. The magnitude of  $\dot{Q}_{cv}$  is small relative to the power developed.

### Skills Developed

Ability to...

- apply the steady-state energy rate balance to a control volume.
- develop an engineering model.
- retrieve property data for water.

### QuickQUIZ

If the change in kinetic energy from inlet to exit were neglected, evaluate the heat transfer rate, in kW, keeping all other data unchanged.  
Comment. **Ans.** -62.9 kW

## compressor, pump

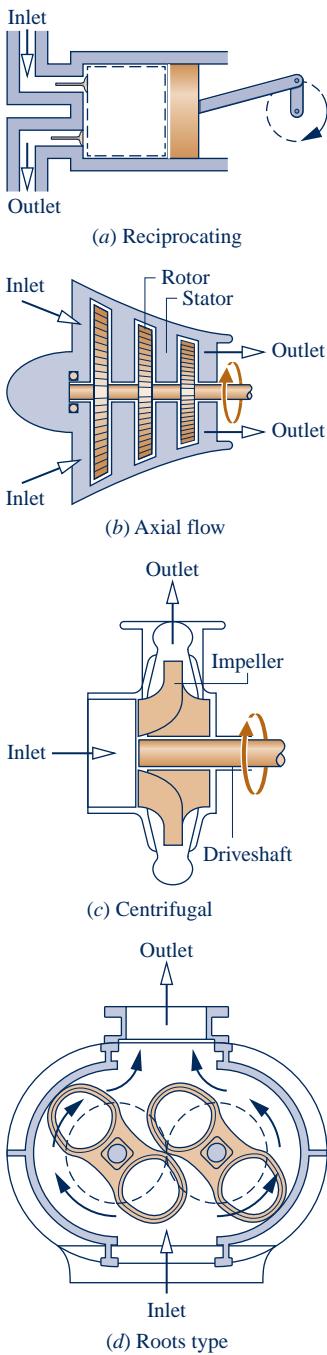


Fig. 4.11 Compressor types.

## 4.8 Compressors and Pumps

**Compressors** and **pumps** are devices in which work is done on the substance flowing through them in order to change the state of the substance, typically to increase the pressure and/or elevation. The term *compressor* is used when the substance is a gas (vapor) and the term *pump* is used when the substance is a liquid. Four compressor types are shown in Fig. 4.11. The reciprocating compressor of Fig. 4.11a features reciprocating motion while the others have rotating motion.

The axial-flow compressor of Fig. 4.11b is a key component of turbojet engines (Sec. 9.11). Compressors also are essential components of refrigeration and heat pump systems (Chap. 10). In the study of Chap. 8, we find that pumps are important in vapor power systems. Pumps also are commonly used to fill water towers, remove water from flooded basements, and for numerous other domestic and industrial applications.

### 4.8.1 Compressor and Pump Modeling Considerations

For a control volume enclosing a compressor, the mass and energy rate balances reduce at steady state as for the case of turbines considered in Sec. 4.7.1. Thus, Eq. 4.20a reduces to read

$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}(h_1 - h_2) \quad (a)$$

Heat transfer with the surroundings is frequently a secondary effect that can be neglected, giving as for turbines

$$\dot{W}_{cv} = \dot{m}(h_1 - h_2) \quad (b)$$

For pumps, heat transfer is generally a secondary effect, but the kinetic and potential energy terms of Eq. 4.20a may be significant depending on the application. Be sure to note that for compressors and pumps, the value of  $\dot{W}_{cv}$  is *negative* because a power *input* is required.

### 4.8.2 Applications to an Air Compressor and a Pump System

In this section, modeling considerations for compressors and pumps are illustrated in Examples 4.5 and 4.6, respectively. Applications of compressors and pumps in energy storage systems are described in Sec. 4.8.3.

In Example 4.5 the objectives include assessing the significance of the heat transfer and kinetic energy terms of the energy balance and illustrating the appropriate use of unit conversion factors.

#### EXAMPLE 4.5

##### Calculating Compressor Power

Air enters a compressor operating at steady state at a pressure of 1 bar, a temperature of 290 K, and a velocity of 6 m/s through an inlet with an area of  $0.1 \text{ m}^2$ . At the exit, the pressure is 7 bar, the temperature is 450 K, and the velocity is 2 m/s. Heat transfer from the compressor to its surroundings occurs at a rate of 180 kJ/min. Employing the ideal gas model, calculate the power input to the compressor, in kW.

**SOLUTION**

**Known:** An air compressor operates at steady state with known inlet and exit states and a known heat transfer rate.

**Find:** Calculate the power required by the compressor.

**Schematic and Given Data:**

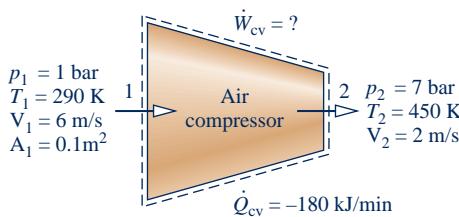


Fig. E4.5

**Analysis:** To calculate the power input to the compressor, begin with the one-inlet, one-exit form of the energy rate balance for a control volume at steady state, Eq. 4.20a. That is

$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m} \left[ (h_1 - h_2) + \frac{(V_1^2 - V_2^2)}{2} + g(z_1 - z_2) \right]$$

Solving

$$\dot{W}_{cv} = \dot{Q}_{cv} + \dot{m} \left[ (h_1 - h_2) + \left( \frac{V_1^2 - V_2^2}{2} \right) \right]$$

The change in potential energy from inlet to exit drops out by assumption 2.

The mass flow rate  $\dot{m}$  can be evaluated with given data at the inlet and the ideal gas equation of state.

$$\dot{m} = \frac{A_1 V_1}{v_1} = \frac{A_1 V_1 p_1}{(\bar{R}/M) T_1} = \frac{(0.1 \text{ m}^2)(6 \text{ m/s})(10^5 \text{ N/m}^2)}{\left( \frac{8314 \text{ N} \cdot \text{m}}{28.97 \text{ kg} \cdot \text{K}} \right)(290 \text{ K})} = 0.72 \text{ kg/s}$$

The specific enthalpies  $h_1$  and  $h_2$  can be found from Table A-22. At 290 K,  $h_1 = 290.16 \text{ kJ/kg}$ . At 450 K,  $h_2 = 451.8 \text{ kJ/kg}$ . Substituting values into the expression for  $\dot{W}_{cv}$ , and applying appropriate unit conversion factors, we get

$$\begin{aligned} \dot{W}_{cv} &= \left( -180 \frac{\text{kJ}}{\text{min}} \right) \left| \frac{1 \text{ min}}{60 \text{ s}} \right| + 0.72 \frac{\text{kg}}{\text{s}} \left[ (290.16 - 451.8) \frac{\text{kJ}}{\text{kg}} \right. \\ &\quad \left. + \left( \frac{(6)^2 - (2)^2}{2} \right) \left( \frac{\text{m}^2}{\text{s}^2} \right) \left| \frac{1 \text{ N}}{1 \text{ kg} \cdot \text{m/s}^2} \right| \left| \frac{1 \text{ kJ}}{10^3 \text{ N} \cdot \text{m}} \right| \right] \\ &= -3 \frac{\text{kJ}}{\text{s}} + 0.72 \frac{\text{kg}}{\text{s}} (-161.64 + 0.02) \frac{\text{kJ}}{\text{kg}} \\ &= -119.4 \frac{\text{kJ}}{\text{s}} \left| \frac{1 \text{ kW}}{1 \text{ kJ/s}} \right| = -119.4 \text{ kW} \end{aligned}$$

- ① The applicability of the ideal gas model can be checked by reference to the generalized compressibility chart.
- ② In this example  $\dot{Q}_{cv}$  and  $\dot{W}_{cv}$  have negative values, indicating that the direction of the heat transfer is *from* the compressor and work is done *on* the air passing through the compressor. The magnitude of the power *input* to the compressor is 119.4 kW. The change in kinetic energy does not contribute significantly.

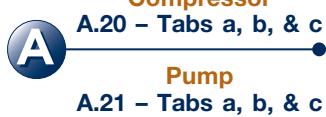
**Skills Developed**

*Ability to...*

- apply the steady-state energy rate balance to a control volume.
- apply the mass flow rate expression, Eq. 4.4b.
- develop an engineering model.
- retrieve property data of air modeled as an ideal gas.

**QuickQUIZ**

If the change in kinetic energy from inlet to exit were neglected, evaluate the compressor power, in kW, keeping all other data unchanged.  
Comment. Ans.  $-119.4 \text{ kW}$ .



In Example 4.6, a pump is a component of an overall system that delivers a high-velocity stream of water at an elevation greater than at the inlet. Note the modeling considerations in this case, particularly the roles of kinetic and potential energy, and the use of appropriate unit conversion factors.

### EXAMPLE 4.6

## Analyzing a Pump System

A pump steadily draws water from a pond at a volumetric flow rate of  $0.83 \text{ m}^3/\text{min}$  through a pipe having a 12-cm diameter inlet. The water is delivered through a hose terminated by a converging nozzle. The nozzle exit has a diameter of 3 cm and is located 10 m above the pipe inlet. Water enters at  $20^\circ\text{C}$ , 1 atm and exits with no significant change in temperature or pressure. The magnitude of the rate of heat transfer *from* the pump *to* the surroundings is 5% of the power input. The acceleration of gravity is  $9.81 \text{ m/s}^2$ . Determine (a) the velocity of the water at the inlet and exit, each in m/s, and (b) the power required by the pump, in kW.

### SOLUTION

**Known:** A pump system operates at steady state with known inlet and exit conditions. The rate of heat transfer from the pump is specified as a percentage of the power input.

**Find:** Determine the velocities of the water at the inlet and exit of the pump system and the power required.

### Schematic and Given Data:

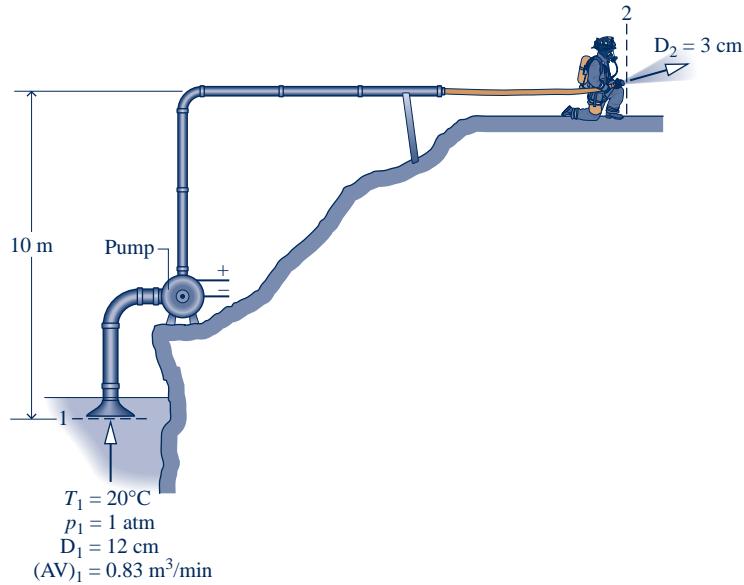


Fig. E4.6

### Analysis:

(a) A mass rate balance reduces at steady state to read  $\dot{m}_2 = \dot{m}_1$ . The common mass flow rate at the inlet and exit,  $\dot{m}$ , can be evaluated using Eq. 4.4b together with  $v \approx v_f(20^\circ\text{C}) = 1.0018 \times 10^{-3} \text{ m}^3/\text{kg}$  from Table A-2. That is,

$$\begin{aligned}\dot{m} &= \frac{\dot{V}}{v} = \left( \frac{0.83 \text{ m}^3/\text{min}}{1.0018 \times 10^{-3} \text{ m}^3/\text{kg}} \right) \left| \frac{1 \text{ min}}{60 \text{ s}} \right| \\ &= 13.8 \frac{\text{kg}}{\text{s}}\end{aligned}$$

### Engineering Model:

1. A control volume encloses the pump, inlet pipe, and delivery hose.
2. The control volume is at steady state.
3. The magnitude of the heat transfer from the control volume is 5% of the power input.
4. There is no significant change in temperature or pressure.
5. For liquid water,  $v \approx v_f(T)$  (Eq. 3.11) and Eq. 3.13 is used to evaluate specific enthalpy.
6.  $g = 9.81 \text{ m/s}^2$ .

Thus, the inlet and exit velocities are, respectively,

$$\textcircled{1} \quad V_1 = \frac{\dot{m}v}{A_1} = \frac{(13.8 \text{ kg/s})(1.0018 \times 10^{-3} \text{ m}^3/\text{kg})}{\pi(0.12 \text{ m})^2/4} = 1.22 \text{ m/s}$$

$$V_2 = \frac{\dot{m}v}{A_2} = \frac{(13.8 \text{ kg/s})(1.0018 \times 10^{-3} \text{ m}^3/\text{kg})}{\pi(0.03 \text{ m})^2/4} = 19.56 \text{ m/s}$$

(b) To calculate the power input, begin with the one-inlet, one-exit form of the energy rate balance for a control volume at steady state, Eq. 4.20a. That is

$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m} \left[ (h_1 - h_2) + \left( \frac{V_1^2 - V_2^2}{2} \right) + g(z_1 - z_2) \right]$$

\textcircled{2} Introducing  $\dot{Q}_{cv} = (0.05)\dot{W}_{cv}$ , and solving for  $\dot{W}_{cv}$

$$\dot{W}_{cv} = \frac{\dot{m}}{0.95} \left[ (h_1 - h_2) + \left( \frac{V_1^2 - V_2^2}{2} \right) + g(z_1 - z_2) \right] \quad \text{(a)}$$

Using Eq. 3.13, the enthalpy term is expressed as

$$h_1 - h_2 = [h_f(T_1) + v_f(T_1)[p_1 - p_{sat}(T_1)]] \\ - [h_f(T_2) + v_f(T_2)[p_2 - p_{sat}(T_2)]] \quad \text{(b)}$$

Since there is no significant change in temperature, Eq. (b) reduces to

$$h_1 - h_2 = v_f(T)(p_1 - p_2)$$

As there is also no significant change in pressure, the enthalpy term drops out of the present analysis. Next, evaluating the kinetic energy term

$$\frac{V_1^2 - V_2^2}{2} = \frac{[(1.22)^2 - (19.56)^2] \left( \frac{\text{m}}{\text{s}} \right)^2}{2} \left| \frac{1 \text{ N}}{1 \text{ kg} \cdot \text{m/s}^2} \right| \left| \frac{1 \text{ kJ}}{10^3 \text{ N} \cdot \text{m}} \right| = -0.191 \text{ kJ/kg}$$

Finally, the potential energy term is

$$g(z_1 - z_2) = (9.81 \text{ m/s}^2)(0 - 10) \left| \frac{1 \text{ N}}{1 \text{ kg} \cdot \text{m/s}^2} \right| \left| \frac{1 \text{ kJ}}{10^3 \text{ N} \cdot \text{m}} \right| = -0.098 \text{ kJ/kg}$$

Inserting values into Eq. (a)

$$\dot{W}_{cv} = \left( \frac{13.8 \text{ kg/s}}{0.95} \right) [0 - 0.191 - 0.098] \left( \frac{\text{kJ}}{\text{kg}} \right) \left| \frac{1 \text{ kW}}{1 \text{ kJ/s}} \right| \\ = -4.2 \text{ kW}$$

where the minus sign indicates that power is provided to the pump.

- \textcircled{1} Alternatively,  $V_1$  can be evaluated from the volumetric flow rate at 1. This is left as an exercise.
- \textcircled{2} Since power is required to operate the pump,  $\dot{W}_{cv}$  is negative in accord with our sign convention. The energy transfer by heat is from the control volume to the surroundings, and thus  $\dot{Q}_{cv}$  is negative as well. Using the value of  $\dot{W}_{cv}$  found in part (b),  $\dot{Q}_{cv} = (0.05)\dot{W}_{cv} = -0.21 \text{ kW}$ .

### Skills Developed

Ability to...

- apply the steady-state energy rate balance to a control volume.
- apply the mass flow rate expression, Eq. 4.4b.
- develop an engineering model.
- retrieve properties of liquid water.

### QuickQUIZ

If the nozzle were removed and water exited directly from the hose, whose diameter is 5 cm, determine the velocity at the exit, in m/s, and the power required, in kW, keeping all other data unchanged.

**Ans.** 7.04 m/s, 1.77 kW.

### 4.8.3 • Pumped-Hydro and Compressed-Air Energy Storage

#### TAKE NOTE...

*Cost* refers to the amount paid to produce a good or service. *Price* refers to what consumers pay to acquire that good or service.

Owing to the dictates of supply and demand and other economic factors, the value of electricity varies with time. Both the cost to generate electricity and increasingly the price paid by consumers for electricity depend on whether the demand for it is *on-peak* or *off-peak*. The on-peak period is typically weekdays—for example from 8 a.m. to 8 p.m., while off-peak includes nighttime hours, weekends, and major holidays. Consumers can expect to pay more for on-peak electricity. Energy storage methods benefiting from variable electricity rates include thermal storage (see box on p. 111) and pumped-hydro and compressed-air storage introduced in the following box.

#### Economic Aspects of Pumped-Hydro and Compressed-Air Energy Storage

Despite the significant costs of owning and operating utility-scale energy storage systems, various economic strategies, including taking advantage of differing on- and off-peak electricity rates, can make pumped-hydro and compressed-air storage good choices for power generators. In this discussion, we focus on the role of variable electricity rates.

In pumped-hydro storage, water is pumped from a lower reservoir to an upper reservoir, thereby storing energy in the form of gravitational potential energy. (For simplicity, think of the hydropower plant of Fig. 4.10 operating in the reverse direction.) Off-peak electricity is used to drive the pumps that deliver water to the upper reservoir. Later, during an on-peak period, stored water is released from the upper reservoir to generate electricity as the water flows through turbines to the lower reservoir. For instance, in the summer water is released from the upper reservoir to generate power to meet a high daytime demand for air conditioning; while at night, when demand is low, water is pumped back to the upper reservoir for use the next day. Owing to friction and other nonidealities, an overall input-to-output loss of electricity occurs with pumped-hydro storage and this adds to operating costs. Still, differing daytime and nighttime electricity rates help make this technology viable.

In compressed-air energy storage, compressors powered with off-peak electricity fill an underground salt cavern, hard-rock mine, or aquifer with pressurized air drawn from the atmosphere. See Fig. 4.12. When electricity demand peaks, high-pressure compressed air is released to the surface, heated by natural gas in combustors, and expanded through a turbine generator, generating electricity for distribution at on-peak rates.

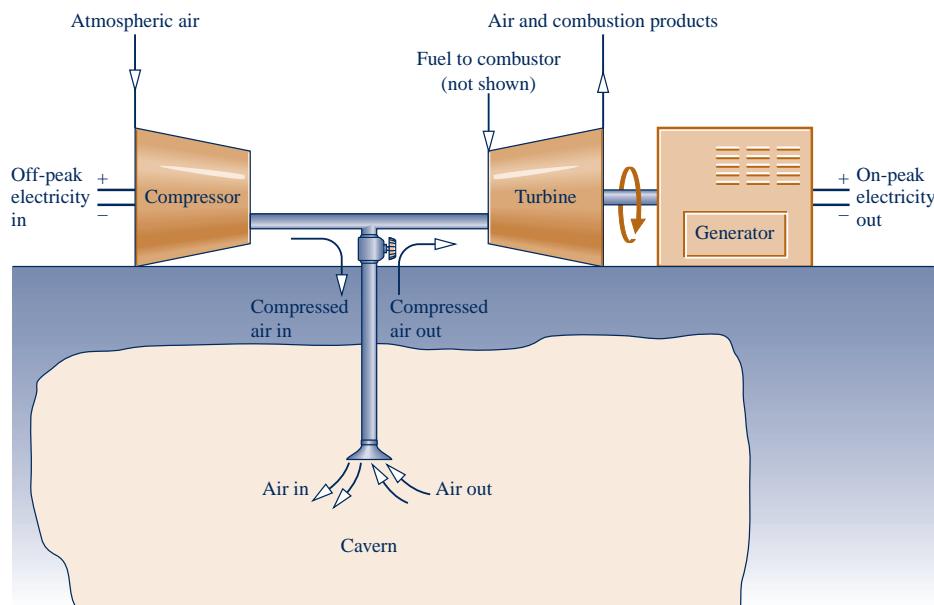
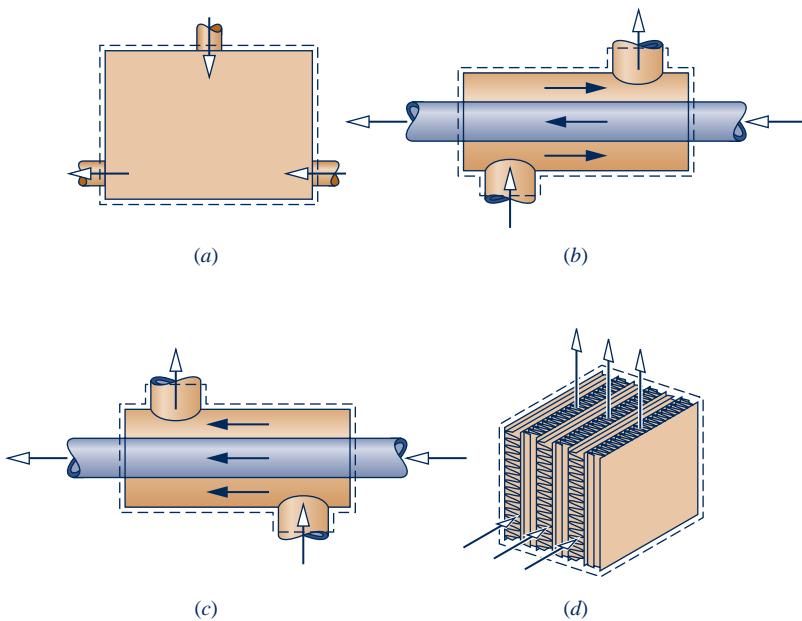


Fig. 4.12 Compressed-air storage.



**Fig. 4.13** Common heat exchanger types. (a) Direct contact heat exchanger. (b) Tube-within-a-tube counterflow heat exchanger. (c) Tube-within-a-tube parallel flow heat exchanger. (d) Cross-flow heat exchanger.

## 4.9 Heat Exchangers

Heat exchangers have innumerable domestic and industrial applications, including use in home heating and cooling systems, automotive systems, electrical power generation, and chemical processing. Indeed, nearly every area of application listed in Table 1.1 (p. 5) involves heat exchangers.

heat exchanger

One common type of heat exchanger is a mixing chamber in which hot and cold streams are mixed directly as shown in Fig. 4.13a. The open feedwater heater, which is a component of the vapor power systems considered in Chap. 8, is an example of this type of device.

Another common type of exchanger is one in which a gas or liquid is *separated* from another gas or liquid by a wall through which energy is conducted. These heat exchangers, known as recuperators, take many different forms. Counterflow and parallel tube-within-a-tube configurations are shown in Figs. 4.13b and 4.13c, respectively. Other configurations include cross-flow, as in automobile radiators, and multiple-pass shell-and-tube condensers and evaporators. Figure 4.13d illustrates a cross-flow heat exchanger.



**BIO CONNECTIONS** Inflatable blankets such as shown in Fig. 4.14 are used to prevent subnormal body temperatures (hypothermia) during and after surgery.

Typically, a heater and blower direct a stream of warm air into the blanket. Air exits the blanket through perforations in its surface. Such *thermal blankets* have been used safely and without incident in millions of surgical procedures. Still, there are obvious risks to patients if temperature controls fail and overheating occurs. Such risks can be anticipated and minimized with good engineering practices.

Warming patients is not always the issue at hospitals; sometimes it is cooling, as in cases involving cardiac arrest, stroke, heart attack, and overheating of the body (hyperthermia). Cardiac arrest, for example, deprives the heart muscle of oxygen and blood, causing part of it to die. This often induces brain damage among survivors, including irreversible cognitive disability. Studies show when the core body temperature of cardiac patients is

reduced to about 33°C (91°F), damage is limited because vital organs function more slowly and require less oxygen. To achieve good outcomes, medical specialists say cooling should be done in about 20 minutes or less. A system approved for cooling cardiac arrest victims includes a disposable plastic body suit, pump, and chiller. The pump provides rapidly flowing cold water around the body, in direct contact with the skin of the patient wearing the suit, then recycles coolant to the chiller and back to the patient.

These biomedical applications provide examples of how engineers well versed in thermodynamics principles can bring into the design process their knowledge of heat exchangers, temperature sensing and control, and safety and reliability requirements.

### 4.9.1 Heat Exchanger Modeling Considerations

As shown by Fig. 4.13, heat exchangers can involve multiple inlets and exits. For a control volume enclosing a heat exchanger, the only work is flow work at the places where matter enters and exits, so the term  $\dot{W}_{cv}$  drops out of the energy rate balance. In addition, the kinetic and potential energies of the flowing streams usually can be ignored at the inlets and exits. Thus, the underlined terms of Eq. 4.18 (repeated below) drop out, leaving the enthalpy and heat transfer terms, as shown by Eq. (a). That is,

$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i \left( h_i + \frac{V_i^2}{2} + gz_i \right) - \sum_e \dot{m}_e \left( h_e + \frac{V_e^2}{2} + gz_e \right)$$

$$0 = \dot{Q}_{cv} + \sum_i \dot{m}_i h_i - \sum_e \dot{m}_e h_e \quad (\text{a})$$

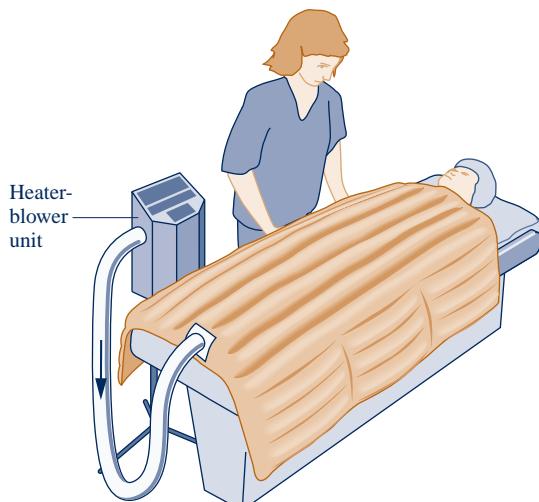
Although high rates of energy transfer *within* the heat exchanger occur, heat transfer with the surroundings is often small enough to be neglected. Thus, the  $\dot{Q}_{cv}$  term of Eq. (a) would drop out, leaving just the enthalpy terms. The final form of the energy rate balance must be solved together with an appropriate expression of the mass rate balance, recognizing both the number and type of inlets and exits for the case at hand.



**Heat Exchanger**  
A.22 – Tabs a, b, & c

### 4.9.2 Applications to a Power Plant Condenser and Computer Cooling

The next example illustrates how the mass and energy rate balances are applied to a condenser at steady state. Condensers are commonly found in power plants and refrigeration systems.



**Fig. 4.14** Inflatable thermal blanket.

▶▶▶ EXAMPLE 4.7

## Evaluating Performance of a Power Plant Condenser

Steam enters the condenser of a vapor power plant at 0.1 bar with a quality of 0.95 and condensate exits at 0.1 bar and 45°C. Cooling water enters the condenser in a separate stream as a liquid at 20°C and exits as a liquid at 35°C with no change in pressure. Heat transfer from the outside of the condenser and changes in the kinetic and potential energies of the flowing streams can be ignored. For steady-state operation, determine

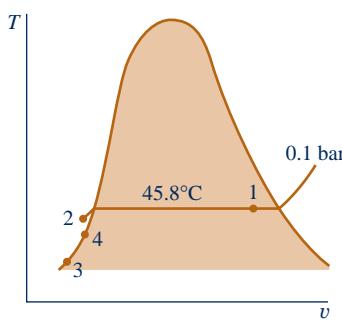
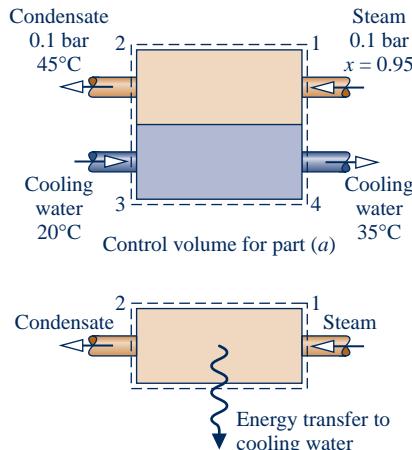
- the ratio of the mass flow rate of the cooling water to the mass flow rate of the condensing steam.
- the rate of energy transfer from the condensing steam to the cooling water, in kJ per kg of steam passing through the condenser.

### SOLUTION

**Known:** Steam is condensed at steady state by interacting with a separate liquid water stream.

**Find:** Determine the ratio of the mass flow rate of the cooling water to the mass flow rate of the steam and the rate of energy transfer from the steam to the cooling water.

### Schematic and Given Data:



### Engineering Model:

- Each of the two control volumes shown on the accompanying sketch is at steady state.
- There is no significant heat transfer between the overall condenser and its surroundings.  $\dot{W}_{cv} = 0$ .
- Changes in the kinetic and potential energies of the flowing streams from inlet to exit can be ignored.
- At states 2, 3, and 4,  $h \approx h_f(T)$  (see Eq. 3.14).

Fig. E4.7

**Analysis:** The steam and the cooling water streams do not mix. Thus, the mass rate balances for each of the two streams reduce at steady state to give

$$\dot{m}_1 = \dot{m}_2 \quad \text{and} \quad \dot{m}_3 = \dot{m}_4$$

(a) The ratio of the mass flow rate of the cooling water to the mass flow rate of the condensing steam,  $\dot{m}_3/\dot{m}_1$ , can be found from the steady-state form of the energy rate balance, Eq. 4.18, applied to the overall condenser as follows:

$$0 = \underline{\dot{Q}_{cv}} - \underline{\dot{W}_{cv}} + \dot{m}_1 \left( h_1 + \frac{V_1^2}{2} + gz_1 \right) + \dot{m}_3 \left( h_3 + \frac{V_3^2}{2} + gz_3 \right) - \dot{m}_2 \left( h_2 + \frac{V_2^2}{2} + gz_2 \right) - \dot{m}_4 \left( h_4 + \frac{V_4^2}{2} + gz_4 \right)$$

The underlined terms drop out by assumptions 2 and 3. With these simplifications, together with the above mass flow rate relations, the energy rate balance becomes simply

$$0 = \dot{m}_1(h_1 - h_2) + \dot{m}_3(h_3 - h_4)$$

Solving, we get

$$\frac{\dot{m}_3}{\dot{m}_1} = \frac{h_1 - h_2}{h_4 - h_3}$$

The specific enthalpy  $h_1$  can be determined using the given quality and data from Table A-3. From Table A-3 at 0.1 bar,  $h_f = 191.83 \text{ kJ/kg}$  and  $h_g = 2584.7 \text{ kJ/kg}$ , so

$$h_1 = 191.83 + 0.95(2584.7 - 191.83) = 2465.1 \text{ kJ/kg}$$

- ① Using assumption 4, the specific enthalpy at 2 is given by  $h_2 \approx h_f(T_2) = 188.45 \text{ kJ/kg}$ . Similarly,  $h_3 \approx h_f(T_3)$  and  $h_4 \approx h_f(T_4)$ , giving  $h_4 - h_3 = 62.7 \text{ kJ/kg}$ . Thus,

$$\frac{\dot{m}_3}{\dot{m}_1} = \frac{2465.1 - 188.45}{62.7} = 36.3$$

- (b) For a control volume enclosing the steam side of the condenser only, begin with the steady-state form of energy rate balance, Eq. 4.20a.

② 
$$0 = \dot{Q}_{cv} - \underline{\dot{W}_{cv}} + \dot{m}_1 \left[ (h_1 - h_2) + \frac{(V_1^2 - V_2^2)}{2} + g(z_1 - z_2) \right]$$

The underlined terms drop out by assumptions 2 and 3. The following expression for the rate of energy transfer between the condensing steam and the cooling water results:

$$\dot{Q}_{cv} = \dot{m}_1(h_2 - h_1)$$

Dividing by the mass flow rate of the steam,  $\dot{m}_1$ , and inserting values

$$\frac{\dot{Q}_{cv}}{\dot{m}_1} = h_2 - h_1 = 188.45 - 2465.1 = -2276.7 \text{ kJ/kg}$$

where the minus sign signifies that energy is transferred *from* the condensing steam *to* the cooling water.

- ① Alternatively,  $(h_4 - h_3)$  can be evaluated using the incompressible liquid model via Eq. 3.20b.
- ② Depending on where the boundary of the control volume is located, two different formulations of the energy rate balance are obtained. In part (a), both streams are included in the control volume. Energy transfer between them occurs internally and not across the boundary of the control volume, so the term  $\dot{Q}_{cv}$  drops out of the energy rate balance. With the control volume of part (b), however, the term  $\dot{Q}_{cv}$  must be included.

### Skills Developed

Ability to...

- apply the steady-state mass and energy rate balances to a control volume.
- develop an engineering model.
- retrieve property data for water.

### QuickQUIZ

If the mass flow rate of the condensing steam is 125 kg/s, determine the mass flow rate of the cooling water, in kg/s. **Ans.** 4538 kg/s.

Excessive temperatures in electronic components are avoided by providing appropriate cooling. In the next example, we analyze the cooling of computer components, illustrating the use of the control volume form of energy rate balance together with property data for air.

### EXAMPLE 4.8 ▶

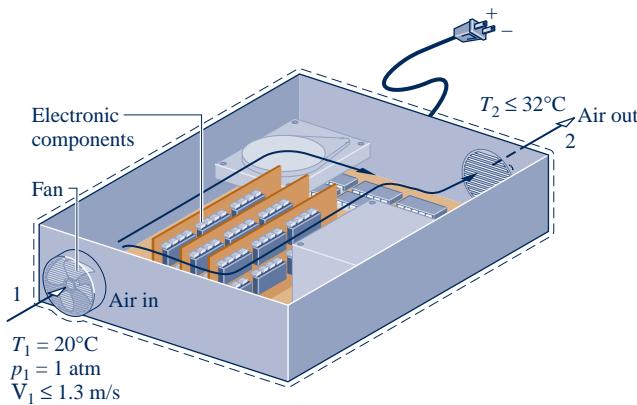
## Cooling Computer Components

The electronic components of a computer are cooled by air flowing through a fan mounted at the inlet of the electronics enclosure. At steady state, air enters at  $20^\circ\text{C}$ , 1 atm. For noise control, the velocity of the entering air cannot exceed 1.3 m/s. For temperature control, the temperature of the air at the exit cannot exceed  $32^\circ\text{C}$ . The electronic components and fan receive, respectively, 80 W and 18 W of electric power. Determine the smallest fan inlet area, in  $\text{cm}^2$ , for which the limits on the entering air velocity and exit air temperature are met.

**SOLUTION**

**Known:** The electronic components of a computer are cooled by air flowing through a fan mounted at the inlet of the electronics enclosure. Conditions are specified for the air at the inlet and exit. The power required by the electronics and the fan are also specified.

**Find:** Determine the smallest fan area for which the specified limits are met.

**Schematic and Given Data:**

**Fig. E4.8**

**Analysis:** The inlet area  $A_1$  can be determined from the mass flow rate  $\dot{m}$  and Eq. 4.4b, which can be rearranged to read

$$A_1 = \frac{\dot{m}V_1}{V_1} \quad (\text{a})$$

The mass flow rate can be evaluated, in turn, from the steady-state energy rate balance, Eq. 4.20a.

$$0 = \underline{\dot{Q}_{cv}} - \dot{W}_{cv} + \dot{m} \left[ (h_1 - h_2) + \underbrace{\left( \frac{V_1^2 - V_2^2}{2} \right)}_{\text{Assumptions 2 and 3}} + g(z_1 - z_2) \right]$$

The underlined terms drop out by assumptions 2 and 3, leaving

$$0 = -\dot{W}_{cv} + \dot{m}(h_1 - h_2)$$

where  $\dot{W}_{cv}$  accounts for the *total* electric power provided to the electronic components and the fan:  $\dot{W}_{cv} = (-80 \text{ W}) + (-18 \text{ W}) = -98 \text{ W}$ . Solving for  $\dot{m}$ , and using assumption 4 with Eq. 3.51 to evaluate  $(h_1 - h_2)$

$$\dot{m} = \frac{(-\dot{W}_{cv})}{c_p(T_2 - T_1)}$$

Introducing this into the expression for  $A_1$ , Eq. (a), and using the ideal gas model to evaluate the specific volume  $v_1$

$$A_1 = \frac{1}{V_1} \left[ \frac{(-\dot{W}_{cv})}{c_p(T_2 - T_1)} \right] \left( \frac{RT_1}{p_1} \right)$$

From this expression we see that  $A_1$  *increases* when  $V_1$  and/or  $T_2$  *decrease*. Accordingly, since  $V_1 \leq 1.3 \text{ m/s}$  and  $T_2 \leq 305 \text{ K}$  ( $32^\circ\text{C}$ ), the inlet area must satisfy

$$A_1 \geq \frac{1}{1.3 \text{ m/s}} \left[ \frac{98 \text{ W}}{\left( 1.005 \frac{\text{kJ}}{\text{kg} \cdot \text{K}} \right) (305 - 293) \text{ K}} \right] \left| \frac{1 \text{ kJ}}{10^3 \text{ J}} \right| \left| \frac{1 \text{ J/s}}{1 \text{ W}} \right| \left( \frac{\left( \frac{8314 \text{ N} \cdot \text{m}}{28.97 \text{ kg} \cdot \text{K}} \right) 293 \text{ K}}{1.01325 \times 10^5 \text{ N/m}^2} \right) \left| \frac{10^4 \text{ cm}^2}{1 \text{ m}^2} \right| \\ \geq 52 \text{ cm}^2$$

For the specified conditions, the smallest fan area is  $52 \text{ cm}^2$ .

**Engineering Model:**

1. The control volume shown on the accompanying figure is at steady state.
2. Heat transfer from the *outer* surface of the electronics enclosure to the surroundings is negligible. Thus,  $\dot{Q}_{cv} = 0$ .
3. Changes in kinetic and potential energies can be ignored.
4. Air is modeled as an ideal gas with  $c_p = 1.005 \text{ kJ/kg} \cdot \text{K}$ .

- Cooling air typically enters and exits electronic enclosures at low velocities, and thus kinetic energy effects are insignificant.
- The applicability of the ideal gas model can be checked by reference to the generalized compressibility chart. Since the temperature of the air increases by no more than 12°C, the specific heat  $c_p$  is nearly constant (Table A-20).

### Skills Developed

*Ability to...*

- apply the steady-state energy rate balance to a control volume.
- apply the mass flow rate expression, Eq. 4.4b.
- develop an engineering model.
- retrieve property data of air modeled as an ideal gas.

### QuickQUIZ

If heat transfer occurs at a rate of 11 W from the outer surface of the computer case to the surroundings, determine the smallest fan inlet area for which the limits on entering air velocity and exit air temperature are met if the total power input remains at 98 W. **Ans.** 46 cm<sup>2</sup>.

## 4.10 Throttling Devices

A significant reduction in pressure can be achieved simply by introducing a restriction into a line through which a gas or liquid flows. This is commonly done by means of a partially opened valve or a porous plug. These *throttling* devices are illustrated in Fig. 4.15.

An application of throttling occurs in vapor-compression refrigeration systems, where a valve is used to reduce the pressure of the refrigerant from the pressure at the exit of the *condenser* to the lower pressure existing in the *evaporator*. We consider this further in Chap. 10. Throttling also plays a role in the *Joule–Thomson* expansion considered in Chap. 11. Another application involves the **throttling calorimeter**, which is a device for determining the quality of a two-phase liquid–vapor mixture. The throttling calorimeter is considered in Example 4.9.

**throttling calorimeter**

### 4.10.1 Throttling Device Modeling Considerations

For a control volume enclosing a throttling device, the only work is flow work at locations where mass enters and exits the control volume, so the term  $\dot{W}_{cv}$  drops out of the energy rate balance. There is usually no significant heat transfer with the surroundings, and the change in potential energy from inlet to exit is negligible. Thus, the underlined terms of Eq. 4.20a (repeated below) drop out, leaving the enthalpy and kinetic energy terms, as shown by Eq. (a). That is,

$$0 = \underline{\dot{Q}_{cv}} - \underline{\dot{W}_{cv}} + \dot{m} \left[ (h_1 - h_2) + \frac{(V_1^2 - V_2^2)}{2} + g(z_1 - z_2) \right]$$

$$0 = (h_1 - h_2) + \frac{V_1^2 - V_2^2}{2} \quad (a)$$

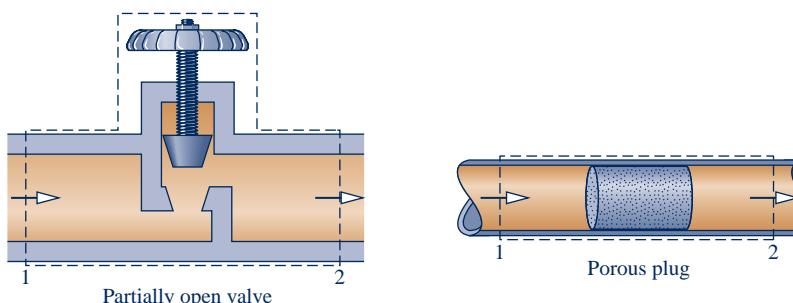


Fig. 4.15 Examples of throttling devices.

Although velocities may be relatively high in the vicinity of the restriction imposed by the throttling device on the flow through it, measurements made upstream and downstream of the reduced flow area show in most cases that the change in the specific kinetic energy of the flowing substance between these locations can be neglected. With this further simplification, Eq. (a) reduces to

$$h_2 = h_1 \quad (p_2 < p_1) \quad (4.22)$$

When the flow through the valve or other restriction is idealized in this way, the process is called a **throttling process**.

**Throttling Dev**  
A.23 – Tabs a, b, & c **A**

**throttling process**

### 4.10.2 Using a Throttling Calorimeter to Determine Quality

The next example illustrates use of a throttling calorimeter to determine steam quality.

#### EXAMPLE 4.9

#### Measuring Steam Quality

A supply line carries a two-phase liquid–vapor mixture of steam at 300 lbf/in.<sup>2</sup> A small fraction of the flow in the line is diverted through a throttling calorimeter and exhausted to the atmosphere at 14.7 lbf/in.<sup>2</sup> The temperature of the exhaust steam is measured as 250°F. Determine the quality of the steam in the supply line.

#### SOLUTION

**Known:** Steam is diverted from a supply line through a throttling calorimeter and exhausted to the atmosphere.

**Find:** Determine the quality of the steam in the supply line.

#### Schematic and Given Data:

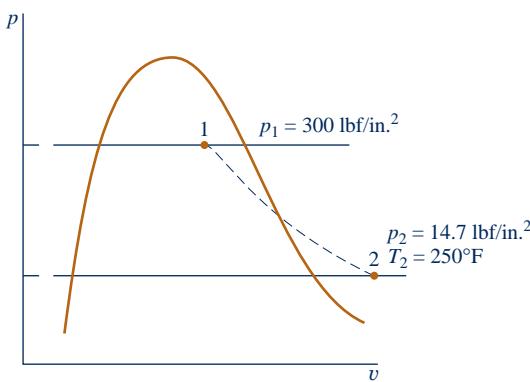
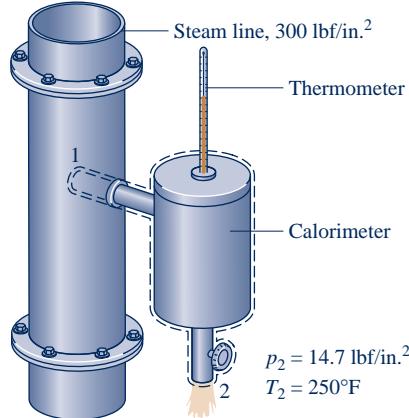


Fig. E4.9

#### Engineering Model:

1. The control volume shown on the accompanying figure is at steady state.
2. The diverted steam undergoes a throttling process.

**Analysis:** For a throttling process, the energy and mass balances reduce to give  $h_2 = h_1$ , which agrees with Eq. 4.22. Thus, with state 2 fixed, the specific enthalpy in the supply line is known, and state 1 is fixed by the known values of  $p_1$  and  $h_1$ .

- 1 As shown on the accompanying  $p$ - $v$  diagram, state 1 is in the two-phase liquid–vapor region and state 2 is in the superheated vapor region. Thus,

$$h_2 = h_1 = h_{f1} + x_1(h_{g1} - h_{f1})$$

Solving for  $x_1$ ,

$$x_1 = \frac{h_2 - h_{f1}}{h_{g1} - h_{f1}}$$

From Table A-3E at 300 lbf/in.<sup>2</sup>,  $h_{f1} = 394.1$  Btu/lb and  $h_{g1} = 1203.9$  Btu/lb. At 14.7 lbf/in.<sup>2</sup> and 250°F,  $h_2 = 1168.8$  Btu/lb from Table A-4E. Inserting values into the above expression, the quality of the steam in the line is  $x_1 = 0.957$  (95.7%).

- 1 For throttling calorimeters exhausting to the atmosphere, the quality of the steam in the line must be greater than about 94% to ensure that the steam leaving the calorimeter is superheated.

### Skills Developed

Ability to...

- apply Eq. 4.22 for a throttling process.
- retrieve property data for water

### QuickQUIZ

If the supply line carried saturated vapor at 300 lbf/in.<sup>2</sup>, determine the temperature at the calorimeter exit, in °F, for the same exit pressure, 14.7 lbf/in.<sup>2</sup> Ans. 324°F.

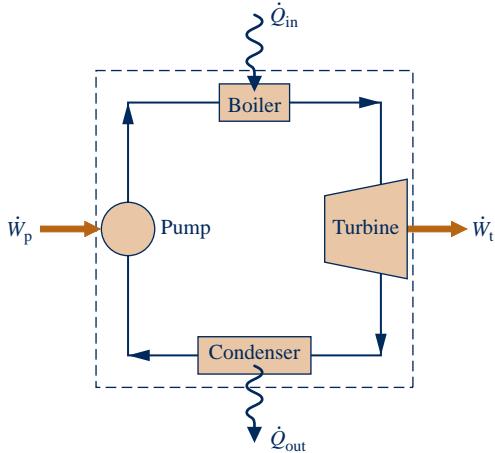


Fig. 4.16 Simple vapor power plant.

## 4.11 System Integration

Thus far, we have studied several types of components selected from those commonly seen in practice. These components are usually encountered in combination, rather than individually. Engineers often must creatively combine components to achieve some overall objective, subject to constraints such as minimum total cost. This important engineering activity is called *system integration*.

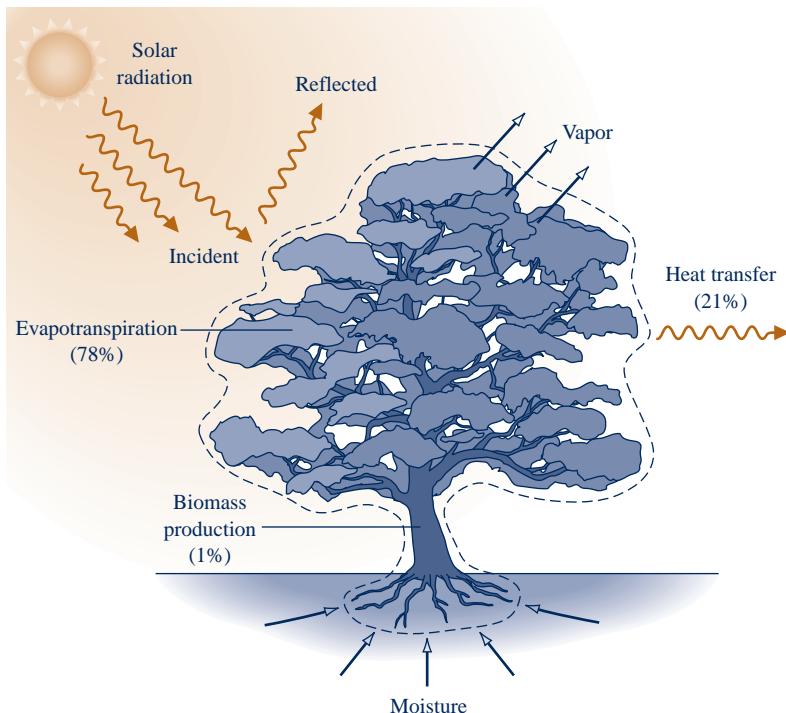
In engineering practice and everyday life, integrated systems are regularly encountered. Many readers are already familiar with a particularly successful system integration: the simple power plant shown in Fig. 4.16. This system consists of four components in series: a turbine-generator, condenser, pump, and boiler. We consider such power plants in detail in subsequent sections of the book.



**BIO CONNECTIONS** Living things also can be considered integrated systems. Figure 4.17 shows a control volume enclosing a tree receiving solar radiation.

As indicated on the figure, a portion of the incident radiation is reflected to the surroundings. Of the net solar energy received by the tree, about 21% is returned to the surroundings by heat transfer, principally convection. Water management accounts for most of the remaining solar input.

Trees sweat as do people; this is called *evapotranspiration*. As shown in Fig. 4.17, about 78% of the net solar energy received by the tree is used to pump liquid water from the surroundings, primarily the ground, convert it to a vapor, and discharge it to the surroundings through tiny pores (called *stomata*) in the leaves. Nearly all the water taken up is lost in this manner and only a small fraction is used within the tree. Applying an energy balance to the control volume enclosing the tree, just 1% of the net solar energy received by the tree is left for use in the production of biomass (wood and leaves). Evapotranspiration benefits trees but also contributes significantly to water loss from watersheds, illustrating that in nature as in engineering there are *trade-offs*.



**Fig. 4.17** Control volume enclosing a tree.

Example 4.10 provides another illustration of an integrated system. This case involves a *waste heat* recovery system.

#### EXAMPLE 4.10

#### Evaluating Performance of a Waste Heat Recovery System

An industrial process discharges  $2 \times 10^5 \text{ ft}^3/\text{min}$  of gaseous combustion products at  $400^\circ\text{F}$ , 1 atm. As shown in Fig. E4.10, a proposed system for utilizing the combustion products combines a heat-recovery steam generator with a turbine. At steady state, combustion products exit the steam generator at  $260^\circ\text{F}$ , 1 atm and a separate stream of water enters at  $40 \text{ lbf/in.}^2$ ,  $102^\circ\text{F}$  with a mass flow rate of  $275 \text{ lb/min}$ . At the exit of the turbine, the pressure is  $1 \text{ lbf/in.}^2$  and the quality is 93%. Heat transfer from the outer surfaces of the steam generator and turbine can be ignored, as can the changes in kinetic and potential energies of the flowing streams. There is no significant pressure drop for the water flowing through the steam generator. The combustion products can be modeled as air as an ideal gas.

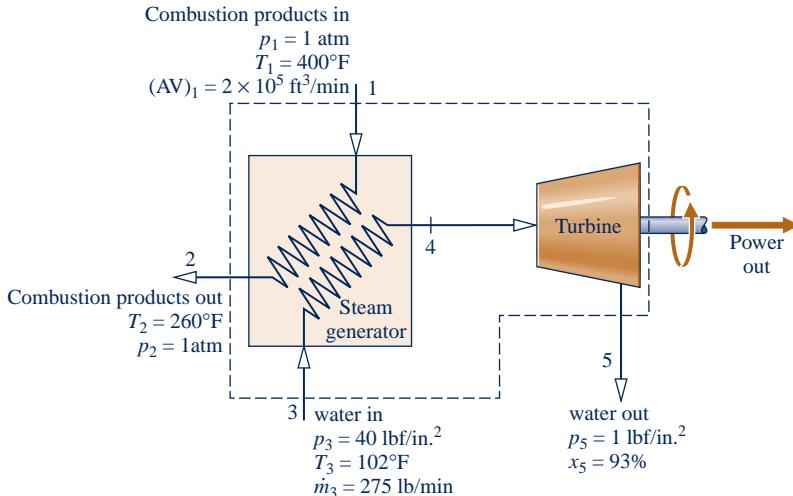
- (a) Determine the power developed by the turbine, in Btu/min.
- (b) Determine the turbine inlet temperature, in  $^\circ\text{F}$ .
- (c) Evaluating the power developed at \$0.08 per  $\text{kW} \cdot \text{h}$ , determine the value of the power, in \$/year, for 8000 hours of operation annually.

#### SOLUTION

**Known:** Steady-state operating data are provided for a system consisting of a heat-recovery steam generator and a turbine.

**Find:** Determine the power developed by the turbine and the turbine inlet temperature. Evaluate the annual value of the power developed.

**Schematic and Given Data:**



**Engineering Model:**

1. The control volume shown on the accompanying figure is at steady state.
2. Heat transfer is negligible, and changes in kinetic and potential energy can be ignored.
3. There is no pressure drop for water flowing through the steam generator.
4. The combustion products are modeled as air as an ideal gas.

**Fig. E4.10**

**Analysis:**

(a) The power developed by the turbine is determined from a control volume enclosing both the steam generator and the turbine. Since the gas and water streams do not mix, mass rate balances for each of the streams reduce, respectively, to give

$$\dot{m}_1 = \dot{m}_2, \quad \dot{m}_3 = \dot{m}_5$$

For this control volume, the appropriate form of the steady-state energy rate balance is Eq. 4.18, which reads

$$0 = \underline{\dot{Q}_{cv}} - \dot{W}_{cv} + \dot{m}_1 \left( h_1 + \frac{V_1^2}{2} + gz_1 \right) + \dot{m}_3 \left( h_3 + \frac{V_3^2}{2} + gz_3 \right) - \underline{\dot{m}_2 \left( h_2 + \frac{V_2^2}{2} + gz_2 \right)} - \underline{\dot{m}_5 \left( h_5 + \frac{V_5^2}{2} + gz_5 \right)}$$

The underlined terms drop out by assumption 2. With these simplifications, together with the above mass flow rate relations, the energy rate balance becomes

$$\dot{W}_{cv} = \dot{m}_1(h_1 - h_2) + \dot{m}_3(h_3 - h_5)$$

The mass flow rate  $\dot{m}_1$  can be evaluated with given data at inlet 1 and the ideal gas equation of state

$$\begin{aligned} \dot{m}_1 &= \frac{(AV)_1}{v_1} = \frac{(AV)_1 p_1}{(\bar{R}/M) T_1} = \frac{(2 \times 10^5 \text{ ft}^3/\text{min})(14.7 \text{ lbf/in.}^2)}{\left( \frac{1545 \text{ ft} \cdot \text{lbf}}{28.97 \text{ lb} \cdot {}^\circ\text{R}} \right)(860^\circ\text{R})} \Big| \frac{144 \text{ in.}^2}{1 \text{ ft}^2} \\ &= 9230.6 \text{ lb/min} \end{aligned}$$

The specific enthalpies  $h_1$  and  $h_2$  can be found from Table A-22E: At  $860^\circ\text{R}$ ,  $h_1 = 206.46 \text{ Btu/lb}$ , and at  $720^\circ\text{R}$   $h_2 = 172.39 \text{ Btu/lb}$ . At state 3, water is a liquid. Using Eq. 3.14 and saturated liquid data from Table A-2E,  $h_3 \approx h_f(T_3) = 70 \text{ Btu/lb}$ . State 5 is a two-phase liquid-vapor mixture. With data from Table A-3E and the given quality

$$\begin{aligned} h_5 &= h_{f5} + x_5(h_{g5} - h_{f5}) \\ &= 69.74 + 0.93(1036.0) = 1033.2 \text{ Btu/lb} \end{aligned}$$

Substituting values into the expression for  $\dot{W}_{cv}$

$$\begin{aligned} \dot{W}_{cv} &= \left( 9230.6 \frac{\text{lb}}{\text{min}} \right) (206.46 - 172.39) \frac{\text{Btu}}{\text{lb}} \\ &\quad + \left( 275 \frac{\text{lb}}{\text{min}} \right) (70 - 1033.2) \frac{\text{Btu}}{\text{lb}} \\ &= 49610 \frac{\text{Btu}}{\text{min}} \end{aligned}$$

(b) To determine  $T_4$ , it is necessary to fix the state at 4. This requires two independent property values. With assumption 3, one of these properties is pressure,  $p_4 = 40 \text{ lbf/in.}^2$ . The other is the specific enthalpy  $h_4$ , which can be found from an energy rate balance for a control volume enclosing just the steam generator. Mass rate balances for each of the two streams give  $\dot{m}_1 = \dot{m}_2$  and  $\dot{m}_3 = \dot{m}_4$ . With assumption 2 and these mass flow rate relations, the steady-state form of the energy rate balance reduces to

$$0 = \dot{m}_1(h_1 - h_2) + \dot{m}_3(h_3 - h_4)$$

Solving for  $h_4$

$$\begin{aligned} 1 \quad h_4 &= h_3 + \frac{\dot{m}_1}{\dot{m}_3}(h_1 - h_2) \\ &= 70 \frac{\text{Btu}}{\text{lb}} + \left( \frac{9230.6 \text{ lb/min}}{275 \text{ lb/min}} \right) (206.46 - 172.39) \frac{\text{Btu}}{\text{lb}} \\ &= 1213.6 \frac{\text{Btu}}{\text{lb}} \end{aligned}$$

Interpolating in Table A-4E at  $p_4 = 40 \text{ lbf/in.}^2$  with  $h_4$ , we get  $T_4 = 354^\circ\text{F}$ .

(c) Using the result of part (a), together with the given economic data and appropriate conversion factors, the value of the power developed for 8000 hours of operation annually is

$$\begin{aligned} 2 \quad \text{annual value} &= \left( 49610 \frac{\text{Btu}}{\text{min}} \left| \frac{60 \text{ min}}{1 \text{ h}} \right| \left| \frac{1 \text{ kW}}{3413 \text{ Btu/h}} \right| \right) \left( 8000 \frac{\text{h}}{\text{year}} \right) \left( 0.08 \frac{\$}{\text{kW} \cdot \text{h}} \right) \\ &= 558,000 \frac{\$}{\text{year}} \end{aligned}$$

- 1 Alternatively, to determine  $h_4$  a control volume enclosing just the turbine can be considered.
- 2 The decision about implementing this solution to the problem of utilizing the hot combustion products discharged from an industrial process would necessarily rest on the outcome of a detailed economic evaluation, including the cost of purchasing and operating the steam generator, turbine, and auxiliary equipment.

### QuickQUIZ

Taking a control volume enclosing just the turbine, evaluate the turbine inlet temperature, in  $^\circ\text{F}$ . **Ans.**  $354^\circ\text{F}$ .

### Skills Developed

Ability to...

- apply the steady-state mass and energy rate balances to a control volume.
- apply the mass flow rate expression, Eq. 4.4b.
- develop an engineering model.
- retrieve property data for water and for air modeled as an ideal gas.
- conduct an elementary economic evaluation.

## 4.12 Transient Analysis

Many devices undergo periods of **transient** operation during which the state changes with time. Examples include the startup or shutdown of turbines, compressors, and motors. Additional examples include vessels being filled or emptied, as considered in Example 4.2 and in the discussion of Fig. 1.5. Because property values, work and heat transfer rates, and mass flow rates may vary with time during transient operation, the steady-state assumption is not appropriate when analyzing such cases. Special care must be exercised when applying the mass and energy rate balances, as discussed next.

**transient**

**System Types**  
A.1 – Tab d



### 4.12.1 The Mass Balance in Transient Analysis

First, we place the control volume mass balance in a form that is suitable for transient analysis. We begin by integrating the mass rate balance, Eq. 4.2, from time 0 to a final

time  $t$ . That is

$$\int_0^t \left( \frac{dm_{cv}}{dt} \right) dt = \int_0^t \left( \sum_i \dot{m}_i \right) dt - \int_0^t \left( \sum_e \dot{m}_e \right) dt$$

This takes the form

$$m_{cv}(t) - m_{cv}(0) = \sum_i \left( \underline{\int_0^t \dot{m}_i dt} \right) - \sum_e \left( \underline{\int_0^t \dot{m}_e dt} \right)$$

Introducing the following symbols for the underlined terms

$$m_i = \int_0^t \dot{m}_i dt \quad \begin{cases} \text{amount of mass} \\ \text{entering the control} \\ \text{volume through inlet } i, \\ \text{from time 0 to } t \end{cases}$$

$$m_e = \int_0^t \dot{m}_e dt \quad \begin{cases} \text{amount of mass} \\ \text{exiting the control} \\ \text{volume through exit } e, \\ \text{from time 0 to } t \end{cases}$$

the mass balance becomes

$$m_{cv}(t) - m_{cv}(0) = \sum_i m_i - \sum_e m_e \quad (4.23)$$

In words, Eq. 4.23 states that the change in the amount of mass contained in the control volume equals the difference between the total incoming and outgoing amounts of mass.

#### 4.12.2 The Energy Balance in Transient Analysis

Next, we integrate the energy rate balance, Eq. 4.15, ignoring the effects of kinetic and potential energy. The result is

$$U_{cv}(t) - U_{cv}(0) = Q_{cv} - W_{cv} + \sum_i \left( \underline{\int_0^t \dot{m}_i h_i dt} \right) - \sum_e \left( \underline{\int_0^t \dot{m}_e h_e dt} \right) \quad (4.24)$$

where  $Q_{cv}$  accounts for the net amount of energy transferred by heat into the control volume and  $W_{cv}$  accounts for the net amount of energy transferred by work, except for flow work. The integrals shown underlined in Eq. 4.24 account for the energy carried in at the inlets and out at the exits.

For the *special case* where the states at the inlets and exits are *constant with time*, the respective specific enthalpies,  $h_i$  and  $h_e$ , are constant, and the underlined terms of Eq. 4.24 become

$$\int_0^t \dot{m}_i h_i dt = h_i \int_0^t \dot{m}_i dt = h_i m_i$$

$$\int_0^t \dot{m}_e h_e dt = h_e \int_0^t \dot{m}_e dt = h_e m_e$$

Equation 4.24 then takes the following *special form*

$$U_{cv}(t) - U_{cv}(0) = Q_{cv} - W_{cv} + \sum_i m_i h_i - \sum_e m_e h_e \quad (4.25)$$

where  $m_i$  and  $m_e$  account, respectively, for the *amount* of mass entering the control volume through inlet  $i$  and exiting the control volume through exit  $e$ , each from time 0 to  $t$ .

Whether in the general form, Eq. 4.24, or the special form, Eq. 4.25, these equations account for the change in the amount of energy contained within the control volume as the difference between the total incoming and outgoing amounts of energy.

Another *special case* is when the intensive properties within the control volume are *uniform with position* at a particular time  $t$ . Accordingly, the specific volume and

the specific internal energy are uniform throughout and can depend only on time—that is,  $v(t)$  and  $u(t)$ , respectively. Then

$$m_{cv}(t) = V_{cv}(t)/v(t) \quad (4.26)$$

$$U_{cv}(t) = m_{cv}(t)u(t) \quad (4.27)$$

If the control volume is comprised of different phases at time  $t$ , the state of each phase is assumed uniform throughout.

Equations 4.23 and 4.25–4.27 are applicable to a wide range of transient cases where inlet and exit states are constant with time and intensive properties within the control volume are uniform with position initially and finally.

**►FOR EXAMPLE** in cases involving the filling of containers having a single inlet and no exit, Eqs. 4.23, 4.25, and 4.27 combine to give

$$m_{cv}(t)u(t) - m_{cv}(0)u(0) = Q_{cv} - W_{cv} + h_i(m_{cv}(t) - m_{cv}(0)) \quad (4.28)$$

The details are left as an exercise. See Examples 4.12 and 4.13 for this type of transient application. ▲ ▲ ▲ ▲ ▲

### 4.12.3 Transient Analysis Applications

The following examples provide illustrations of the transient analysis of control volumes using the conservation of mass and energy principles. In each case considered, to emphasize fundamentals we begin with general forms of the mass and energy balances and reduce them to forms suited for the case at hand, invoking the idealizations discussed in this section as warranted.

The first example considers a vessel that is partially emptied as mass exits through a valve.

#### ►►►► EXAMPLE 4.11 ►

### Evaluating Heat Transfer for a Partially-Emptying Tank

A tank having a volume of  $0.85 \text{ m}^3$  initially contains water as a two-phase liquid–vapor mixture at  $260^\circ\text{C}$  and a quality of 0.7. Saturated water vapor at  $260^\circ\text{C}$  is slowly withdrawn through a pressure-regulating valve at the top of the tank as energy is transferred by heat to maintain the pressure constant in the tank. This continues until the tank is filled with saturated vapor at  $260^\circ\text{C}$ . Determine the amount of heat transfer, in kJ. Neglect all kinetic and potential energy effects.

#### SOLUTION

**Known:** A tank initially holding a two-phase liquid–vapor mixture is heated while saturated water vapor is slowly removed. This continues at constant pressure until the tank is filled only with saturated vapor.

**Find:** Determine the amount of heat transfer.

#### Schematic and Given Data:

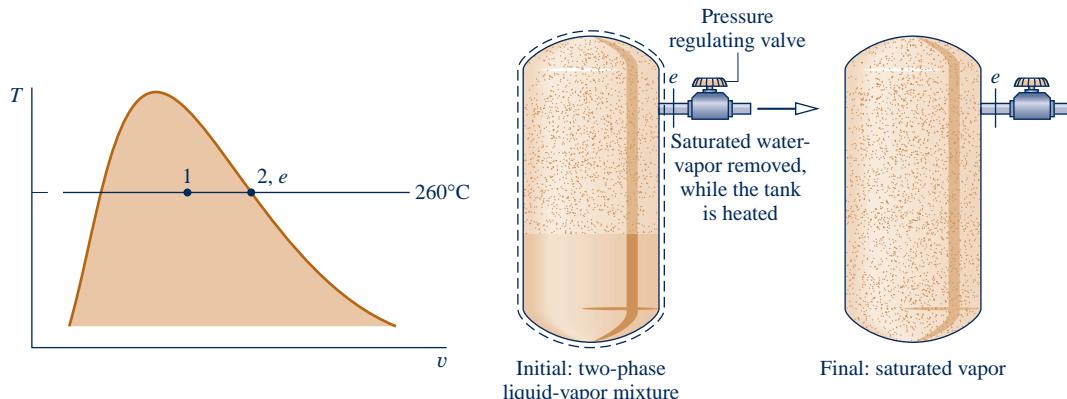


Fig. E4.11

**Engineering Model:**

1. The control volume is defined by the dashed line on the accompanying diagram.
2. For the control volume,  $\dot{W}_{cv} = 0$  and kinetic and potential energy effects can be neglected.
3. At the exit the state remains constant.
- ① 4. The initial and final states of the mass within the vessel are equilibrium states.

**Analysis:** Since there is a single exit and no inlet, the mass rate balance Eq. 4.2 takes the form

$$\frac{dm_{cv}}{dt} = -\dot{m}_e$$

With assumption 2, the energy rate balance Eq. 4.15 reduces to

$$\frac{dU_{cv}}{dt} = \dot{Q}_{cv} - \dot{m}_e h_e$$

Combining the mass and energy rate balances results in

$$\frac{dU_{cv}}{dt} = \dot{Q}_{cv} + h_e \frac{dm_{cv}}{dt}$$

By assumption 3, the specific enthalpy at the exit is constant. Accordingly, integration of the last equation gives

$$\Delta U_{cv} = Q_{cv} + h_e \Delta m_{cv}$$

Solving for the heat transfer  $Q_{cv}$ ,

$$Q_{cv} = \Delta U_{cv} - h_e \Delta m_{cv}$$

or

$$② Q_{cv} = (m_2 u_2 - m_1 u_1) - h_e (m_2 - m_1)$$

where  $m_1$  and  $m_2$  denote, respectively, the initial and final amounts of mass within the tank.

The terms  $u_1$  and  $m_1$  of the foregoing equation can be evaluated with property values from Table A-2 at 260°C and the given value for quality. Thus

$$\begin{aligned} u_1 &= u_f + x_1(u_g - u_f) \\ &= 1128.4 + (0.7)(2599.0 - 1128.4) = 2157.8 \text{ kJ/kg} \end{aligned}$$

Also,

$$\begin{aligned} v_1 &= v_f + x_1(v_g - v_f) \\ &= 1.2755 \times 10^{-3} + (0.7)(0.04221 - 1.2755 \times 10^{-3}) = 29.93 \times 10^{-3} \text{ m}^3/\text{kg} \end{aligned}$$

Using the specific volume  $v_1$ , the mass initially contained in the tank is

$$m_1 = \frac{V}{v_1} = \frac{0.85 \text{ m}^3}{(29.93 \times 10^{-3} \text{ m}^3/\text{kg})} = 28.4 \text{ kg}$$

The final state of the mass in the tank is saturated vapor at 260°C so Table A-2 gives

$$u_2 = u_g(260^\circ\text{C}) = 2599.0 \text{ kJ/kg}, \quad v_2 = v_g(260^\circ\text{C}) = 42.21 \times 10^{-3} \text{ m}^3/\text{kg}$$

The mass contained within the tank at the end of the process is

$$m_2 = \frac{V}{v_2} = \frac{0.85 \text{ m}^3}{(42.21 \times 10^{-3} \text{ m}^3/\text{kg})} = 20.14 \text{ kg}$$

Table A-2 also gives  $h_e = h_g(260^\circ\text{C}) = 2796.6 \text{ kJ/kg}$ .

Substituting values into the expression for the heat transfer yields

$$\begin{aligned} Q_{cv} &= (20.14)(2599.0) - (28.4)(2157.8) - 2796.6(20.14 - 28.4) \\ &= 14,162 \text{ kJ} \end{aligned}$$

- ① In this case, idealizations are made about the state of the vapor exiting *and* the initial and final states of the mass contained within the tank.
- ② This expression for  $Q_{cv}$  can be obtained by applying Eqs. 4.23, 4.25, and 4.27. The details are left as an exercise.



### Skills Developed

*Ability to...*

- apply the time-dependent mass and energy rate balances to a control volume.
- develop an engineering model.
- retrieve property data for water.

### QuickQUIZ

If the initial quality were 90%, determine the heat transfer, in

kJ, keeping all other data unchanged. **Ans.** 3707 kJ.

In the next two examples we consider cases where tanks are filled. In Example 4.12, an initially evacuated tank is filled with steam as power is developed. In Example 4.13, a compressor is used to store air in a tank.

### EXAMPLE 4.12

## Using Steam for Emergency Power Generation

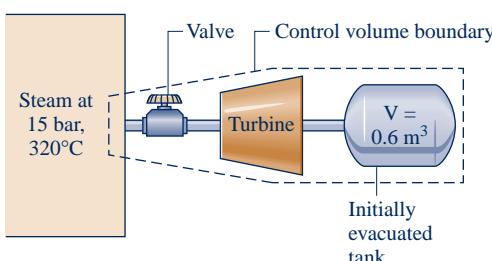
Steam at a pressure of 15 bar and a temperature of 320°C is contained in a large vessel. Connected to the vessel through a valve is a turbine followed by a small initially evacuated tank with a volume of 0.6 m<sup>3</sup>. When emergency power is required, the valve is opened and the tank fills with steam until the pressure is 15 bar. The temperature in the tank is then 400°C. The filling process takes place adiabatically and kinetic and potential energy effects are negligible. Determine the amount of work developed by the turbine, in kJ.

### SOLUTION

**Known:** Steam contained in a large vessel at a known state flows from the vessel through a turbine into a small tank of known volume until a specified final condition is attained in the tank.

**Find:** Determine the work developed by the turbine.

### Schematic and Given Data:



**Fig. E4.12**

### Engineering Model:

1. The control volume is defined by the dashed line on the accompanying diagram.
2. For the control volume,  $\dot{Q}_{cv} = 0$  and kinetic and potential energy effects are negligible.
3. The state of the steam within the large vessel remains constant. The final state of the steam in the smaller tank is an equilibrium state.
4. The amount of mass stored within the turbine and the interconnecting piping at the end of the filling process is negligible.

**Analysis:** Since the control volume has a single inlet and no exits, the mass rate balance, Eq. 4.2, reduces to

$$\frac{dm_{cv}}{dt} = \dot{m}_i$$

The energy rate balance, Eq. 4.15, reduces with assumption 2 to

$$\frac{dU_{cv}}{dt} = -\dot{W}_{cv} + \dot{m}_i h_i$$

Combining the mass and energy rate balances gives

$$\frac{dU_{cv}}{dt} = -\dot{W}_{cv} + h_i \frac{dm_{cv}}{dt}$$

Integrating

$$\Delta U_{cv} = -W_{cv} + h_i \Delta m_{cv}$$

In accordance with assumption 3, the specific enthalpy of the steam entering the control volume is constant at the value corresponding to the state in the large vessel.

Solving for  $W_{cv}$

$$W_{cv} = h_i \Delta m_{cv} - \Delta U_{cv}$$

$\Delta U_{cv}$  and  $\Delta m_{cv}$  denote, respectively, the changes in internal energy and mass of the control volume. With assumption 4, these terms can be identified with the small tank only.

Since the tank is initially evacuated, the terms  $\Delta U_{cv}$  and  $\Delta m_{cv}$  reduce to the internal energy and mass within the tank at the end of the process. That is

$$\Delta U_{cv} = (m_2 u_2) - (m_1 u_1)^0, \quad \Delta m_{cv} = m_2 - m_1^0$$

where 1 and 2 denote the initial and final states within the tank, respectively.

Collecting results yields

$$② ③ \quad W_{cv} = m_2(h_i - u_2) \quad (a)$$

The mass within the tank at the end of the process can be evaluated from the known volume and the specific volume of steam at 15 bar and 400°C from Table A-4

$$m_2 = \frac{V}{v_2} = \frac{0.6 \text{ m}^3}{(0.203 \text{ m}^3/\text{kg})} = 2.96 \text{ kg}$$

The specific internal energy of steam at 15 bar and 400°C from Table A-4 is 2951.3 kJ/kg. Also, at 15 bar and 320°C,  $h_1 = 3081.9 \text{ kJ/kg}$ .

Substituting values into Eq. (a)

$$W_{cv} = 2.96 \text{ kg} (3081.9 - 2951.3) \text{ kJ/kg} = 386.6 \text{ kJ}$$

- ① In this case idealizations are made about the state of the steam entering the tank and the final state of the steam in the tank. These idealizations make the transient analysis manageable.
- ② A significant aspect of this example is the energy transfer into the control volume by flow work, incorporated in the  $pv$  term of the specific enthalpy at the inlet.
- ③ This result can also be obtained by reducing Eq. 4.28. The details are left as an exercise.

### Skills Developed

Ability to...

- apply the time-dependent mass and energy rate balances to a control volume.
- develop an engineering model.
- retrieve property data for water.

### QuickQUIZ

If the turbine were removed, and the steam allowed to flow adiabatically into the small tank until the pressure in the tank is 15 bar, determine the final steam temperature in the tank, in °C. **Ans.** 477°C.

## EXAMPLE 4.13

## Storing Compressed Air in a Tank

An air compressor rapidly fills a 10-ft<sup>3</sup> tank, initially containing air at 70°F, 1 atm, with air drawn from the atmosphere at 70°F, 1 atm. During filling, the relationship between the pressure and specific volume of the air in the tank is  $pv^{1.4} = \text{constant}$ . The ideal gas model applies for the air, and kinetic and potential energy effects are negligible. Plot the pressure, in atm, and the temperature, in °F, of the air within the tank, each versus the ratio  $m/m_1$ , where  $m_1$  is the initial mass in the tank and  $m$  is the mass in the tank at time  $t > 0$ . Also, plot the compressor work input, in Btu, versus  $m/m_1$ . Let  $m/m_1$  vary from 1 to 3.

## SOLUTION

**Known:** An air compressor rapidly fills a tank having a known volume. The initial state of the air in the tank and the state of the entering air are known.

**Find:** Plot the pressure and temperature of the air within the tank, and plot the air compressor work input, each versus  $m/m_1$  ranging from 1 to 3.

## Schematic and Given Data:

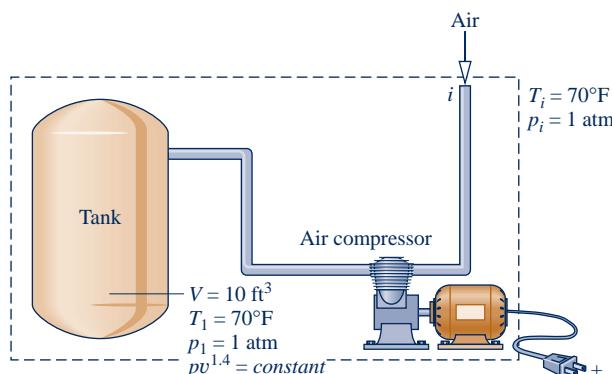


Fig. E4.13a

## Engineering Model:

1. The control volume is defined by the dashed line on the accompanying diagram.
2. Because the tank is filled rapidly,  $\dot{Q}_{cv}$  is ignored.
3. Kinetic and potential energy effects are negligible.
4. The state of the air entering the control volume remains constant.
5. The air stored within the air compressor and interconnecting pipes can be ignored.
6. The relationship between pressure and specific volume for the air in the tank is  $pv^{1.4} = \text{constant}$ .
7. The ideal gas model applies for the air.

**Analysis:** The required plots are developed using *Interactive Thermodynamics: IT*. The *IT* program is based on the following analysis. The pressure  $p$  in the tank at time  $t > 0$  is determined from

$$pv^{1.4} = p_1v_1^{1.4}$$

where the corresponding specific volume  $v$  is obtained using the known tank volume  $V$  and the mass  $m$  in the tank at that time. That is,  $v = V/m$ . The specific volume of the air in the tank initially,  $v_1$ , is calculated from the ideal gas equation of state and the known initial temperature,  $T_1$ , and pressure,  $p_1$ . That is

$$v_1 = \frac{RT_1}{p_1} = \frac{\left(\frac{1545 \text{ ft} \cdot \text{lbf}}{28.97 \text{ lb} \cdot ^\circ\text{R}}\right)(530^\circ\text{R})}{(14.7 \text{ lbf/in.}^2)} \left| \frac{1 \text{ ft}^2}{144 \text{ in.}^2} \right| = 13.35 \frac{\text{ft}^3}{\text{lb}}$$

Once the pressure  $p$  is known, the corresponding temperature  $T$  can be found from the ideal gas equation of state,  $T = pv/R$ .

To determine the work, begin with the mass rate balance Eq. 4.2, which reduces for the single-inlet control volume to

$$\frac{dm_{cv}}{dt} = \dot{m}_i$$

Then, with assumptions 2 and 3, the energy rate balance Eq. 4.15 reduces to

$$\frac{dU_{cv}}{dt} = -\dot{W}_{cv} + \dot{m}_i h_i$$

Combining the mass and energy rate balances and integrating using assumption 4 gives

$$\Delta U_{cv} = -W_{cv} + h_i \Delta m_{cv}$$

Denoting the work *input* to the compressor by  $W_{in} = -W_{cv}$  and using assumption 5, this becomes

$$2 \quad W_{in} = mu - m_1 u_1 - (m - m_1) h_i \quad (a)$$

where  $m_1$  is the initial amount of air in the tank, determined from

$$m_1 = \frac{V}{v_1} = \frac{10 \text{ ft}^3}{13.35 \text{ ft}^3/\text{lb}} = 0.75 \text{ lb}$$

As a *sample* calculation to validate the *IT* program below, consider the case  $m = 1.5 \text{ lb}$ , which corresponds to  $m/m_1 = 2$ . The specific volume of the air in the tank at that time is

$$v = \frac{V}{m} = \frac{10 \text{ ft}^3}{1.5 \text{ lb}} = 6.67 \frac{\text{ft}^3}{\text{lb}}$$

The corresponding pressure of the air is

$$p = p_1 \left( \frac{v_1}{v} \right)^{1.4} = (1 \text{ atm}) \left( \frac{13.35 \text{ ft}^3/\text{lb}}{6.67 \text{ ft}^3/\text{lb}} \right)^{1.4} \\ = 2.64 \text{ atm}$$

and the corresponding temperature of the air is

$$T = \frac{pv}{R} = \left( \frac{(2.64 \text{ atm})(6.67 \text{ ft}^3/\text{lb})}{\left( \frac{1545 \text{ ft} \cdot \text{lbf}}{28.97 \text{ lb} \cdot {}^\circ\text{R}} \right)} \right) \left| \frac{14.7 \text{ lbf/in.}^2}{1 \text{ atm}} \right| \left| \frac{144 \text{ in.}^2}{1 \text{ ft}^2} \right| \\ = 699 \text{ R} (239^\circ\text{F})$$

Evaluating  $u_1$ ,  $u$ , and  $h_i$  at the appropriate temperatures from Table A-22E,  $u_1 = 90.3 \text{ Btu/lb}$ ,  $u = 119.4 \text{ Btu/lb}$ ,  $h_i = 126.7 \text{ Btu/lb}$ . Using Eq. (a), the required work input is

$$W_{in} = mu - m_1 u_1 - (m - m_1) h_i \\ = (1.5 \text{ lb}) \left( 119.4 \frac{\text{Btu}}{\text{lb}} \right) - (0.75 \text{ lb}) \left( 90.3 \frac{\text{Btu}}{\text{lb}} \right) - (0.75 \text{ lb}) \left( 126.7 \frac{\text{Btu}}{\text{lb}} \right) \\ = 16.4 \text{ Btu}$$

**IT Program:** Choosing English units from the **Units** menu, and selecting Air from the **Properties** menu, the *IT* program for solving the problem is

```
//Given Data
p1 = 1//atm
T1 = 70//°F
Ti = 70//°F
V = 10//ft³
n = 1.4

// Determine the pressure and temperature for t > 0
v1 = v_TP("Air", T1, p1)
v = V/m
p * v ^ n = p1 * v1 ^ n
v = v_TP("Air", T, p)

// Specify the mass and mass ratio r
v1 = V/m1
r = m/m1
r = 2
```

```
// Calculate the work using Eq. (a)
Win = m * u - m1 * u1 - hi * (m - m1)
u1 = u_T("Air", T1)
u = u_T("Air", T)
hi = h_T("Air", Ti)
```

Using the **Solve** button, obtain a solution for the sample case  $r = m/m_1 = 2$  considered above to validate the program. Good agreement is obtained, as can be verified. Once the program is validated, use the **Explore** button to vary the ratio  $m/m_1$  from 1 to 3 in steps of 0.01. Then, use the **Graph** button to construct the required plots. The results are:

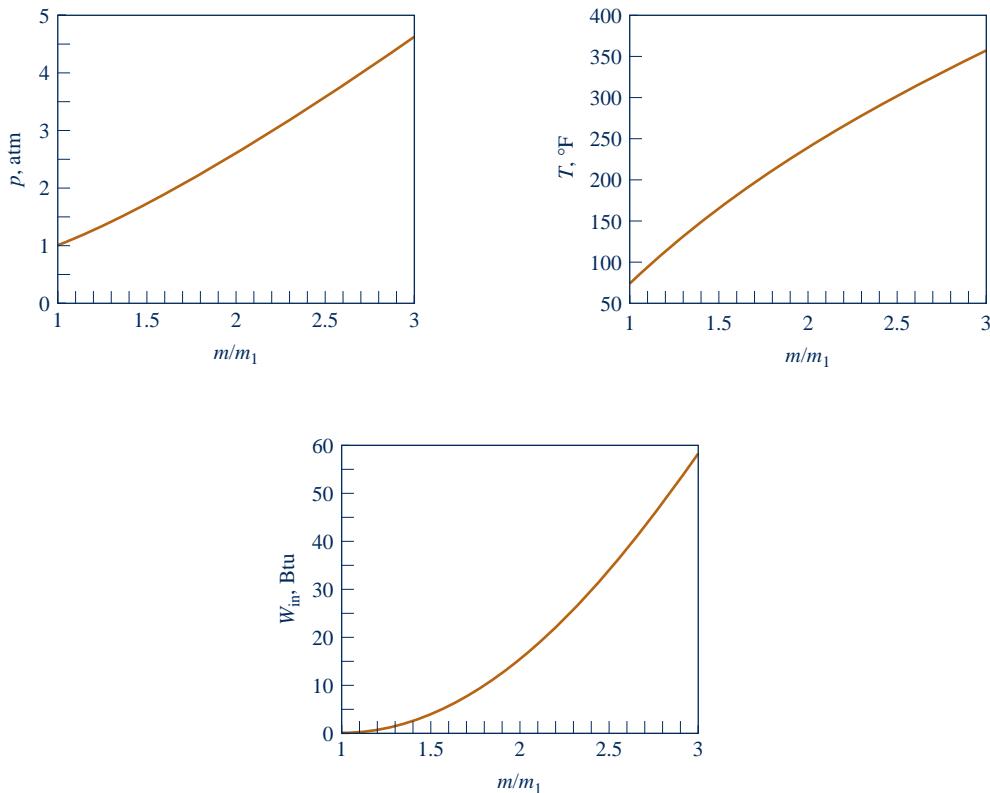


Fig. E4.13b

We conclude from the first two plots that the pressure and temperature each increase as the tank fills. The work required to fill the tank increases as well. These results are as expected.

- ① This pressure-specific volume relationship is in accord with what might be measured. The relationship is also consistent with the uniform state idealization, embodied by Eqs. 4.26 and 4.27.
- ② This expression can also be obtained by reducing Eq. 4.28. The details are left as an exercise.

### QuickQUIZ

As a *sample* calculation, for the case  $m = 2.25$  lb, evaluate  $p$ , in atm. Compare with the value read from the plot of Fig. E4.13b. **Ans.** 4.67 atm.



### Skills Developed

Ability to...

- apply the time-dependent mass and energy rate balances to a control volume.
- develop an engineering model.
- retrieve property data for air modeled as an ideal gas.
- solve iteratively and plot the results using IT.

The final example of transient analysis is an application with a *well-stirred* tank. Such process equipment is commonly employed in the chemical and food processing industries.

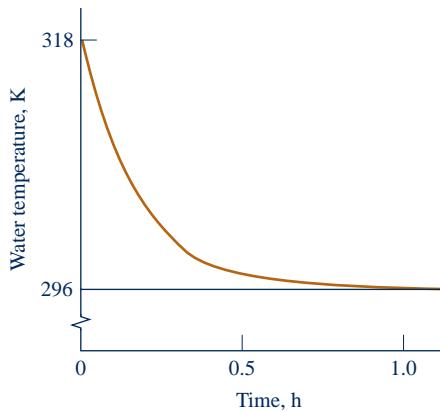
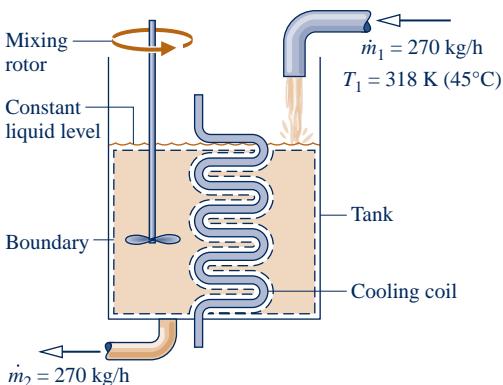
**EXAMPLE 4.14****Determining Temperature-Time Variation in a Well-Stirred Tank**

A tank containing 45 kg of liquid water initially at 45°C has one inlet and one exit with equal mass flow rates. Liquid water enters at 45°C and a mass flow rate of 270 kg/h. A cooling coil immersed in the water removes energy at a rate of 7.6 kW. The water is well mixed by a paddle wheel so that the water temperature is uniform throughout. The power input to the water from the paddle wheel is 0.6 kW. The pressures at the inlet and exit are equal and all kinetic and potential energy effects can be ignored. Plot the variation of water temperature with time.

**SOLUTION**

**Known:** Liquid water flows into and out of a well-stirred tank with equal mass flow rates as the water in the tank is cooled by a cooling coil.

**Find:** Plot the variation of water temperature with time.

**Schematic and Given Data:****Fig. E4.14****Engineering Model:**

1. The control volume is defined by the dashed line on the accompanying diagram.
2. For the control volume, the only significant heat transfer is with the cooling coil. Kinetic and potential energy effects can be neglected.
- ① 3. The water temperature is uniform with position throughout and varies only with time:  $T = T(t)$ .
4. The water in the tank is incompressible, and there is no change in pressure between inlet and exit.

**Analysis:** The energy rate balance, Eq. 4.15, reduces with assumption 2 to

$$\frac{dU_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}(h_1 - h_2)$$

where  $\dot{m}$  denotes the mass flow rate.

The mass contained within the control volume remains constant with time, so the term on the left side of the energy rate balance can be expressed as

$$\frac{dU_{cv}}{dt} = \frac{d(m_{cv}u)}{dt} = m_{cv} \frac{du}{dt}$$

Since the water is assumed incompressible, the specific internal energy depends on temperature only. Hence, the chain rule can be used to write

$$\frac{du}{dt} = \frac{du}{dT} \frac{dT}{dt} = c \frac{dT}{dt}$$

where  $c$  is the specific heat. Collecting results

$$\frac{dU_{cv}}{dt} = m_{cv}c \frac{dT}{dt}$$

With Eq. 3.20b the enthalpy term of the energy rate balance can be expressed as

$$h_1 - h_2 = c(T_1 - T_2) + v(p_1 - p_2^0)$$

where the pressure term is dropped by assumption 4. Since the water is well mixed, the temperature at the exit equals the temperature of the overall quantity of liquid in the tank, so

$$h_1 - h_2 = c(T_1 - T)$$

where  $T$  represents the uniform water temperature at time  $t$ .

With the foregoing considerations the energy rate balance becomes

$$m_{cv}c \frac{dT}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}c(T_1 - T)$$

As can be verified by direct substitution, the solution of this first-order, ordinary differential equation is

$$T = C_1 \exp\left(-\frac{\dot{m}}{m_{cv}}t\right) + \left(\frac{\dot{Q}_{cv} - \dot{W}_{cv}}{\dot{m}c}\right) + T_1$$

The constant  $C_1$  is evaluated using the initial condition: at  $t = 0$ ,  $T = T_1$ . Finally

$$T = T_1 + \left(\frac{\dot{Q}_{cv} - \dot{W}_{cv}}{\dot{m}c}\right) \left[1 - \exp\left(-\frac{\dot{m}}{m_{cv}}t\right)\right]$$

Substituting given numerical values together with the specific heat  $c$  for liquid water from Table A-19

$$\begin{aligned} T &= 318 \text{ K} + \left[ \frac{[-7.6 - (-0.6)] \text{ kJ/s}}{\left(\frac{270 \text{ kg}}{3600 \text{ s}}\right) \left(4.2 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}\right)} \right] \left[ 1 - \exp\left(-\frac{270 \text{ kg/h}}{45 \text{ kg}} t\right) \right] \\ &= 318 - 22[1 - \exp(-6t)] \end{aligned}$$

where  $t$  is in hours. Using this expression, we construct the accompanying plot showing the variation of temperature with time.

- ① In this case idealizations are made about the state of the mass contained within the system and the states of the liquid entering and exiting. These idealizations make the transient analysis manageable.



### Skills Developed

*Ability to...*

- apply the time-dependent mass and energy rate balances to a control volume.
- develop an engineering model.
- apply the incompressible substance model for water.
- solve an ordinary differential equation and plot the solution.

### QuickQUIZ

What is the water temperature, in °C, when *steady-state* is achieved? **Ans. 23°C.**

## ► CHAPTER SUMMARY AND STUDY GUIDE

The conservation of mass and energy principles for control volumes are embodied in the mass and energy rate balances developed in this chapter. Although the primary emphasis is on cases in which one-dimensional flow is assumed, mass and energy

balances are also presented in integral forms that provide a link to subsequent fluid mechanics and heat transfer courses. Control volumes at steady state are featured, but discussions of transient cases are also provided.

The use of mass and energy balances for control volumes at steady state is illustrated for nozzles and diffusers, turbines, compressors and pumps, heat exchangers, throttling devices, and integrated systems. An essential aspect of all such applications is the careful and explicit listing of appropriate assumptions. Such model-building skills are stressed throughout the chapter.

The following checklist provides a study guide for this chapter. When your study of the text and end-of-chapter exercises has been completed you should be able to

- write out the meanings of the terms listed in the margins throughout the chapter and understand each of the related

concepts. The subset of key concepts listed below is particularly important in subsequent chapters.

- list the typical modeling assumptions for nozzles and diffusers, turbines, compressors and pumps, heat exchangers, and throttling devices.
- apply Eqs. 4.6, 4.18, and 4.20 to control volumes at steady state, using appropriate assumptions and property data for the case at hand.
- apply mass and energy balances for the transient analysis of control volumes, using appropriate assumptions and property data for the case at hand.

## ► KEY ENGINEERING CONCEPTS

**conservation of mass, p. 164**  
**mass flow rates, p. 164**  
**mass rate balance, p. 164**  
**one-dimensional flow, p. 166**  
**volumetric flow rate, p. 167**  
**steady state, p. 167**

**flow work, p. 173**  
**energy rate balance, p. 174**  
**nozzle, p. 177**  
**diffuser, p. 177**  
**turbine, p. 180**  
**compressor, p. 184**

**pump, p. 184**  
**heat exchanger, p. 189**  
**throttling process, p. 195**  
**system integration, p. 196**  
**transient analysis, p. 199**

## ► KEY EQUATIONS

$$\dot{m} = \frac{AV}{v}$$

(4.4b) p. 166

Mass flow rate, one-dimensional flow (See Fig. 4.3.)

$$\frac{dm_{cv}}{dt} = \sum_i \dot{m}_i - \sum_e \dot{m}_e$$

(4.2) p. 164

Mass rate balance.

$$\sum_i \dot{m}_i = \sum_e \dot{m}_e$$

(mass rate in)      (mass rate out)

(4.6) p. 167

Mass rate balance at steady state.

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i \left( h_i + \frac{V_i^2}{2} + gz_i \right) - \sum_e \dot{m}_e \left( h_e + \frac{V_e^2}{2} + gz_e \right)$$

(4.15) p. 174

Energy rate balance.

$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i \left( h_i + \frac{V_i^2}{2} + gz_i \right) - \sum_e \dot{m}_e \left( h_e + \frac{V_e^2}{2} + gz_e \right)$$

(4.18) p. 175

Energy rate balance at steady state.

$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m} \left[ (h_1 - h_2) + \frac{(V_1^2 - V_2^2)}{2} + g(z_1 - z_2) \right]$$

(4.20a) p. 175

Energy rate balance for one-inlet, one-exit control volumes at steady state.

$$0 = \frac{\dot{Q}_{cv}}{\dot{m}} - \frac{\dot{W}_{cv}}{\dot{m}} + (h_1 - h_2) + \frac{(V_1^2 - V_2^2)}{2} + g(z_1 - z_2)$$

(4.20b) p. 175

$$h_2 = h_1 \quad (p_2 < p_1)$$

(4.22) p. 195

Throttling process. (See Fig. 4.15.)

## ► EXERCISES: THINGS ENGINEERS THINK ABOUT

1. How does the control volume energy rate balance account for work where mass flows across the boundary?
2. Why does the relative velocity *normal* to the flow boundary,  $V_n$ , appear in Eqs. 4.3 and 4.8?
3. When a slice of bread is placed in a toaster and the toaster is activated, is the toaster in steady-state operation, transient operation, both?
4. As a tree grows, its mass increases. Does this violate the conservation of mass principle? Explain.
5. Wind turbines and hydraulic turbines develop mechanical power from moving streams of air and water, respectively. In each case, what aspect of the stream is tapped for power?
6. How is the work done by the heart measured?
7. How does a heart-lung machine maintain blood circulation and oxygen content during surgery?
8. Where do you encounter *microelectromechanical* systems in daily life?
9. Where are compressors found within households?
10. How does the operator of a pumper-tanker fire engine control water flow to all the hoses in use?
11. For air flowing through a converging-diverging channel, sketch the variation of the air pressure as air accelerates in the converging section and decelerates in the diverging section.
12. Why is it that when air at 1 atm is *throttled* to a pressure of 0.5 atm, its temperature at the valve exit is closely the same as at the valve inlet, yet when air at 1 atm *leaks* into an insulated, rigid, initially-evacuated tank until the tank pressure is 0.5 atm, the temperature of the air in the tank is greater than the air temperature outside the tank?
13. If the expansion valve of a refrigerator becomes ice encased, does the *throttling process* model still apply? Explain.
14. Why does *evapotranspiration* in a tree require so much energy?
15. What are intra-articular pain pumps?

## ► PROBLEMS: DEVELOPING ENGINEERING SKILLS

### Applying Conservation of Mass

- 4.1** An 8-ft<sup>3</sup> tank contains air at an initial temperature of 80°F and initial pressure of 100 lbf/in.<sup>2</sup> The tank develops a small hole, and air leaks from the tank at a constant rate of 0.03 lb/s for 90 s until the pressure of the air remaining in the tank is 30 lbf/in.<sup>2</sup> Employing the ideal gas model, determine the final temperature, in °F, of the air remaining in the tank.
- 4.2** Liquid propane enters an initially empty cylindrical storage tank at a mass flow rate of 10 kg/s. Flow continues until the tank is filled with propane at 20°C, 9 bar. The tank is 25-m long and has a 4-m diameter. Determine the time, in minutes, to fill the tank.
- 4.3** A 380-L tank contains steam, initially at 400°C, 3 bar. A valve is opened, and steam flows out of the tank at a constant mass flow rate of 0.005 kg/s. During steam removal, a heater maintains the temperature within the tank constant. Determine the time, in s, at which 75% of the initial mass remains in the tank; also determine the specific volume, in m<sup>3</sup>/kg, and pressure, in bar, in the tank at that time.

- 4.4** Data are provided for the crude oil storage tank shown in Fig. P4.4. The tank initially contains 1000 m<sup>3</sup> of crude oil. Oil is pumped into the tank through a pipe at a rate of 2 m<sup>3</sup>/min and out of the tank at a velocity of 1.5 m/s through another pipe having a diameter of 0.15 m. The crude oil has a specific volume of 0.0015 m<sup>3</sup>/kg. Determine

- (a) the mass of oil in the tank, in kg, after 24 hours, and  
 (b) the volume of oil in the tank, in m<sup>3</sup>, at that time.

- 4.5** If a kitchen-sink water tap leaks one drop per second, how many gallons of water are wasted annually? What is the mass

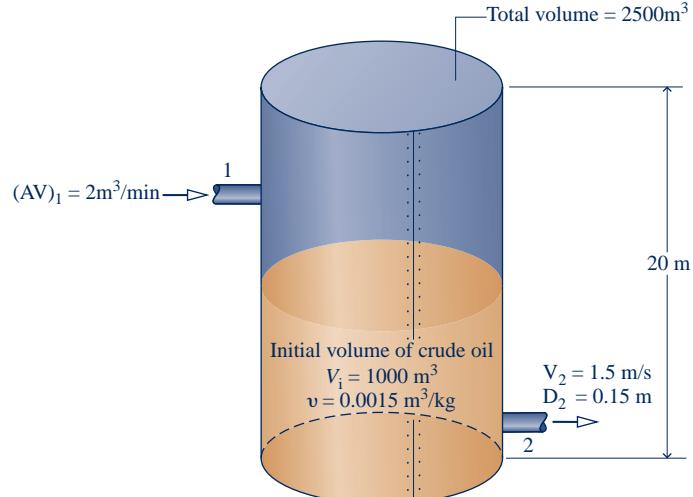


Fig. P4.4

of the wasted water, in lb? Assume that there are 46,000 drops per gallon and that the density of water is 62.3 lb/ft<sup>3</sup>.

- 4.6** Figure P4.6 shows a mixing tank initially containing 3000 lb of liquid water. The tank is fitted with two inlet pipes, one delivering hot water at a mass flow rate of 0.8 lb/s and the other delivering cold water at a mass flow rate of 1.3 lb/s. Water exits through a single exit pipe at a mass flow rate of 2.6 lb/s. Determine the amount of water, in lb, in the tank after one hour.

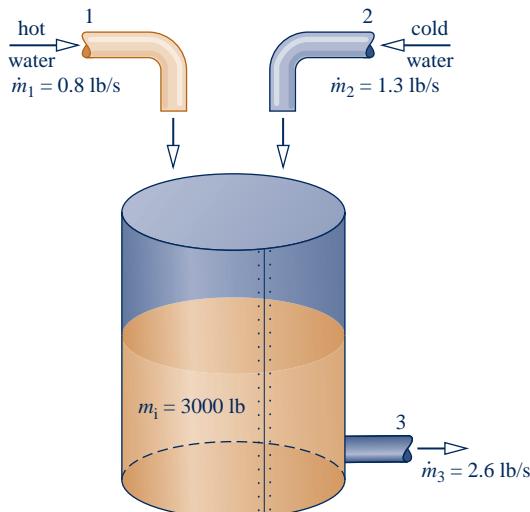


Fig. P4.6

**4.7** Figure P4.7 provides data for water entering and exiting a tank. At the inlet and exit of the tank, determine the mass flow rate, each in kg/s. Also find the time rate of change of mass contained within the tank, in kg/s.

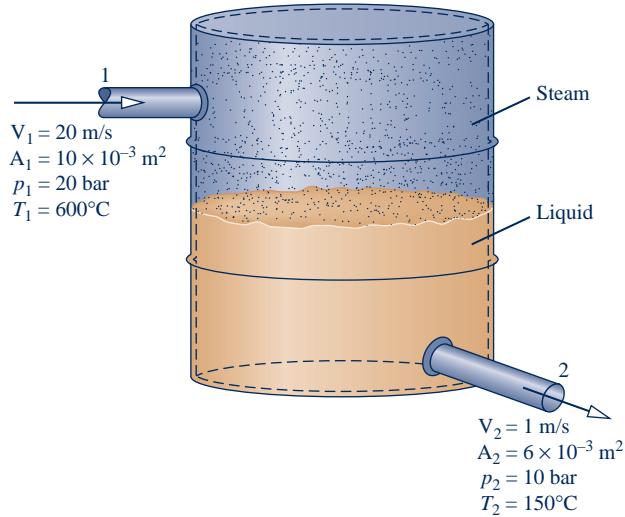


Fig. P4.7

**4.8** Liquid water flows isothermally at  $20^\circ\text{C}$  through a one-inlet, one-exit duct operating at steady state. The duct's inlet and exit diameters are  $0.02 \text{ m}$  and  $0.04 \text{ m}$ , respectively. At the inlet, the velocity is  $40 \text{ m/s}$  and pressure is  $1 \text{ bar}$ . At the exit, determine the mass flow rate, in kg/s, and velocity, in m/s.

**4.9** Air enters a one-inlet, one-exit control volume at  $6 \text{ bar}$ ,  $500 \text{ K}$ , and  $30 \text{ m/s}$  through a flow area of  $28 \text{ cm}^2$ . At the exit, the pressure is  $3 \text{ bar}$ , the temperature is  $456.5 \text{ K}$ , and the velocity is  $300 \text{ m/s}$ . The air behaves as an ideal gas. For steady-state operation, determine

- the mass flow rate, in kg/s.
- the exit flow area, in  $\text{cm}^2$ .

**4.10** The small two-story office building shown in Fig. P4.10 has  $36,000 \text{ ft}^3$  of occupied space. Due to cracks around windows and outside doors, air leaks in on the windward side of the building and leaks out on the leeward side of the building. Outside air also enters the building when outer doors are opened. On a particular day, tests were conducted. The outdoor temperature was measured to be  $15^\circ\text{F}$ . The inside temperature was controlled at  $70^\circ\text{F}$ . Keeping the doors closed, the infiltration rate through the cracks was determined to be  $75 \text{ ft}^3/\text{min}$ . The infiltration rate associated with door openings, averaged over the work day, was  $50 \text{ ft}^3/\text{min}$ . The pressure difference was negligible between the inside and outside of the building. (a) Assuming ideal gas behavior, determine at steady state the volumetric flow rate of air exiting the building, in  $\text{ft}^3/\text{min}$ . (b) When expressed in terms of the volume of the occupied space, determine the number of building air changes per hour.

**4.11** As shown in Fig. P4.11, air with a volumetric flow rate of  $15,000 \text{ ft}^3/\text{min}$  enters an air-handling unit at  $35^\circ\text{F}$ ,  $1 \text{ atm}$ . The air-handling unit delivers air at  $80^\circ\text{F}$ ,  $1 \text{ atm}$  to a duct system with three branches consisting of two  $26\text{-in.-diameter}$  ducts and one  $50\text{-in.}$  duct. The velocity in each  $26\text{-in.}$  duct is  $10 \text{ ft/s}$ . Assuming ideal gas behavior for the air, determine at steady state

- the mass flow rate of air entering the air-handling unit, in lb/s.

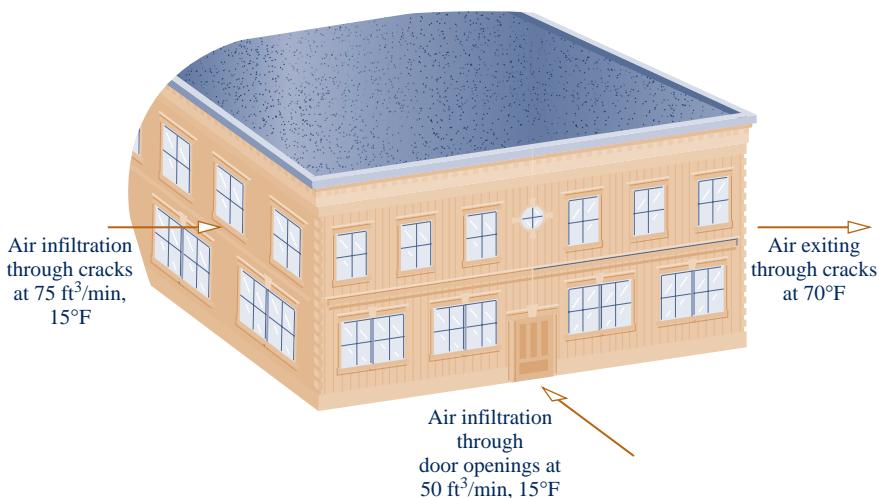
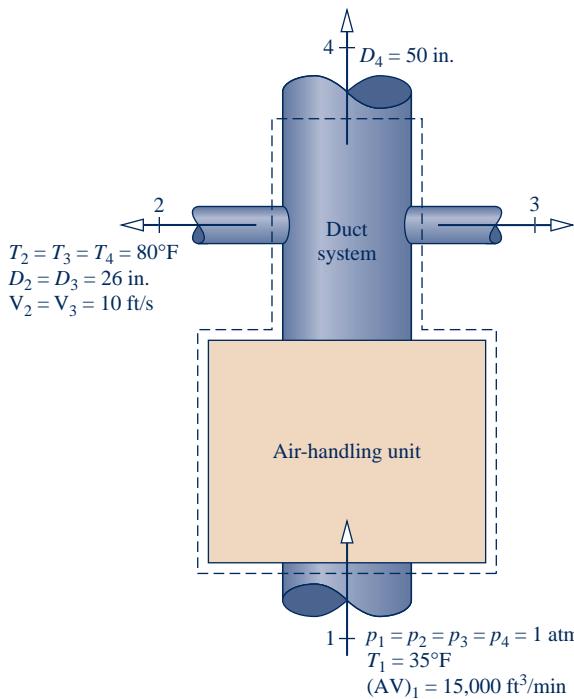


Fig. P4.10

- (b) the volumetric flow rate in each 26-in. duct, in  $\text{ft}^3/\text{min}$ .  
 (c) the velocity in the 50-in. duct, in  $\text{ft/s}$ .

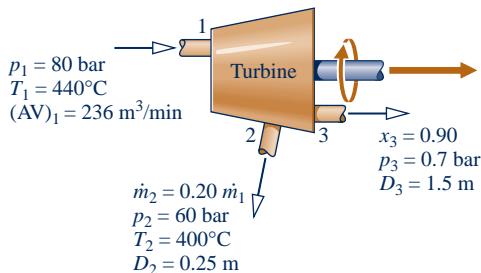


**Fig. P4.11**

- 4.12** Refrigerant 134a enters the evaporator of a refrigeration system operating at steady state at  $-4^\circ\text{C}$  and quality of 20% at a velocity of 7 m/s. At the exit, the refrigerant is a saturated vapor at a temperature of  $-4^\circ\text{C}$ . The evaporator flow channel has constant diameter. If the mass flow rate of the entering refrigerant is 0.1 kg/s, determine

- (a) the diameter of the evaporator flow channel, in cm.  
 (b) the velocity at the exit, in m/s.

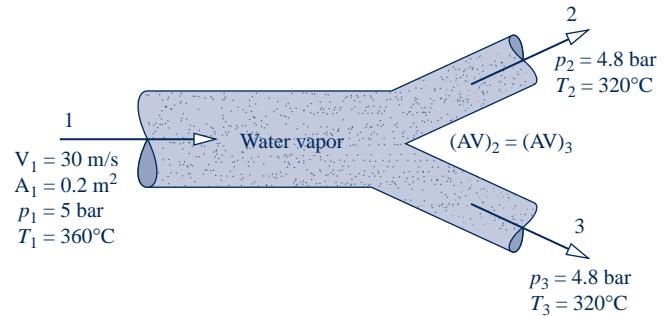
- 4.13** As shown in Fig. P4.13, steam at 80 bar,  $440^\circ\text{C}$ , enters a turbine operating at steady state with a volumetric flow rate of  $236 \text{ m}^3/\text{min}$ . Twenty percent of the entering mass flow exits through a diameter of 0.25 m at 60 bar,  $400^\circ\text{C}$ . The rest



**Fig. P4.13**

exits through a diameter of 1.5 m with a pressure of 0.7 bar and a quality of 90%. Determine the velocity at each exit duct, in m/s.

- 4.14** Figure P4.14 provides steady-state data for water vapor flowing through a piping configuration. At each exit, the volumetric flow rate, pressure, and temperature are equal. Determine the mass flow rate at the inlet and exits, each in kg/s.



**Fig. P4.14**

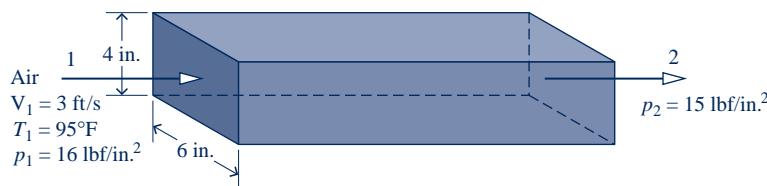
- 4.15** Air enters a compressor operating at steady state with a pressure of  $14.7 \text{ lbf/in.}^2$  and a volumetric flow rate of  $8 \text{ ft}^3/\text{s}$ . The air velocity in the exit pipe is 225 ft/s and the exit pressure is  $150 \text{ lbf/in.}^2$ . If each unit mass of air passing from inlet to exit undergoes a process described by  $p v^{1.3} = \text{constant}$ , determine the diameter of the exit pipe, in inches.

- 4.16** Ammonia enters a control volume operating at steady state at  $p_1 = 16 \text{ bar}$ ,  $T_1 = 32^\circ\text{C}$ , with a mass flow rate of 1.5 kg/s. Saturated vapor at 6 bar leaves through one exit and saturated liquid at 6 bar leaves through a second exit with a volumetric flow rate of  $0.10 \text{ m}^3/\text{min}$ . Determine

- (a) the minimum diameter of the inlet pipe, in cm, so the ammonia velocity at the inlet does not exceed 18 m/s.  
 (b) the volumetric flow rate of the exiting saturated vapor, in  $\text{m}^3/\text{min}$ .

- 4.17** Liquid water at  $70^\circ\text{F}$  enters a pump though an inlet pipe having a diameter of 6 in. The pump operates at steady state and supplies water to two exit pipes having diameters of 3 in. and 4 in., respectively. The velocity of the water exiting the 3-in. pipe is 1.31 ft/s. At the exit of the 4-in. pipe the velocity is 0.74 ft/s. The temperature of the water in each exit pipe is  $72^\circ\text{F}$ . Determine (a) the mass flow rate, in lb/s, in the inlet pipe and each of the exit pipes, and (b) the volumetric flow rate at the inlet, in  $\text{ft}^3/\text{min}$ .

- 4.18** Figure P4.18 provides steady-state data for air flowing through a rectangular duct. Assuming ideal gas behavior for the air, determine the inlet volumetric flow rate, in  $\text{ft}^3/\text{s}$ , and inlet mass flow rate, in kg/s. If you can determine the



**Fig. P4.18**

volumetric flow rate and mass flow rate at the exit, evaluate them. If not, explain.

- 4.19** A water storage tank initially contains 100,000 gal of water. The average daily usage is 10,000 gal. If water is added to the tank at an average rate of  $5000[\exp(-t/20)]$  gallons per day, where  $t$  is time in days, for how many days will the tank contain water?

- 4.20** A pipe carrying an incompressible liquid contains an expansion chamber as illustrated in Fig. P4.20.

- (a) Develop an expression for the time rate of change of liquid level in the chamber,  $dL/dt$ , in terms of the diameters  $D_1$ ,  $D_2$ , and  $D$ , and the velocities  $V_1$  and  $V_2$ .  
 (b) Compare the relative magnitudes of the mass flow rates  $\dot{m}_1$  and  $\dot{m}_2$  when  $dL/dt > 0$ ,  $dL/dt = 0$ , and  $dL/dt < 0$ , respectively.

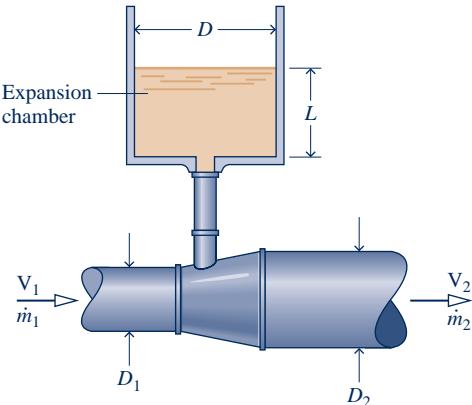


Fig. P4.20

- 4.21** Velocity distributions for *laminar* and *turbulent* flow in a circular pipe of radius  $R$  carrying an incompressible liquid of density  $\rho$  are given, respectively, by

$$\frac{V}{V_0} = [1 - (r/R)^2]$$

$$\frac{V}{V_0} = [1 - (r/R)]^{1/7}$$

where  $r$  is the radial distance from the pipe centerline and  $V_0$  is the centerline velocity. For each velocity distribution

- (a) plot  $V/V_0$  versus  $r/R$ .  
 (b) derive expressions for the mass flow rate and the average velocity of the flow,  $V_{ave}$ , in terms of  $V_0$ ,  $R$ , and  $\rho$ , as required.  
 (c) derive an expression for the *specific* kinetic energy carried through an area normal to the flow. What is the percent error if the specific kinetic energy is evaluated in terms of the average velocity as  $(V_{ave})^2/2$ ?

Which velocity distribution adheres most closely to the idealizations of one-dimensional flow? Discuss.

- 4.22** Figure P4.22 shows a cylindrical tank being drained through a duct whose cross-sectional area is  $3 \times 10^{-4} \text{ m}^2$ . The velocity of the water at the exit varies according to  $(2gz)^{1/2}$ , where  $z$  is the water level, in m, and  $g$  is the acceleration of gravity,  $9.81 \text{ m/s}^2$ . The tank initially contains 2500 kg of liquid water. Taking the density of the water as  $10^3 \text{ kg/m}^3$ , determine the time, in minutes, when the tank contains 900 kg of water.

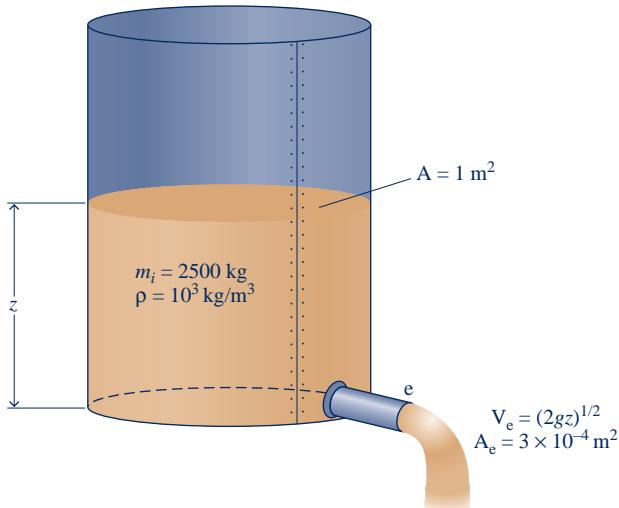


Fig. P4.22

#### Energy Analysis of Control Volumes at Steady State

- 4.23** Steam enters a horizontal pipe operating at steady state with a specific enthalpy of 3000 kJ/kg and a mass flow rate of 0.5 kg/s. At the exit, the specific enthalpy is 1700 kJ/kg. If there is no significant change in kinetic energy from inlet to exit, determine the rate of heat transfer between the pipe and its surroundings, in kW.

- 4.24** Refrigerant 134a enters a horizontal pipe operating at steady state at  $40^\circ\text{C}$ , 300 kPa and a velocity of 40 m/s. At the exit, the temperature is  $50^\circ\text{C}$  and the pressure is 240 kPa. The pipe diameter is 0.04 m. Determine (a) the mass flow rate of the refrigerant, in kg/s, (b) the velocity at the exit, in m/s, and (c) the rate of heat transfer between the pipe and its surroundings, in kW.

- 4.25** As shown in Fig. P4.25, air enters a pipe at  $25^\circ\text{C}$ , 100 kPa with a volumetric flow rate of  $23 \text{ m}^3/\text{h}$ . On the outer pipe surface is an electrical resistor covered with insulation. With a voltage of 120 V, the resistor draws a current of 4 amps. Assuming the ideal gas model with  $c_p = 1.005 \text{ kJ/kg} \cdot \text{K}$  for air and ignoring kinetic and potential energy effects, determine (a) the mass flow rate of the air, in kg/h, and (b) the temperature of the air at the exit, in  $^\circ\text{C}$ .

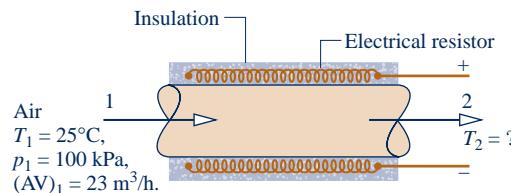


Fig. P4.25

- 4.26** Air enters a horizontal, constant-diameter heating duct operating at steady state at  $290 \text{ K}$ , 1 bar, with a volumetric flow rate of  $0.25 \text{ m}^3/\text{s}$ , and exits at  $325 \text{ K}$ , 0.95 bar. The flow area is  $0.04 \text{ m}^2$ . Assuming the ideal gas model with  $k = 1.4$  for the air, determine (a) the mass flow rate, in kg/s, (b) the velocity at the inlet and exit, each in m/s, and (c) the rate of heat transfer, in kW.

**4.27** Air at 600 kPa, 330 K enters a well-insulated, horizontal pipe having a diameter of 1.2 cm and exits at 120 kPa, 300 K. Applying the ideal gas model for air, determine at steady state (a) the inlet and exit velocities, each in m/s, and (b) the mass flow rate, in kg/s.

**4.28** At steady state, air at 200 kPa, 52°C and a mass flow rate of 0.5 kg/s enters an insulated duct having differing inlet and exit cross-sectional areas. At the duct exit, the pressure of the air is 100 kPa, the velocity is 255 m/s, and the cross-sectional area is  $2 \times 10^{-3}$  m<sup>2</sup>. Assuming the ideal gas model, determine

- (a) the temperature of the air at the exit, in °C.
- (b) the velocity of the air at the inlet, in m/s.
- (c) the inlet cross-sectional area, in m<sup>2</sup>.

**4.29** Refrigerant 134a flows at steady state through a horizontal pipe having an inside diameter of 4 cm, entering as saturated vapor at -8°C with a mass flow rate of 17 kg/min. Refrigerant vapor exits at a pressure of 2 bar. If the heat transfer rate to the refrigerant is 3.4 kW, determine the exit temperature, in °C, and the velocities at the inlet and exit, each in m/s.

**4.30** Water vapor enters an insulated nozzle operating at steady state at 500°C, 40 bar, with a velocity of 100 m/s, and exits at 300°C, 10 bar. The velocity at the exit, in m/s, is approximately

- (a) 104, (c) 888,
- (b) 636, (d) 894.

**4.31** Steam enters a nozzle operating at steady state at 20 bar, 280°C, with a velocity of 80 m/s. The exit pressure and temperature are 7 bar and 180°C, respectively. The mass flow rate is 1.5 kg/s. Neglecting heat transfer and potential energy, determine

- (a) the exit velocity, in m/s.
- (b) the inlet and exit flow areas, in cm<sup>2</sup>.

**4.32** Refrigerant 134a enters a well-insulated nozzle at 200 lbf/in.<sup>2</sup>, 220°F, with a velocity of 120 ft/s and exits at 20 lbf/in.<sup>2</sup> with a velocity of 1500 ft/s. For steady-state operation, and neglecting potential energy effects, determine the exit temperature, in °F.

**4.33** Air enters a nozzle operating at steady state at 720°R with negligible velocity and exits the nozzle at 500°R with a velocity of 1450 ft/s. Assuming ideal gas behavior and neglecting potential energy effects, determine the heat transfer in Btu per lb of air flowing.

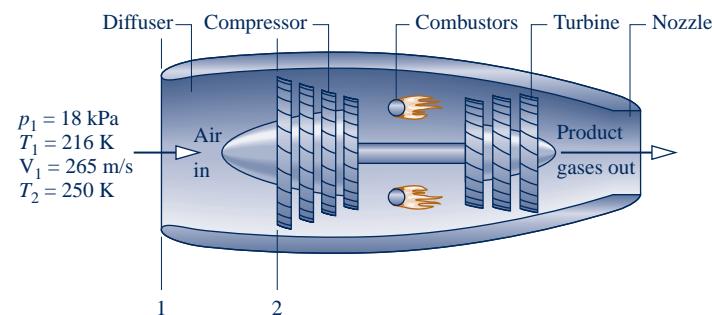
**4.34** Air with a mass flow rate of 5 lb/s enters a horizontal nozzle operating at steady state at 800°R, 50 lbf/in.<sup>2</sup> and a velocity of 10 ft/s. At the exit, the temperature is 570°R and the velocity is 1510 ft/s. Using the ideal gas model for air, determine (a) the area at the inlet, in ft<sup>2</sup>, and (b) the heat transfer between the nozzle and its surroundings, in Btu per lb of air flowing.

**4.35** Helium gas flows through a well-insulated nozzle at steady state. The temperature and velocity at the inlet are 550°R and 150 ft/s, respectively. At the exit, the temperature is 400°R and the pressure is 40 lbf/in.<sup>2</sup> The area of the exit is 0.0085 ft<sup>2</sup>. Using the ideal gas model with  $k = 1.67$ , and neglecting potential energy effects, determine the mass flow rate, in lb/s, through the nozzle.

**4.36** Methane (CH<sub>4</sub>) gas enters a horizontal, well-insulated nozzle operating at steady state at 80°C and a velocity of

10 m/s. Assuming ideal gas behavior for the methane, plot the temperature of the gas exiting the nozzle, in °C, versus the exit velocity ranging from 500 to 600 m/s.

**4.37** As shown in Fig. P4.37, air enters the diffuser of a jet engine operating at steady state at 18 kPa, 216 K and a velocity of 265 m/s, all data corresponding to high-altitude flight. The air flows adiabatically through the diffuser and achieves a temperature of 250 K at the diffuser exit. Using the ideal gas model for air, determine the velocity of the air at the diffuser exit, in m/s.



**Fig. P4.37**

**4.38** Air enters a diffuser operating at steady state at 540°R, 15 lbf/in.<sup>2</sup>, with a velocity of 600 ft/s, and exits with a velocity of 60 ft/s. The ratio of the exit area to the inlet area is 8. Assuming the ideal gas model for the air and ignoring heat transfer, determine the temperature, in °R, and pressure, in lbf/in.<sup>2</sup>, at the exit.

**4.39** Refrigerant 134a enters an insulated diffuser as a saturated vapor at 80°F with a velocity of 1453.4 ft/s. At the exit, the temperature is 280°F and the velocity is negligible. The diffuser operates at steady state and potential energy effects can be neglected. Determine the exit pressure, in lbf/in.<sup>2</sup>.

**4.40** Oxygen gas enters a well-insulated diffuser at 30 lbf/in.<sup>2</sup>, 440°R, with a velocity of 950 ft/s through a flow area of 2.0 in.<sup>2</sup>. At the exit, the flow area is 15 times the inlet area, and the velocity is 25 ft/s. The potential energy change from inlet to exit is negligible. Assuming ideal gas behavior for the oxygen and steady-state operation of the nozzle, determine the exit temperature, in °R, the exit pressure, in lbf/in.<sup>2</sup>, and the mass flow rate, in lb/s.

**4.41** Steam enters a well-insulated turbine operating at steady state at 4 MPa with a specific enthalpy of 3015.4 kJ/kg and a velocity of 10 m/s. The steam expands to the turbine exit where the pressure is 0.07 MPa, specific enthalpy is 2431.7 kJ/kg, and the velocity is 90 m/s. The mass flow rate is 11.95 kg/s. Neglecting potential energy effects, determine the power developed by the turbine, in kW.

**4.42** Hot combustion gases, modeled as air behaving as an ideal gas, enter a turbine at 145 lbf/in.<sup>2</sup>, 2700°R with a mass flow rate of 0.22 lb/s and exit at 29 lbf/in.<sup>2</sup> and 1620°R. If heat transfer from the turbine to its surroundings occurs at a rate of 14 Btu/s, determine the power output of the turbine, in hp.

**4.43** Air expands through a turbine from 8 bar, 960 K to 1 bar, 450 K. The inlet velocity is small compared to the exit velocity of 90 m/s. The turbine operates at steady state and

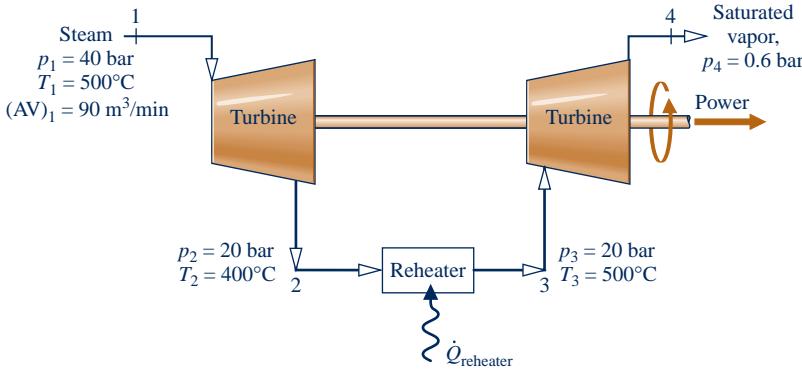


Fig. P4.50

develops a power output of 2500 kW. Heat transfer between the turbine and its surroundings and potential energy effects are negligible. Modeling air as an ideal gas, calculate the mass flow rate of air, in kg/s, and the exit area, in m<sup>2</sup>.

- 4.44** Air expands through a turbine operating at steady state. At the inlet,  $p_1 = 150 \text{ lbf/in.}^2$ ,  $T_1 = 1400^\circ\text{R}$ , and at the exit,  $p_2 = 14.8 \text{ lbf/in.}^2$ ,  $T_2 = 700^\circ\text{R}$ . The mass flow rate of air entering the turbine is 11 lb/s, and 65,000 Btu/h of energy is rejected by heat transfer. Neglecting kinetic and potential energy effects, determine the power developed, in hp.

- 4.45** Steam enters a turbine operating at steady state at 700°F and 450 lbf/in.<sup>2</sup> and leaves as a saturated vapor at 1.2 lbf/in.<sup>2</sup>. The turbine develops 12,000 hp, and heat transfer from the turbine to the surroundings occurs at a rate of  $2 \times 10^6 \text{ Btu/h}$ . Neglecting kinetic and potential energy changes from inlet to exit, determine the volumetric flow rate of the steam at the inlet, in ft<sup>3</sup>/s.

- 4.46** A well-insulated turbine operating at steady state develops 28.75 MW of power for a steam flow rate of 50 kg/s. The steam enters at 25 bar with a velocity of 61 m/s and exits as saturated vapor at 0.06 bar with a velocity of 130 m/s. Neglecting potential energy effects, determine the inlet temperature, in °C.

- 4.47** Steam enters a turbine operating at steady state with a mass flow of 10 kg/min, a specific enthalpy of 3100 kJ/kg, and a velocity of 30 m/s. At the exit, the specific enthalpy is 2300 kJ/kg and the velocity is 45 m/s. The elevation of the inlet is 3 m higher than at the exit. Heat transfer from the turbine to its surroundings occurs at a rate of 1.1 kJ per kg of steam flowing. Let  $g = 9.81 \text{ m/s}^2$ . Determine the power developed by the turbine, in kW.

- 4.48** Steam enters a turbine operating at steady state at 2 MPa, 360°C with a velocity of 100 m/s. Saturated vapor exits at 0.1 MPa and a velocity of 50 m/s. The elevation of the inlet is 3 m higher than at the exit. The mass flow rate of the steam is 15 kg/s, and the power developed is 7 MW. Let  $g = 9.81 \text{ m/s}^2$ . Determine (a) the area at the inlet, in m<sup>2</sup>, and (b) the rate of heat transfer between the turbine and its surroundings, in kW.

- 4.49** Water vapor enters a turbine operating at steady state at 500°C, 40 bar, with a velocity of 200 m/s, and expands adiabatically to the exit, where it is saturated vapor at 0.8 bar, with a velocity of 150 m/s and a volumetric flow rate of 9.48 m<sup>3</sup>/s. The power developed by the turbine, in kW, is approximately

- (a) 3500, (c) 3580,  
(b) 3540, (d) 7470.

- 4.50** Steam enters the first-stage turbine shown in Fig. P4.50 at 40 bar and 500°C with a volumetric flow rate of 90 m<sup>3</sup>/min. Steam exits the turbine at 20 bar and 400°C. The steam is then reheated at constant pressure to 500°C before entering the second-stage turbine. Steam leaves the second stage as saturated vapor at 0.6 bar. For operation at steady state, and ignoring stray heat transfer and kinetic and potential energy effects, determine the

- (a) mass flow rate of the steam, in kg/h.  
(b) total power produced by the two stages of the turbine, in kW.  
(c) rate of heat transfer to the steam flowing through the reheat stage, in kW.

- 4.51** Steam at 1800 lbf/in.<sup>2</sup> and 1100°F enters a turbine operating at steady state. As shown in Fig. P4.51, 20% of the entering mass flow is extracted at 600 lbf/in.<sup>2</sup> and 500°F. The rest of the steam exits as a saturated vapor at 1 lbf/in.<sup>2</sup>. The turbine develops a power output of  $6.8 \times 10^6 \text{ Btu/h}$ . Heat transfer from the turbine to the surroundings occurs at a rate of  $5 \times 10^4 \text{ Btu/h}$ . Neglecting kinetic and potential energy effects, determine the mass flow rate of the steam entering the turbine, in lb/s.

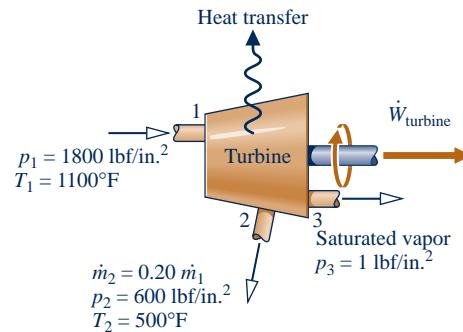


Fig. P4.51

- 4.52** Air enters a compressor operating at steady state at 1 atm with a specific enthalpy of 290 kJ/kg and exits at a higher pressure with a specific enthalpy of 1023 kJ/kg. The mass flow rate is 0.1 kg/s. If the compressor power input is 77 kW, determine the rate of heat transfer between the compressor and its surroundings, in kW. Neglect kinetic and potential energy effects and assume the ideal gas model.

**4.53** Air enters a compressor operating at steady state at 1.05 bar, 300 K, with a volumetric flow rate of  $12 \text{ m}^3/\text{min}$  and exits at 12 bar, 400 K. Heat transfer occurs at a rate of 2 kW from the compressor to its surroundings. Assuming the ideal gas model for air and neglecting kinetic and potential energy effects, determine the power input, in kW.

**4.54** Nitrogen is compressed in an axial-flow compressor operating at steady state from a pressure of  $15 \text{ lbf/in.}^2$  and a temperature of  $50^\circ\text{F}$  to a pressure  $60 \text{ lbf/in.}^2$ . The gas enters the compressor through a 6-in.-diameter duct with a velocity of 30 ft/s and exits at  $198^\circ\text{F}$  with a velocity of 80 ft/s. Using the ideal gas model, and neglecting stray heat transfer and potential energy effects, determine the compressor power input, in hp.

**4.55** Refrigerant 134a enters a compressor operating at steady state as saturated vapor at 0.12 MPa and exits at 1.2 MPa and  $70^\circ\text{C}$  at a mass flow rate of 0.108 kg/s. As the refrigerant passes through the compressor, heat transfer to the surroundings occurs at a rate of 0.32 kJ/s. Determine at steady state the power input to the compressor, in kW.

**4.56** Carbon dioxide gas is compressed at steady state from a pressure of  $20 \text{ lbf/in.}^2$  and a temperature of  $32^\circ\text{F}$  to a pressure of  $50 \text{ lbf/in.}^2$  and a temperature of  $120^\circ\text{F}$ . The gas enters the compressor with a velocity of 30 ft/s and exits with a velocity of 80 ft/s. The mass flow rate is 0.98 lb/s. The magnitude of the heat transfer rate from the compressor to its surroundings is 5% of the compressor power input. Using the ideal gas model with  $c_p = 0.21 \text{ Btu/lb} \cdot ^\circ\text{R}$  and neglecting potential energy effects, determine the compressor power input, in horsepower.

**4.57** At steady state, a well-insulated compressor takes in nitrogen at  $60^\circ\text{F}$ ,  $14.2 \text{ lbf/in.}^2$ , with a volumetric flow rate of  $1200 \text{ ft}^3/\text{min}$ . Compressed nitrogen exits at  $500^\circ\text{F}$ ,  $120 \text{ lbf/in.}^2$ . Kinetic and potential energy changes from inlet to exit can be neglected. Determine the compressor power, in hp, and the volumetric flow rate at the exit, in  $\text{ft}^3/\text{min}$ .

**4.58** Air enters a compressor operating at steady state with a pressure of  $14.7 \text{ lbf/in.}^2$ , a temperature of  $80^\circ\text{F}$ , and a volumetric flow rate of  $18 \text{ ft}^3/\text{s}$ . The air exits the compressor at a pressure of  $90 \text{ lbf/in.}^2$ . Heat transfer from the compressor to its surroundings occurs at a rate of 9.7 Btu per lb of air flowing. The compressor power input is 90 hp. Neglecting kinetic and potential energy effects and modeling air as an ideal gas, determine the exit temperature, in  $^\circ\text{F}$ .

**4.59** Refrigerant 134a enters an air conditioner compressor at 4 bar,  $20^\circ\text{C}$ , and is compressed at steady state to 12 bar,  $80^\circ\text{C}$ . The volumetric flow rate of the refrigerant entering is  $4 \text{ m}^3/\text{min}$ . The power input to the compressor is 60 kJ per kg of refrigerant flowing. Neglecting kinetic and potential energy effects, determine the heat transfer rate, in kW.

**4.60** Refrigerant 134a enters an insulated compressor operating at steady state as saturated vapor at  $-20^\circ\text{C}$  with a mass flow rate of 1.2 kg/s. Refrigerant exits at 7 bar,  $70^\circ\text{C}$ . Changes in kinetic and potential energy from inlet to exit can be ignored. Determine (a) the volumetric flow rates at the inlet and exit, each in  $\text{m}^3/\text{s}$ , and (b) the power input to the compressor, in kW.

**4.61** Refrigerant 134a enters a water-jacketed compressor operating at steady state at  $-10^\circ\text{C}$ , 1.4 bar, with a mass flow

rate of  $4.2 \text{ kg/s}$ , and exits at  $50^\circ\text{C}$ , 12 bar. The compressor power required is 150 kW. Neglecting kinetic and potential energy effects, determine the rate of heat transfer to the cooling water circulating through the water jacket.

**4.62** Air is compressed at steady state from 1 bar, 300 K, to 6 bar with a mass flow rate of  $4 \text{ kg/s}$ . Each unit of mass passing from inlet to exit undergoes a process described by  $pv^{1.27} = \text{constant}$ . Heat transfer occurs at a rate of 46.95 kJ per kg of air flowing to cooling water circulating in a water jacket enclosing the compressor. If kinetic and potential energy changes of the air from inlet to exit are negligible, determine the compressor power, in kW.

**4.63** Air enters a compressor operating at steady state with a pressure of  $14.7 \text{ lbf/in.}^2$  and a temperature of  $70^\circ\text{F}$ . The volumetric flow rate at the inlet is  $16.6 \text{ ft}^3/\text{s}$ , and the flow area is  $0.26 \text{ ft}^2$ . At the exit, the pressure is  $35 \text{ lbf/in.}^2$ , the temperature is  $280^\circ\text{F}$ , and the velocity is 50 ft/s. Heat transfer from the compressor to its surroundings occurs at a rate of 1.0 Btu per lb of air flowing. Potential energy effects are negligible, and the ideal gas model can be assumed for the air. Determine (a) the velocity of the air at the inlet, in ft/s, (b) the mass flow rate, in lb/s, and (c) the compressor power, in Btu/s and hp.

**4.64** Air enters a compressor operating at steady state at  $14.7 \text{ lbf/in.}^2$  and  $60^\circ\text{F}$  and is compressed to a pressure of  $150 \text{ lbf/in.}^2$ . As the air passes through the compressor, it is cooled at a rate of 10 Btu per lb of air flowing by water circulated through the compressor casing. The volumetric flow rate of the air at the inlet is  $5000 \text{ ft}^3/\text{min}$ , and the power input to the compressor is 700 hp. The air behaves as an ideal gas, there is no stray heat transfer, and kinetic and potential effects are negligible. Determine (a) the mass flow rate of the air, lb/s, and (b) the temperature of the air at the compressor exit, in  $^\circ\text{F}$ .

**4.65** As shown in Fig. P4.65, a pump operating at steady state draws water from a pond and delivers it through a pipe whose exit is 90 ft above the inlet. At the exit, the mass flow rate is  $10 \text{ lb/s}$ . There is no significant change in water temperature, pressure, or kinetic energy from inlet to exit. If the power required by the pump is 1.68 hp, determine the rate of heat transfer between the pump and its surroundings, in hp and Btu/min. Let  $g = 32.0 \text{ ft/s}^2$ .

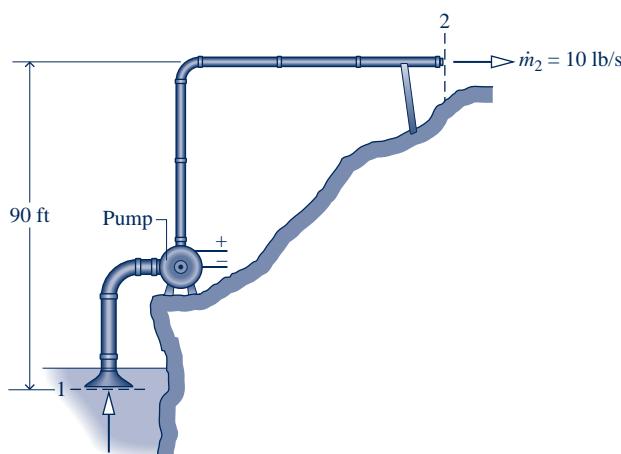


Fig. P4.65

**4.66** Figure P4.66 provides steady-state operating data for a pump drawing water from a reservoir and delivering it at a pressure of 3 bar to a storage tank perched above the reservoir. The mass flow rate of the water is 1.5 kg/s. The water temperature remains nearly constant at 15°C, there is no significant change in kinetic energy from inlet to exit, and heat transfer between the pump and its surroundings is negligible. Determine the power required by the pump, in kW. Let  $g = 9.81 \text{ m/s}^2$ .

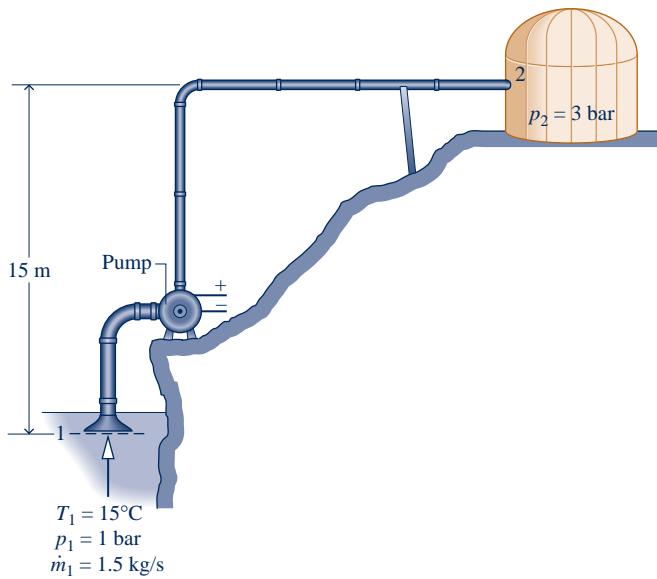


Fig. P4.66

**4.67** Figure P4.67 provides steady-state operating data for a submerged pump and an attached delivery pipe. At the inlet, the volumetric flow rate is  $0.75 \text{ m}^3/\text{min}$  and the temperature is 15°C. At the exit, the pressure is 1 atm. There is no significant change in water temperature or kinetic energy

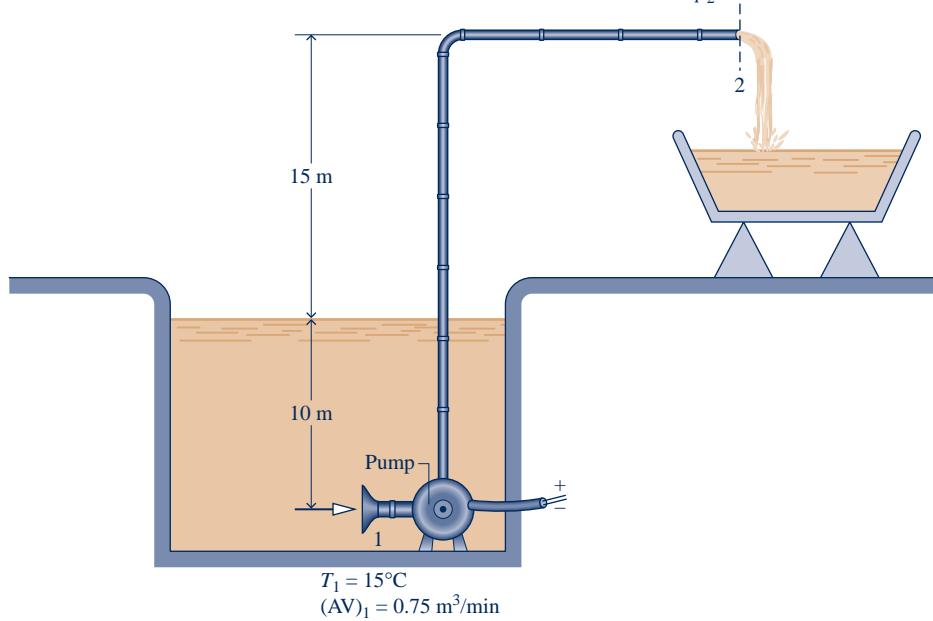


Fig. P4.67

from inlet to exit. Heat transfer between the pump and its surroundings is negligible. Determine the power required by the pump, in kW. Let  $g = 9.81 \text{ m/s}^2$ .

**4.68** As shown in Fig. P4.68, a power washer used to clean the siding of a house has water entering through a hose at 20°C, 1 atm and a velocity of 0.2 m/s. A jet of water exits with a velocity of 20 m/s at an average elevation of 5 m with no significant change in temperature or pressure. At steady state, the magnitude of the heat transfer rate *from* the power washer to the surroundings is 10% of the electrical power *input*. Evaluating electricity at 8 cents per kW · h, determine the cost of the power required, in cents per liter of water delivered. Compare with the cost of water, assuming 0.05 cents per liter, and comment.

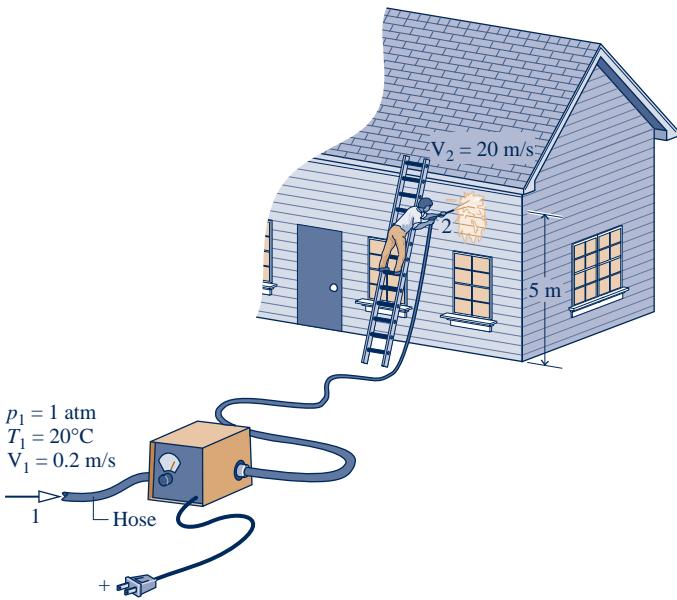


Fig. P4.68

**4.69** An oil pump operating at steady state delivers oil at a rate of 12 lb/s through a 1-in.-diameter pipe. The oil, which can be modeled as incompressible, has a density of 100 lb/ft<sup>3</sup> and experiences a pressure rise from inlet to exit of 40 lbf/in.<sup>2</sup> There is no significant elevation difference between inlet and exit, and the inlet kinetic energy is negligible. Heat transfer between the pump and its surroundings is negligible, and there is no significant change in temperature as the oil passes through the pump. If pumps are available in 1/4-horsepower increments, determine the horsepower rating of the pump needed for this application.

**4.70** Steam enters a counterflow heat exchanger operating at steady state at 0.07 MPa with a specific enthalpy of 2431.6 kJ/kg and exits at the same pressure as saturated liquid. The steam mass flow rate is 1.5 kg/min. A separate stream of air with a mass flow rate of 100 kg/min enters at 30°C and exits at 60°C. The ideal gas model with  $c_p = 1.005 \text{ kJ/kg} \cdot \text{K}$  can be assumed for air. Kinetic and potential energy effects are negligible. Determine (a) the quality of the entering steam and (b) the rate of heat transfer between the heat exchanger and its surroundings, in kW.

**4.71** Refrigerant 134a at a flow rate of 0.5 lb/s enters a heat exchanger in a refrigeration system operating at steady state as saturated liquid at 0°F and exits at 20°F at a pressure of 20 lbf/in.<sup>2</sup> A separate air stream passes in counterflow to the Refrigerant 134a stream, entering at 120°F and exiting at 77°F. The outside of the heat exchanger is well insulated. Neglecting kinetic and potential energy effects and modeling the air as an ideal gas, determine the mass flow rate of air, in lb/s.

**4.72** Oil enters a counterflow heat exchanger at 450 K with a mass flow rate of 10 kg/s and exits at 350 K. A separate stream of liquid water enters at 20°C, 5 bar. Each stream experiences no significant change in pressure. Stray heat transfer with the surroundings of the heat exchanger and kinetic and potential energy effects can be ignored. The specific heat of the oil is constant,  $c = 2 \text{ kJ/kg} \cdot \text{K}$ . If the designer wants to ensure no water vapor is present in the exiting water stream, what is the allowed range of mass flow rates for the water, in kg/s?

**4.73** As shown in Fig. P4.73, Refrigerant 134a enters a condenser operating at steady state at 70 lbf/in.<sup>2</sup>, 160°F and is condensed to saturated liquid at 60 lbf/in.<sup>2</sup> on the outside of tubes through which cooling water flows. In passing through the tubes, the

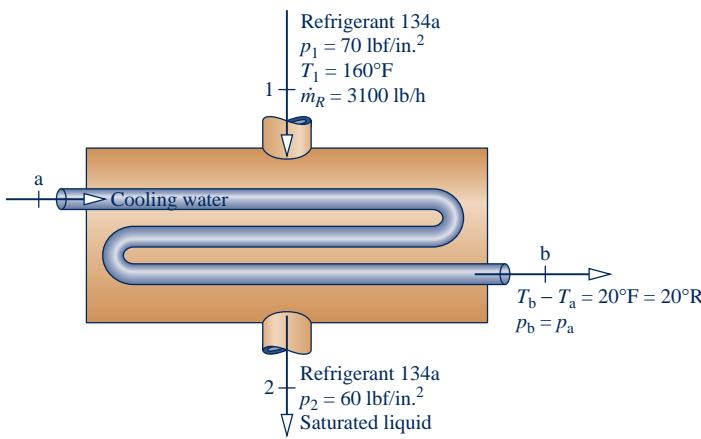


Fig. P4.73

cooling water increases in temperature by 20°F and experiences no significant pressure drop. Cooling water can be modeled as incompressible with  $\nu = 0.0161 \text{ ft}^3/\text{lb}$  and  $c = 1 \text{ Btu/lb} \cdot ^\circ\text{R}$ . The mass flow rate of the refrigerant is 3100 lb/h. Neglecting kinetic and potential energy effects and ignoring heat transfer from the outside of the condenser, determine

- the volumetric flow rate of the entering cooling water, in gal/min.
- the rate of heat transfer, in Btu/h, to the cooling water from the condensing refrigerant.

**4.74** Steam at a pressure of 0.08 bar and a quality of 93.2% enters a shell-and-tube heat exchanger where it condenses on the outside of tubes through which cooling water flows, exiting as saturated liquid at 0.08 bar. The mass flow rate of the condensing steam is  $3.4 \times 10^5 \text{ kg/h}$ . Cooling water enters the tubes at 15°C and exits at 35°C with negligible change in pressure. Neglecting stray heat transfer and ignoring kinetic and potential energy effects, determine the mass flow rate of the cooling water, in kg/h, for steady-state operation.

**4.75** An air-conditioning system is shown in Fig. P4.75 in which air flows over tubes carrying Refrigerant 134a. Air enters with a volumetric flow rate of  $50 \text{ m}^3/\text{min}$  at 32°C, 1 bar, and exits at 22°C, 0.95 bar. Refrigerant enters the tubes at 5 bar with a quality of 20% and exits at 5 bar, 20°C. Ignoring heat transfer at the outer surface of the air conditioner, and neglecting kinetic and potential energy effects, determine at steady state

- the mass flow rate of the refrigerant, in kg/min.
- the rate of heat transfer, in kJ/min, between the air and refrigerant.

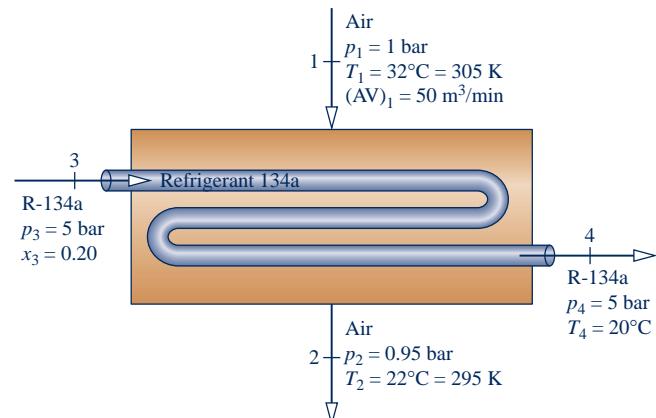


Fig. P4.75

**4.76** Steam enters a heat exchanger operating at steady state at 250 kPa and a quality of 90% and exits as saturated liquid at the same pressure. A separate stream of oil with a mass flow rate of 29 kg/s enters at 20°C and exits at 100°C with no significant change in pressure. The specific heat of the oil is  $c = 2.0 \text{ kJ/kg} \cdot \text{K}$ . Kinetic and potential energy effects are negligible. If heat transfer from the heat exchanger to its surroundings is 10% of the energy required to increase the temperature of the oil, determine the steam mass flow rate, in kg/s.

**4.77** Refrigerant 134a enters a heat exchanger at  $-12^\circ\text{C}$  and a quality of 42% and exits as saturated vapor at the same temperature with a volumetric flow rate of  $0.85 \text{ m}^3/\text{min}$ . A separate stream of air enters at 22°C with a mass flow rate

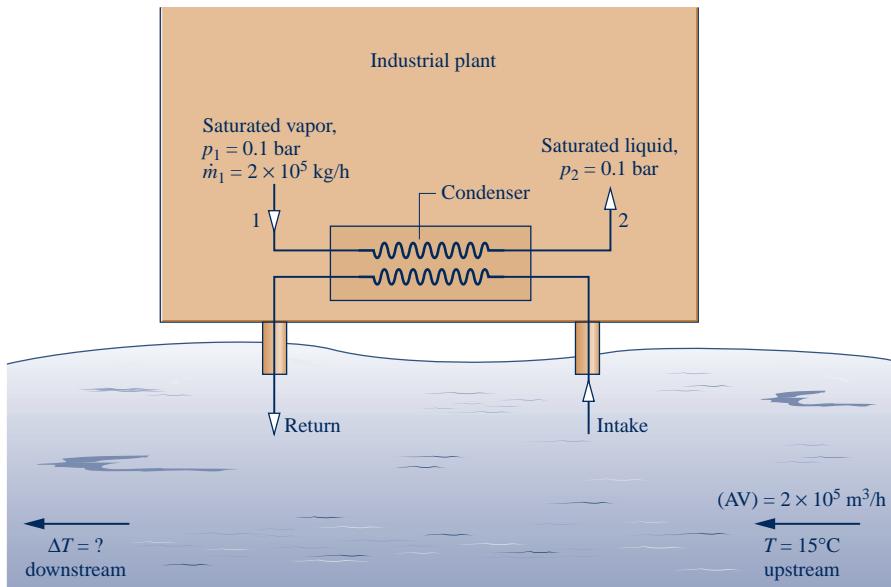


Fig. P4.78

of 188 kg/min and exits at 17°C. Assuming the ideal gas model for air and ignoring kinetic and potential energy effects, determine (a) the mass flow rate of the Refrigerant 134a, in kg/min, and (b) the heat transfer between the heat exchanger and its surroundings, in kJ/min.

**4.78** As sketched in Fig. P4.78, a condenser using river water to condense steam with a mass flow rate of  $2 \times 10^5 \text{ kg/h}$  from saturated vapor to saturated liquid at a pressure of 0.1 bar is proposed for an industrial plant. Measurements indicate that several hundred meters upstream of the plant, the river has a volumetric flow rate of  $2 \times 10^5 \text{ m}^3/\text{h}$  and a temperature of 15°C. For operation at steady state and ignoring changes in kinetic and potential energy, determine the river-water temperature rise, in °C, downstream of the plant traceable to use of such a condenser, and comment.

**4.79** Figure P4.79 shows a solar collector panel embedded in a roof. The panel, which has a surface area of  $24 \text{ ft}^2$ , receives

energy from the sun at a rate of 200 Btu/h per  $\text{ft}^2$  of collector surface. Twenty-five percent of the incoming energy is lost to the surroundings. The remaining energy is used to heat domestic hot water from 90 to 120°F. The water passes through the solar collector with a negligible pressure drop. Neglecting kinetic and potential effects, determine at steady state how many gallons of water at 120°F the collector generates per hour.

**4.80** A feedwater heater in a vapor power plant operates at steady state with liquid entering at inlet 1 with  $T_1 = 45^\circ\text{C}$  and  $p_1 = 3.0 \text{ bar}$ . Water vapor at  $T_2 = 320^\circ\text{C}$  and  $p_2 = 3.0 \text{ bar}$  enters at inlet 2. Saturated liquid water exits with a pressure of  $p_3 = 3.0 \text{ bar}$ . Ignore heat transfer with the surroundings and all kinetic and potential energy effects. If the mass flow rate of the liquid entering at inlet 1 is  $\dot{m}_1 = 3.2 \times 10^5 \text{ kg/h}$ , determine the mass flow rate at inlet 2,  $\dot{m}_2$ , in kg/h.

**4.81** An open feedwater heater operates at steady state with liquid water entering inlet 1 at 10 bar, 50°C, and a mass flow rate of 60 kg/s. A separate stream of steam enters inlet 2 at 10 bar and 200°C. Saturated liquid at 10 bar exits the feedwater heater at exit 3. Ignoring heat transfer with the surroundings and neglecting kinetic and potential energy effects, determine the mass flow rate, in kg/s, of the steam at inlet 2.

**4.82** For the *desuperheater* shown in Fig. P4.82, liquid water at state 1 is injected into a stream of superheated vapor entering at state 2. As a result, saturated vapor exits at state 3. Data for steady state operation are shown on the figure. Ignoring stray heat transfer and kinetic and potential energy effects,

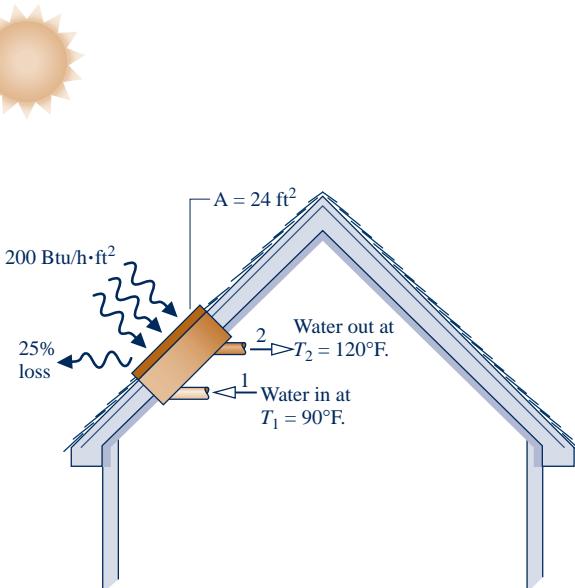


Fig. P4.79

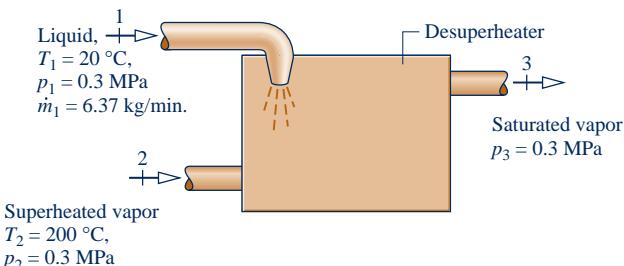
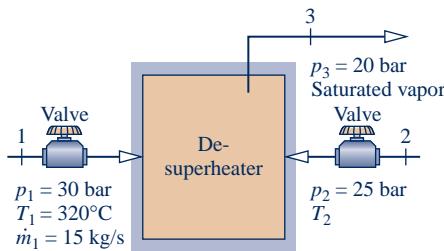


Fig. P4.82

determine the mass flow rate of the incoming superheated vapor, in kg/min.

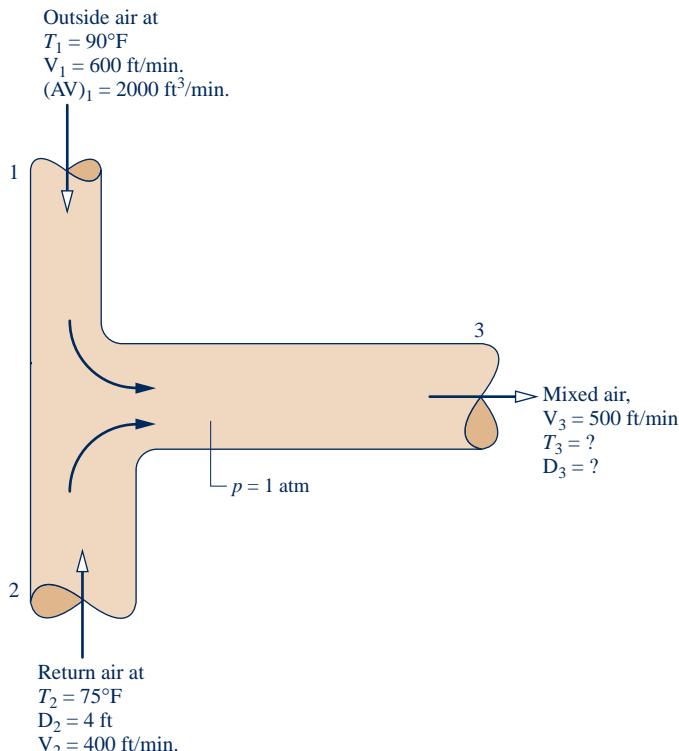
- 4.83** As shown in Fig. P4.83, 15 kg/s of steam enters a *desuperheater* operating at steady state at 30 bar, 320°C, where it is mixed with liquid water at 25 bar and temperature  $T_2$  to produce saturated vapor at 20 bar. Heat transfer between the device and its surroundings and kinetic and potential energy effects can be neglected.

- (a) If  $T_2 = 200^\circ\text{C}$ , determine the mass flow rate of liquid,  $\dot{m}_2$ , in kg/s.  
 (b) Plot  $\dot{m}_2$ , in kg/s, versus  $T_2$  ranging from 20 to 220°C.



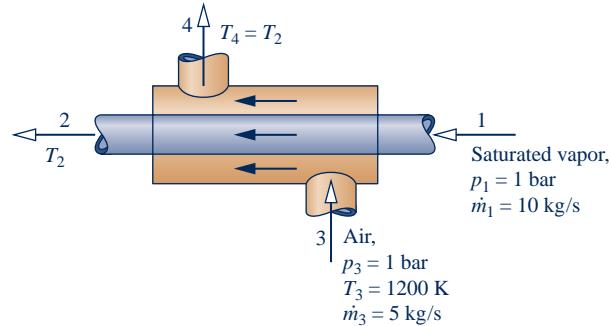
**Fig. P4.83**

- 4.84** Figure P4.84 provides steady-state data for the ducting ahead of the chiller coils in an air conditioning system. Outside air at 90°F is mixed with return air at 75°F. Stray heat transfer is negligible, kinetic and potential energy effects can be ignored, and the pressure throughout is 1 atm. Modeling the air as an ideal gas with  $c_p = 0.24 \text{ Btu/lb} \cdot \text{R}$ , determine (a) the mixed-air temperature, in °F, and (b) the diameter of the mixed-air duct, in ft.



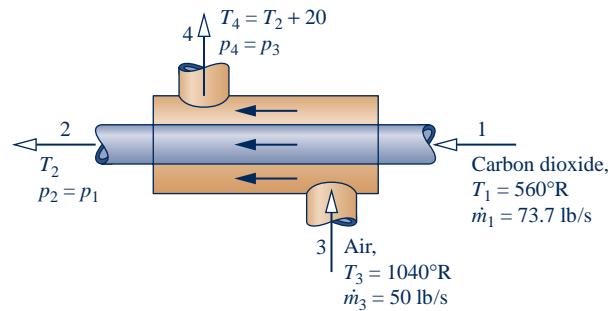
**Fig. P4.84**

- 4.85** Figure P4.85 provides steady-state operating data for a *parallel flow* heat exchanger in which there are separate streams of air and water. Each stream experiences no significant change in pressure. Stray heat transfer with the surroundings of the heat exchanger and kinetic and potential energy effects can be ignored. The ideal gas model applies to the air. If each stream exits at the same temperature, determine the value of that temperature, in K.



**Fig. P4.85**

- 4.86** Figure P4.86 provides steady-state operating data for a *parallel flow* heat exchanger in which there are separate streams of air and carbon dioxide ( $\text{CO}_2$ ). Stray heat transfer with the surroundings of the heat exchanger and kinetic and potential energy effects can be ignored. The ideal gas model applies to each gas. A constraint on heat exchanger size requires the temperature of the exiting air to be 20 degrees greater than the temperature of the exiting  $\text{CO}_2$ . Determine the exit temperature of each stream, in °R.



**Fig. P4.86**

- 4.87** Ten kg/min of cooling water circulates through a water jacket enclosing a housing filled with electronic components. At steady state, water enters the water jacket at 22°C and exits with a negligible change in pressure at a temperature that cannot exceed 26°C. There is no significant energy transfer by heat from the outer surface of the water jacket to the surroundings, and kinetic and potential energy effects can be ignored. Determine the maximum electric power the electronic components can receive, in kW, for which the limit on the temperature of the exiting water is met.

- 4.88** As shown in Fig. P4.88, electronic components mounted on a flat plate are cooled by convection to the surroundings and by liquid water circulating through a U-tube bonded to the plate. At steady state, water enters the tube at 20°C and a velocity of 0.4 m/s and exits at 24°C with a negligible

change in pressure. The electrical components receive 0.5 kW of electrical power. The rate of energy transfer by convection from the plate-mounted electronics is estimated to be 0.08 kW. Kinetic and potential energy effects can be ignored. Determine the tube diameter, in cm.

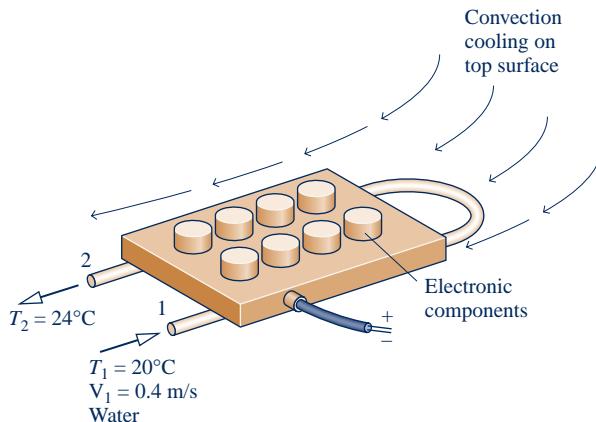


Fig. P4.88

**4.89** Ammonia enters the expansion valve of a refrigeration system at a pressure of 10 bar and a temperature of  $24^\circ\text{C}$  and exits at 1 bar. If the refrigerant undergoes a throttling process, what is the quality of the refrigerant exiting the expansion valve?

**4.90** Propane vapor enters a valve at 1.0 MPa,  $60^\circ\text{C}$ , and leaves at 0.3 MPa. If the propane undergoes a throttling process, what is the temperature of the propane leaving the valve, in  $^\circ\text{C}$ ?

**4.91** A large pipe carries steam as a two-phase liquid-vapor mixture at 1.0 MPa. A small quantity is withdrawn through a throttling calorimeter, where it undergoes a throttling process to an exit pressure of 0.1 MPa. For what range of exit temperatures, in  $^\circ\text{C}$ , can the calorimeter be used to determine the quality of the steam in the pipe? What is the corresponding range of steam quality values?

**4.92** At steady state, a valve and steam turbine operate in series. The steam flowing through the valve undergoes a throttling process. At the valve inlet, the conditions are 600 lbf/in.<sup>2</sup>,  $800^\circ\text{F}$ . At the valve exit, corresponding to the turbine inlet, the pressure is 300 lbf/in.<sup>2</sup>. At the turbine exit, the pressure is 5 lbf/in.<sup>2</sup>. The power developed by the turbine is 350 Btu per lb of steam flowing. Stray heat transfer and kinetic and potential energy effects can be ignored. Fix the state at the turbine exit: If the state is superheated vapor, determine the temperature, in  $^\circ\text{F}$ . If the state is a two-phase liquid-vapor mixture, determine the quality.

**4.93** Steam at 500 lbf/in.<sup>2</sup>,  $500^\circ\text{F}$  enters a well-insulated valve operating at steady state with a mass flow rate of 0.11 lb/s through a 1-in.-diameter pipe. The steam expands to 200 lbf/in.<sup>2</sup> with no significant change in elevation. The expansion is not necessarily a throttling process.

- (a) Determine the exit velocity, in ft/s, and the exit temperature, in  $^\circ\text{F}$ , if the ratio of inlet to exit pipe diameters,  $d_1/d_2$ , is 0.64.
- (b) To explore the effects of area change as the steam expands, plot the exit velocity, in ft/s, the exit temperature, in  $^\circ\text{F}$ , and the exit specific enthalpy, in Btu/lb, for  $d_1/d_2$  ranging from 0.25 to 4.

## Reviewing Concepts

**4.94** For review, complete the following:

- Answer the following true or false. Explain.
  - For a one-inlet, one-exit control volume at steady state, the mass flow rates at the inlet and exit are equal but the inlet and exit *volumetric* flow rates may not be equal.
  - Flow work* is the work done on a flowing stream by a paddlewheel or piston.
  - Transient* operation denotes a change in state with time.
  - In this book the flow at control volume inlets and exits is normally taken as *one-dimensional*.
  - Where mass crosses the boundary of a control volume, the accompanying energy transfer is accounted for by the internal energy of the mass only.
- Answer the following true or false. Explain.
  - A *diffuser* is a flow passage of varying cross-sectional area in which the velocity of a gas or liquid increases in the direction of flow.
  - The human body is an example of an *integrated* system.
  - When a substance undergoes a *throttling process* through a valve, the specific enthalpies of the substance at the valve inlet and valve exit are equal.
  - The hot and cold streams of *cross-flow* heat exchangers flow in the same direction.
  - The thermodynamic performance of a device such as a turbine through which mass flows is best analyzed by studying the flowing mass alone.
- Answer the following true or false. Explain.
  - For *every* control volume at steady state, the total of the entering rates of mass flow equals the total of the exiting rates of mass flow.
  - An *open feedwater* heater is a special type of a counterflow heat exchanger.
  - A key step in thermodynamic analysis is the careful listing of modeling assumptions.
  - An automobile's radiator is an example of a cross-flow heat exchanger.
  - At steady state, identical electric fans discharging air at the same temperature in New York City and Denver will deliver the same volumetric flow rate of air.

## Advanced Energy Systems at Steady State

**4.95** Figure P4.95 shows a turbine operating at a steady state that provides power to an air compressor and an electric generator. Air enters the turbine with a mass flow rate of 5.4 kg/s at  $527^\circ\text{C}$  and exits the turbine at  $107^\circ\text{C}$ , 1 bar. The turbine provides power at a rate of 900 kW to the compressor and at a rate of 1400 kW to the generator. Air can be

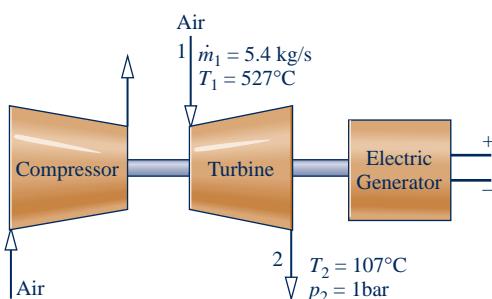


Fig. P4.95



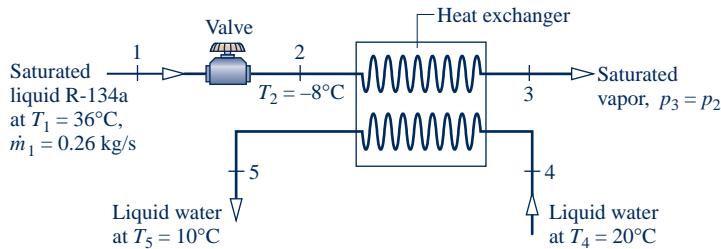


Fig. P4.96

modeled as an ideal gas, and kinetic and potential energy changes are negligible. Determine (a) the volumetric flow rate of the air at the turbine exit, in  $\text{m}^3/\text{s}$ , and (b) the rate of heat transfer between the turbine and its surroundings, in kW.

**4.96** Figure P4.96 provides steady-state data for a throttling valve in series with a heat exchanger. Saturated liquid Refrigerant 134a enters the valve at  $T_1 = 36^\circ\text{C}$  with a mass flow rate of 0.26 kg/s and is throttled to  $T_2 = -8^\circ\text{C}$ . The refrigerant then enters the heat exchanger, exiting as saturated vapor with no significant decrease in pressure. In a separate stream, liquid water enters the heat exchanger at  $T_4 = 20^\circ\text{C}$  and exits as a liquid at  $T_5 = 10^\circ\text{C}$ . Stray heat transfer and kinetic and potential energy effects can be ignored. Determine (a) the pressure at state 2, in kPa, and (b) the mass flow rate of the liquid water stream, in kg/s.

**4.97** As shown in Fig. P4.97, Refrigerant 22 enters the compressor of an air conditioning unit operating at steady state at  $40^\circ\text{F}$ ,  $80 \text{ lbf/in.}^2$  and is compressed to  $140^\circ\text{F}$ ,  $200 \text{ lbf/in.}^2$ . The refrigerant exiting the compressor enters a condenser where energy transfer to air as a separate stream occurs and the refrigerant exits as a liquid at  $200 \text{ lbf/in.}^2$ ,  $90^\circ\text{F}$ . Air enters the condenser at  $80^\circ\text{F}$ ,  $14.7 \text{ lbf/in.}^2$  with a volumetric flow rate of  $750 \text{ ft}^3/\text{min}$  and exits at  $110^\circ\text{F}$ . Neglecting stray heat transfer and kinetic and potential energy effects, and assuming ideal gas behavior for the air, determine (a) the mass flow rate of refrigerant, in  $\text{lb}/\text{min}$ , and (b) the compressor power, in horsepower.

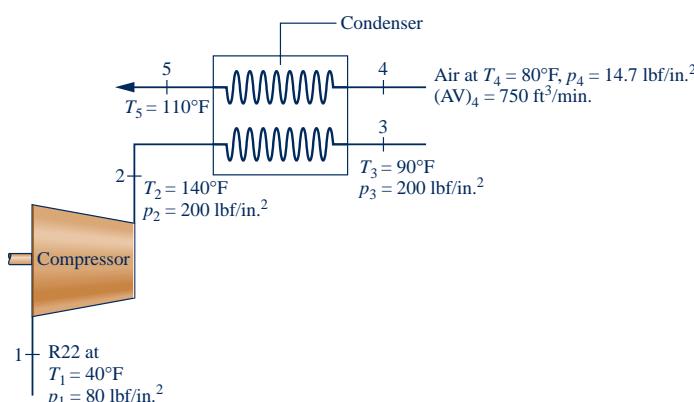


Fig. P4.97

**4.98** Fig. P4.98 shows part of a refrigeration system consisting of a heat exchanger, an evaporator, a throttling valve, and associated piping. Data for steady-state operation with Refrigerant 134a are given in the figure. There is no

significant heat transfer to or from the heat exchanger, valve, and piping. Kinetic and potential energy effects are negligible. Determine the rate of heat transfer between the evaporator and its surroundings, in Btu/h.

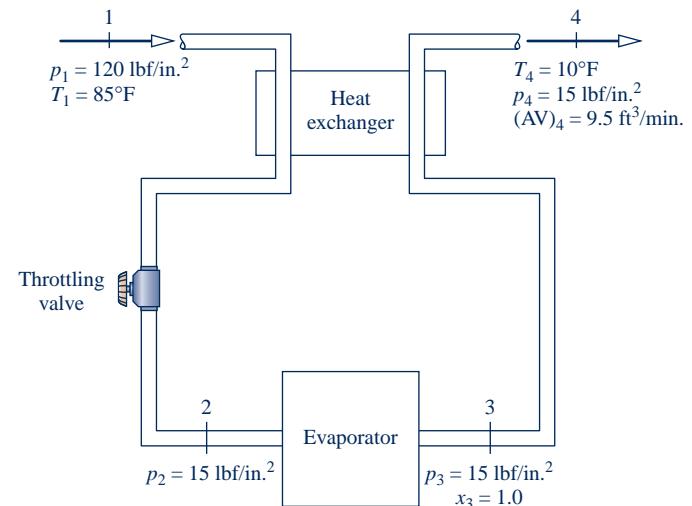


Fig. P4.98

**4.99** Refrigerant 134a enters the flash chamber operating at steady state shown in Fig. P4.99 at 10 bar,  $36^\circ\text{C}$ , with a mass flow rate of 482 kg/h. Saturated liquid and saturated vapor exit as separate streams, each at pressure  $p$ . Heat transfer to

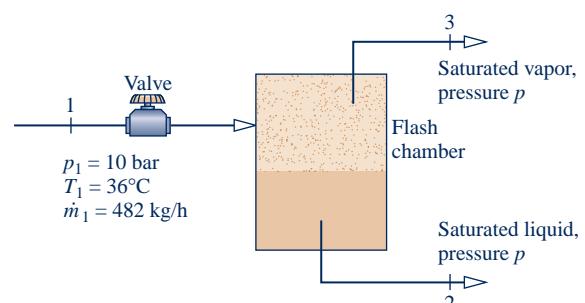


Fig. P4.99

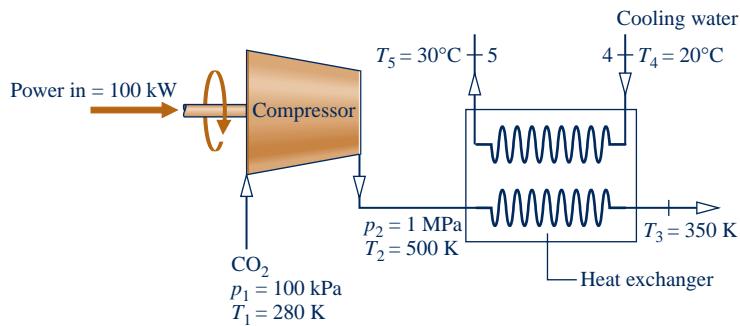


Fig. P4.100

the surroundings and kinetic and potential energy effects can be ignored.

(a) Determine the mass flow rates of the exiting streams, each in kg/h, if  $p = 4$  bar.



(b) Plot the mass flow rates of the exiting streams, each in kg/h, versus  $p$  ranging from 1 to 9 bar.

- 4.100** Carbon dioxide (CO<sub>2</sub>) modeled as an ideal gas flows through the compressor and heat exchanger shown in Fig. P4.100. The power input to the compressor is 100 kW. A separate liquid cooling water stream flows through the heat exchanger. All data are for operation at steady state. Stray heat transfer with the surroundings can be neglected, as can all kinetic and potential energy changes. Determine (a) the

mass flow rate of the CO<sub>2</sub>, in kg/s, and (b) the mass flow rate of the cooling water, in kg/s.

- 4.101** Figure P4.101 shows a *pumped-hydro* energy storage system delivering water at steady state from a lower reservoir to an upper reservoir using *off-peak* electricity (see Sec. 4.8.3). Water is delivered to the upper reservoir at a volumetric flow rate of 150 m<sup>3</sup>/s with an increase in elevation of 20 m. There is no significant change in temperature, pressure, or kinetic energy from inlet to exit. Heat transfer from the pump to its surroundings occurs at a rate of 0.6 MW and  $g = 9.81 \text{ m/s}^2$ . Determine the pump power required, in MW. Assuming the same volumetric flow rate when the system generates *on-peak* electricity using this water, will the power be greater, less, or the same as the pump power? Explain.

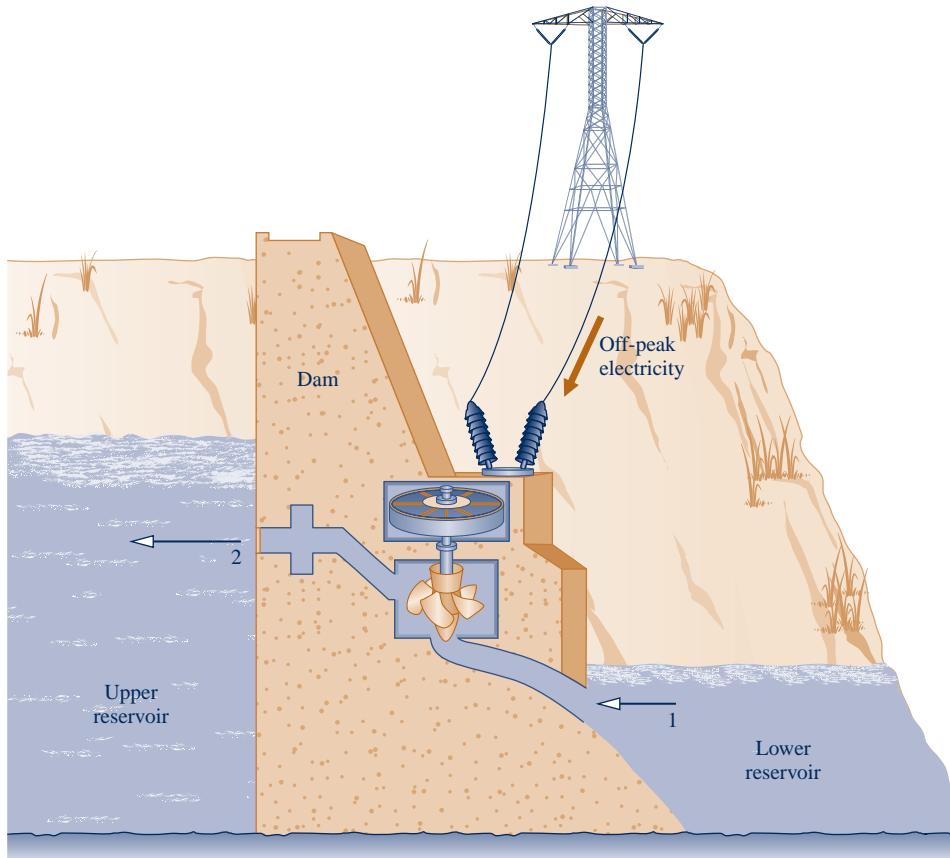


Fig. P4.101

**4.102** Steady-state operating data for a simple steam power plant are provided in Fig. P4.102. Stray heat transfer and kinetic and potential energy effects can be ignored. Determine the (a) thermal efficiency and (b) the mass flow rate of the cooling water, in kg per kg of steam flowing.

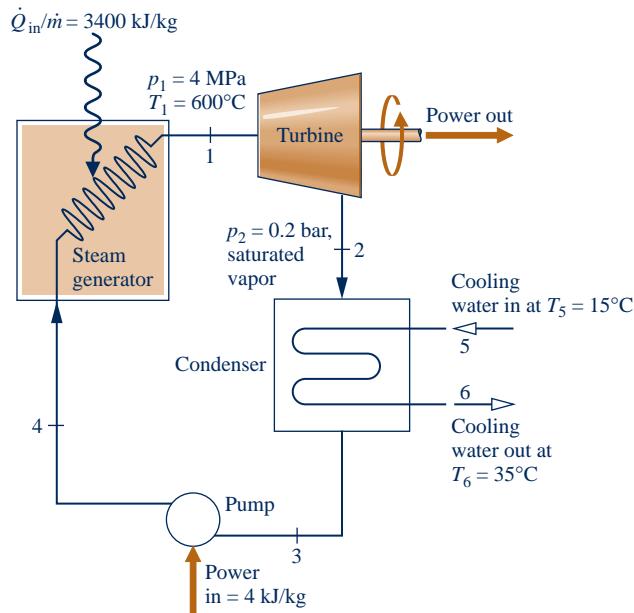


Fig. P4.102

**4.104** Figure P4.104 provides steady-state operating data for a *cogeneration system* with water vapor at 20 bar, 360°C entering at location 1. Power is developed by the system at a rate of 2.2 MW. Process steam leaves at location 2, and hot water for other process uses leaves at location 3. Evaluate the rate of heat transfer, in MW, between the system and its surroundings. Let  $g = 9.81 \text{ m/s}^2$ .

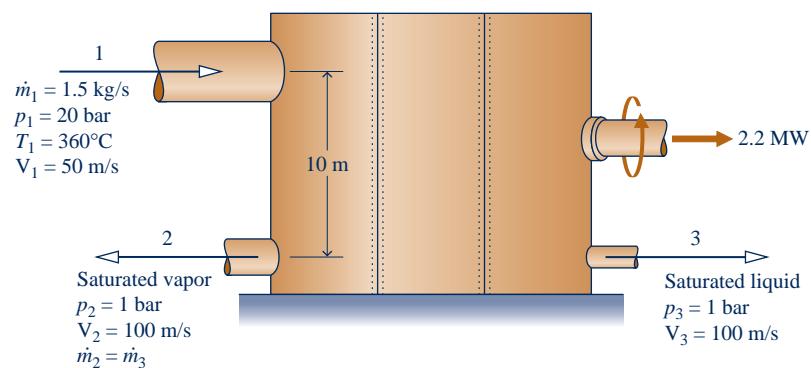


Fig. P4.104

**4.103** Steady-state operating data are provided for a compressor and heat exchanger in Fig. P4.103. The power input to the compressor is 50 kW. As shown in the figure, nitrogen ( $\text{N}_2$ ) flows through the compressor and heat exchanger with a mass flow rate of 0.25 kg/s. The nitrogen is modeled as an ideal gas. A separate cooling stream of helium, modeled as an ideal gas with  $k = 1.67$ , also flows through the heat exchanger. Stray heat transfer and kinetic and potential energy effects are negligible. Determine the mass flow rate of the helium, in kg/s.

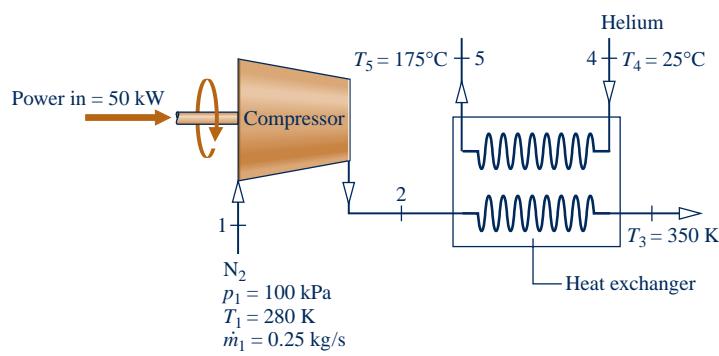


Fig. P4.103

**4.105** As shown in Fig. P4.105, hot industrial waste water at 15 bar, 180°C with a mass flow rate of 5 kg/s enters a *flash chamber* via a valve. Saturated vapor and saturated liquid streams, each at 4 bar, exit the flash chamber. The saturated vapor enters the turbine and expands to 0.08 bar,  $x = 90\%$ . Stray heat transfer and kinetic and potential energy effects are negligible. For operation at steady state, determine the power, in hp, developed by the turbine.

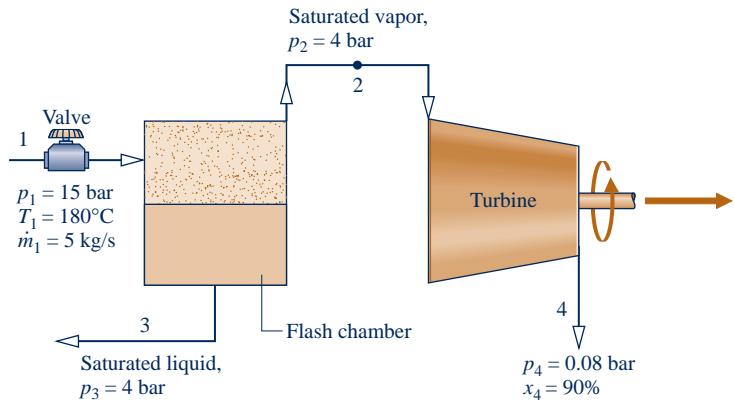


Fig. P4.105

**4.106** A simple gas turbine power cycle operating at steady state with air as the working substance is shown in Fig. P4.106. The cycle components include an air compressor mounted on the same shaft as the turbine. The air is heated in the high-pressure heat exchanger before entering the turbine. The air exiting the turbine is cooled in the low-pressure heat exchanger before returning to the compressor. Kinetic and potential effects are negligible. The compressor and turbine are adiabatic. Using the ideal gas model for air, determine the (a) power required for the compressor, in hp, (b) power output of the turbine, in hp, and (c) thermal efficiency of the cycle.

**4.107** A residential air conditioning system operates at steady state, as shown in Fig. P4.107. Refrigerant 22 circulates

through the components of the system. Property data at key locations are given on the figure. If the evaporator removes energy by heat transfer from the room air at a rate of 600 Btu/min, determine (a) the rate of heat transfer between the compressor and the surroundings, in Btu/min, and (b) the coefficient of performance.

**4.108** Separate streams of steam and air flow through the turbine and heat exchanger arrangement shown in Fig. P4.108. Steady-state operating data are provided on the figure. Heat transfer with the surroundings can be neglected, as can all kinetic and potential energy effects. Determine (a)  $T_3$ , in K, and (b) the power output of the second turbine, in kW.

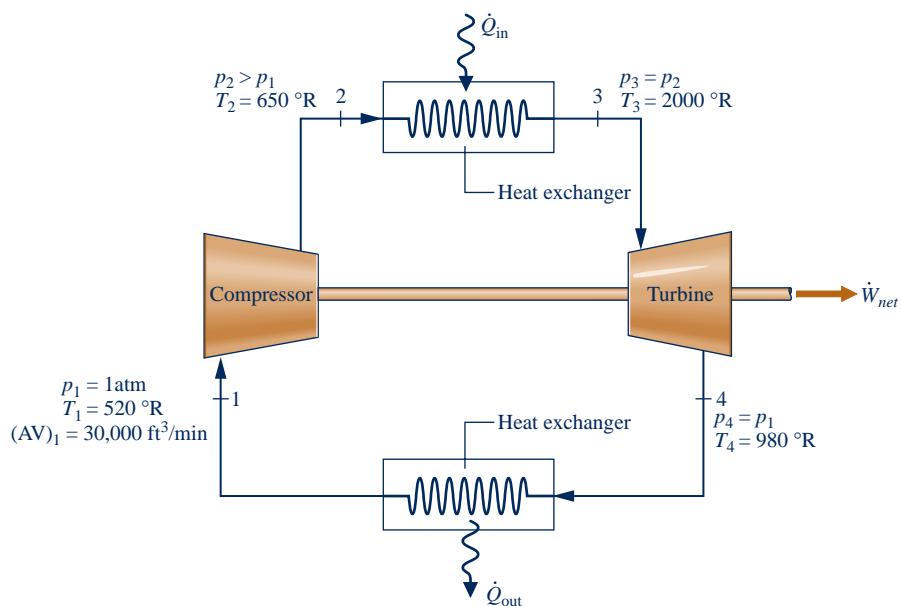


Fig. P4.106

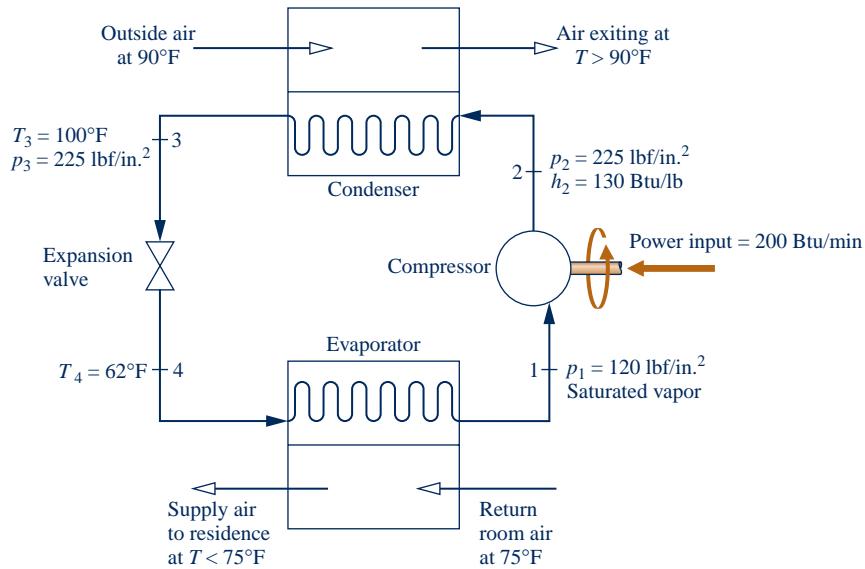


Fig. P4.107

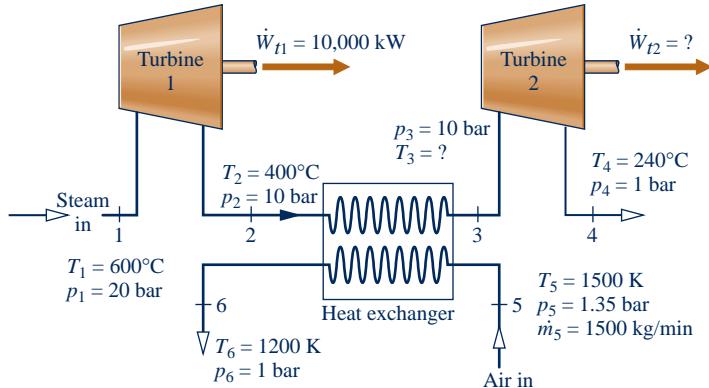


Fig. P4.108

### Transient Analysis

**4.109** A rigid tank whose volume is 10 L is initially evacuated. A pinhole develops in the wall, and air from the surroundings at 1 bar, 25°C enters until the pressure in the tank becomes 1 bar. No significant heat transfer between the contents of the tank and the surroundings occurs. Assuming the ideal gas model with  $k = 1.4$  for the air, determine (a) the final temperature in the tank, in °C, and (b) the amount of air that leaks into the tank, in g.

**4.110** A tank whose volume is 0.01 m<sup>3</sup> is initially evacuated. A pinhole develops in the wall, and air from the surroundings at 21°C, 1 bar enters until the pressure in the tank is 1 bar. If the final temperature of the air in the tank is 21°C, determine (a) the final mass in the tank, in g, and (b) the heat transfer between the tank contents and the surroundings, in kJ.

**4.111** A rigid tank whose volume is 2 m<sup>3</sup>, initially containing air at 1 bar, 295 K, is connected by a valve to a large vessel holding air at 6 bar, 295 K. The valve is opened only as long as required to fill the tank with air to a pressure of 6 bar and a temperature of 350 K. Assuming the ideal gas model for the air, determine the heat transfer between the tank contents and the surroundings, in kJ.

**4.112** An insulated, rigid tank whose volume is 0.5 m<sup>3</sup> is connected by a valve to a large vessel holding steam at 40 bar, 500°C. The tank is initially evacuated. The valve is opened only as long as required to fill the tank with steam to a pressure of 20 bar. Determine the final temperature of the steam in the tank, in °C, and the final mass of the steam in the tank, in kg.

**4.113** An insulated, rigid tank whose volume is 10 ft<sup>3</sup> is connected by a valve to a large steam line through which steam flows at 500 lbf/in.<sup>2</sup>, 800°F. The tank is initially evacuated. The valve is opened only as long as required to fill the tank with steam to a pressure of 500 lbf/in.<sup>2</sup>. Determine the final temperature of the steam in the tank, in °F, and the final mass of steam in the tank, in lb.

**4.114** Figure P4.114 provides operating data for a *compressed-air* energy storage system using *off-peak* electricity to power a compressor that fills a cavern with pressurized air (see Sec. 4.8.3). The cavern shown in the figure has a volume of 10<sup>5</sup> m<sup>3</sup> and initially holds air at 290 K, 1 bar, which corresponds to ambient air. After filling, the air in the cavern is at 790 K, 21 bar. Assuming ideal gas behavior for the air, determine (a) the initial and final mass of air in the cavern, each in kg, and (b) the work required by the compressor, in GJ. Ignore heat transfer and kinetic and potential energy effects.

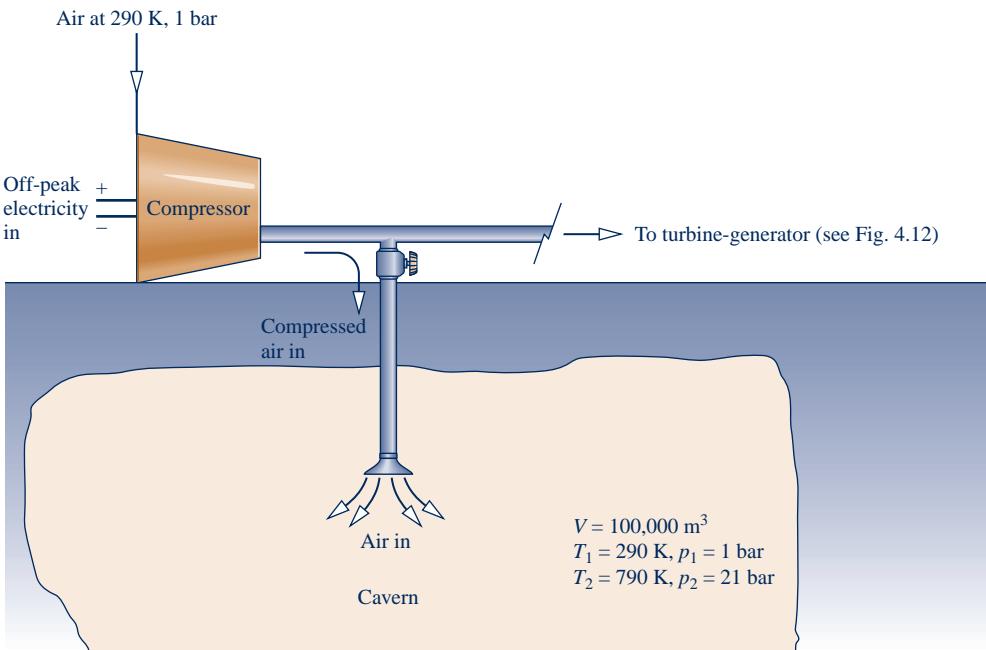


Fig. P4.114

**4.115** A rigid tank whose volume is  $0.5 \text{ m}^3$ , initially containing ammonia at  $20^\circ\text{C}$ , 1.5 bar, is connected by a valve to a large supply line carrying ammonia at 12 bar,  $60^\circ\text{C}$ . The valve is opened only as long as required to fill the tank with additional ammonia, bringing the total mass of ammonia in the tank to 143.36 kg. Finally, the tank holds a two-phase liquid-vapor mixture at  $20^\circ\text{C}$ . Determine the heat transfer between the tank contents and the surroundings, in kJ, ignoring kinetic and potential energy effects.

**4.116** As shown in Fig. P4.116, a 300-ft<sup>3</sup> tank contains  $\text{H}_2\text{O}$  initially at 30 lbf/in.<sup>2</sup> and a quality of 80%. The tank is connected to a large steam line carrying steam at 200 lbf/in.<sup>2</sup>,  $450^\circ\text{F}$ . Steam flows into the tank through a valve until the tank pressure reaches 100 lbf/in.<sup>2</sup> and the temperature is  $400^\circ\text{F}$ , at which time the valve is closed. Determine the amount of mass, in lb, that enters the tank and the heat transfer between the tank and its surroundings, in Btu.

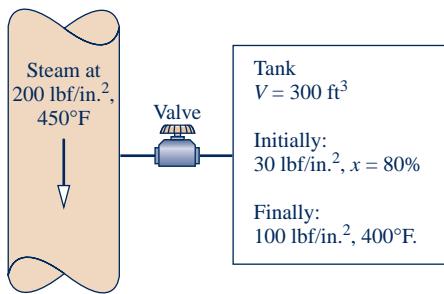


Fig. P4.116

**4.117** A rigid copper tank, initially containing  $1 \text{ m}^3$  of air at 295 K, 5 bar, is connected by a valve to a large supply line carrying air at 295 K, 15 bar. The valve is opened only as long as required to fill the tank with air to a pressure of 15 bar.

Finally, the air in the tank is at 310 K. The copper tank, which has a mass of 20 kg, is at the same temperature as the air in the tank, initially and finally. The specific heat of the copper is  $c = 0.385 \text{ kJ/kg} \cdot \text{K}$ . Assuming ideal gas behavior for the air, determine (a) the initial and final mass of air within the tank, each in kg, and (b) the heat transfer to the surroundings from the tank and its contents, in kJ, ignoring kinetic and potential energy effects.

**4.118** A rigid, insulated tank, initially containing  $0.4 \text{ m}^3$  of saturated water vapor at 3.5 bar, is connected by a valve to a large vessel holding steam at 15 bar,  $320^\circ\text{C}$ . The valve is opened only as long as required to bring the tank pressure to 15 bar. For the tank contents, determine the final temperature, in  $^\circ\text{C}$ , and final mass, in kg.

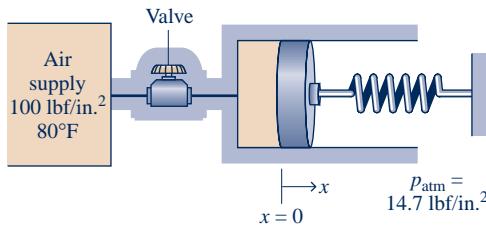
**4.119** A rigid, well-insulated tank of volume  $0.5 \text{ m}^3$  is initially evacuated. At time  $t = 0$ , air from the surroundings at 1 bar,  $21^\circ\text{C}$  begins to flow into the tank. An electric resistor transfers energy to the air in the tank at a constant rate of 100 W for 500 s, after which time the pressure in the tank is 1 bar. What is the temperature of the air in the tank, in  $^\circ\text{C}$ , at the final time?

**4.120** A well-insulated rigid tank of volume  $10 \text{ m}^3$  is connected to a large steam line through which steam flows at 15 bar and  $280^\circ\text{C}$ . The tank is initially evacuated. Steam is allowed to flow into the tank until the pressure inside is  $p$ .

- (a) Determine the amount of mass in the tank, in kg, and the temperature in the tank, in  $^\circ\text{C}$ , when  $p = 15 \text{ bar}$ .
- (b) Plot the quantities of part (a) versus  $p$  ranging from 0.1 to 15 bar.

**4.121** A well-insulated piston-cylinder assembly is connected by a valve to an air supply at 100 lbf/in.<sup>2</sup>,  $80^\circ\text{F}$ , as shown in Fig. P4.121. The air inside the cylinder is initially at 14.7 lbf/in.<sup>2</sup>,  $80^\circ\text{F}$ , and occupies a volume of  $0.1 \text{ ft}^3$ . Initially, the piston

face is located at  $x = 0$  and the spring exerts no force on the piston. The atmospheric pressure is 14.7 lbf/in.<sup>2</sup>, and the area of the piston face is 0.22 ft<sup>2</sup>. The valve is opened, and air is admitted slowly until the volume of the air inside the cylinder is 0.4 ft<sup>3</sup>. During the process, the spring exerts a force on the piston that varies according to  $F = kx$ . The ideal gas model applies for the air, and there is no friction between the piston and the cylinder wall. For the air within the cylinder, plot the final pressure, in lbf/in.<sup>2</sup>, and the final temperature, in °F, versus  $k$  ranging from 650 to 750 lbf/ft.



**Fig. P4.121**

- 4.122** A rigid tank having a volume of 0.1 m<sup>3</sup> initially contains water as a two-phase liquid–vapor mixture at 1 bar and a quality of 1%. The water is heated in two stages:

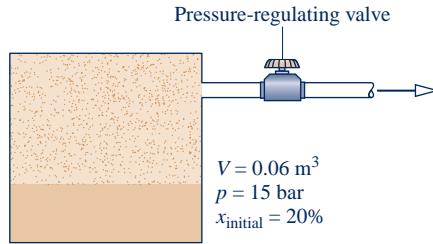
Stage 1: Constant-volume heating until the pressure is 20 bar.

Stage 2: Continued heating while saturated water vapor is slowly withdrawn from the tank at a constant pressure of 20 bar. Heating ceases when all the water remaining in the tank is saturated vapor at 20 bar.

For the water, evaluate the heat transfer, in kJ, for each stage of heating. Ignore kinetic and potential energy effects.

- 4.123** A rigid, insulated tank having a volume of 50 ft<sup>3</sup> initially contains a two-phase liquid–vapor mixture of ammonia at 100°F and a quality of 1.9%. Saturated vapor is slowly withdrawn from the tank until a two-phase liquid–vapor mixture at 80°F remains. Determine the mass of ammonia in the tank initially and finally, each in lb.

- 4.124** The rigid tank illustrated in Fig. P4.124 has a volume of 0.06 m<sup>3</sup> and initially contains a two-phase liquid–vapor mixture of H<sub>2</sub>O at a pressure of 15 bar and a quality of 20%. As the tank contents are heated, a pressure-regulating valve keeps



**Fig. P4.124**

the pressure constant in the tank by allowing saturated vapor to escape. Neglecting kinetic and potential energy effects

(a) determine the total mass in the tank, in kg, and the amount of heat transfer, in kJ, if heating continues until the final quality is  $x = 0.5$ .

(b) plot the total mass in the tank, in kg, and the amount of heat transfer, in kJ, versus the final quality  $x$  ranging from 0.2 to 1.0.

- 4.125** A well-insulated rigid tank of volume 7 ft<sup>3</sup> initially contains helium at 160°F and 30 lbf/in.<sup>2</sup> A valve connected to the tank is opened, and helium is withdrawn slowly until the pressure within the tank drops to  $p$ . An electrical resistor inside the tank maintains the temperature at 160°F.

(a) Determine the mass of helium withdrawn, in lb, and the energy input to the resistor, in Btu, when  $p = 18$  lbf/in.<sup>2</sup>

(b) Plot the quantities of part (a) versus  $p$  ranging from 15 to 30 lbf/in.<sup>2</sup>

- 4.126** A tank of volume 1 m<sup>3</sup> initially contains steam at 6 MPa and 320°C. Steam is withdrawn slowly from the tank until the pressure drops to  $p$ . Heat transfer to the tank contents maintains the temperature constant at 320°C. Neglecting all kinetic and potential energy effects,

(a) determine the heat transfer, in kJ, if  $p = 1.5$  MPa.

(b) plot the heat transfer, in kJ, versus  $p$  ranging from 0.5 to 6 MPa.

- 4.127** A 1 m<sup>3</sup> tank initially contains air at 300 kPa, 300 K. Air slowly escapes from the tank until the pressure drops to 100 kPa. The air that remains in the tank undergoes a process described by  $pv^{1.2} = \text{constant}$ . For a control volume enclosing the tank, determine the heat transfer, in kJ. Assume ideal gas behavior with constant specific heats.

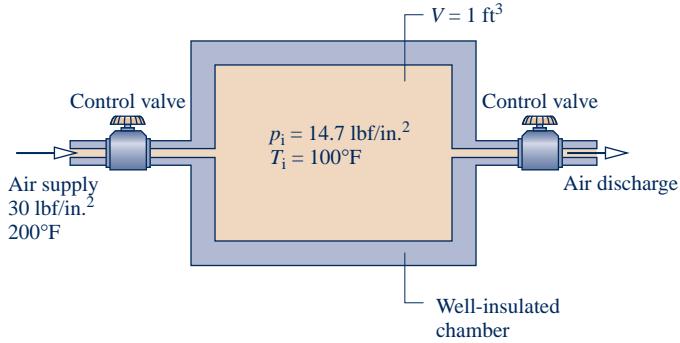
- 4.128** Nitrogen gas is contained in a rigid 1-m tank, initially at 10 bar, 300 K. Heat transfer to the contents of the tank occurs until the temperature has increased to 400 K. During the process, a pressure-relief valve allows nitrogen to escape, maintaining constant pressure in the tank. Neglecting kinetic and potential energy effects, and using the ideal gas model with constant specific heats evaluated at 350 K, determine the mass of nitrogen that escapes, in kg, and the amount of energy transfer by heat, in kJ.

- 4.129** The air supply to a 2000-ft<sup>3</sup> office has been shut off overnight to conserve utilities, and the room temperature has dropped to 40°F. In the morning, a worker resets the thermostat to 70°F, and 200 ft<sup>3</sup>/min of air at 120°F begins to flow in through a supply duct. The air is well mixed within the room, and an equal mass flow of air at room temperature is withdrawn through a return duct. The air pressure is nearly 1 atm everywhere. Ignoring heat transfer with the surroundings and kinetic and potential energy effects, estimate how long it takes for the room temperature to reach 70°F. Plot the room temperature as a function of time.

- 4.130** A well-insulated chamber of volume 1 ft<sup>3</sup> is shown in Fig. P4.130. Initially, the chamber contains air at 14.7 lbf/in.<sup>2</sup> and 100°F. Connected to the chamber are supply and discharge pipes equipped with valves that control the flow rates into and out of the chamber. The supply air is at 30 lbf/in.<sup>2</sup>, 200°F. Both valves are opened simultaneously,

allowing air to flow with a mass flow rate  $\dot{m}$  through each valve. The air within the chamber is well mixed, so the temperature and pressure at any time can be taken as uniform throughout. Neglecting kinetic and potential energy

effects, and using the ideal gas model with constant specific heats for the air, plot the temperature, in °F, and the pressure, in lbf/in.<sup>2</sup>, of the air in the chamber versus time for  $\dot{m} = 1, 2$ , and 5 lb/min.



**Fig. P4.130**

## ► DESIGN & OPEN-ENDED PROBLEMS: EXPLORING ENGINEERING PRACTICE

**4.1D** Using the Internet, identify at least five medical applications of *MEMS* technology. In each case, explain the scientific and technological basis for the application, discuss the state of current research, and determine how close the technology is in terms of commercialization. Write a report of your findings, including at least three references.

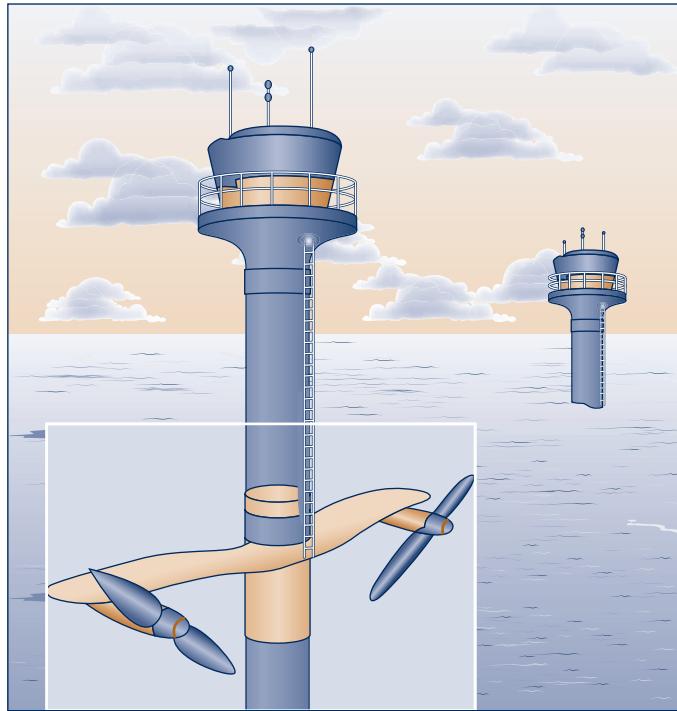
**4.2D** A group of cells called the *sinus node* is the natural pacemaker of the heart and controls the heartbeat. Sinus node dysfunction is one source of the medical condition known as heart *arrhythmia*: irregular heartbeat. Significant arrhythmias are treated in several ways, including the use of an artificial pacemaker, which is an electrical device that sends the signals needed to make the heart beat properly. Research how both natural and artificial pacemakers operate to achieve their goal of maintaining a regular heartbeat. Place your findings in a memorandum that includes annotated sketches of each type of pacemaker.

**4.3D** Conduct a term-length project centered on using a *low-wind* turbine to meet the electricity needs of a small business, farm, or neighborhood selected by, or assigned to, your project group. Take several days to research the project and then prepare a brief written plan having a statement of purpose, a list of objectives, and several references. As part of your plan, schedule on-site wind-speed measurements for at least three different days to achieve a good match between the requirements of candidate low-wind turbines and local conditions. Your plan also should recognize the need for compliance with applicable zoning codes. During the project, observe good

practices such as discussed in Sec. 1.3 of *Thermal Design and Optimization*, John Wiley & Sons Inc., New York, 1996, by A. Bejan, G. Tsatsaronis, and M.J. Moran. Provide a well-documented report, including an assessment of the economic viability of the selected turbine for the application considered.

**4.4D** Generation of electricity by harnessing currents, waves, and tides is being studied across the globe. Electricity can be generated from currents using underwater turbines, as illustrated in Fig. P4.4D. Electricity also can be generated from the *undulating motion* of waves using tethered buoys. Like means can be used to generate power from tidal movements. Although currents and waves have long been used to meet relatively modest power needs, many observers today are thinking of large-scale power generation systems. Some see the oceans as providing a nearly unlimited renewable source of power. For a site in U.S. coastal waters, estuaries, or rivers, critically evaluate the viability of currents and/or waves for large-scale power generation by 2025. Consider technical and economic factors and effects on the ecosystem. Write a report including at least three references.

**4.5D** Owing to their relatively compact size, simple construction, and modest power requirement, centrifugal-type blood pumps are under consideration for several medical applications. Still, centrifugal pumps have met with limited success thus far for blood flow because they can cause damage to blood cells and are subject to mechanical failure. The goal of current development efforts is a device having sufficient long-term biocompatibility, performance, and reliability for widespread deployment. Investigate the status of centrifugal blood pump



**Fig. P4.4D**

development, including identifying key technical challenges and prospects for overcoming them. Summarize your findings in a report, including at least three references.

**4.6D** Identify sites in your state where wind turbines for utility-scale electrical generation are feasible but do not yet exist. Prepare a memorandum to an appropriate governing or corporate entity with your recommendations as to whether wind-turbine electrical generation should be developed at the most promising sites. Consider engineering, economic, and societal aspects.

**4.7D** Recent disasters, including major oil spills, floods, hurricanes, and tsunamis have revealed the vulnerability of municipal water distribution systems to water-borne contamination. For the water distribution system of a municipality selected by, or assigned to, your project group, study the existing procedure for restoring the system to safe use after contamination. If no suitable decontamination procedure exists, make recommendations. Suggest easy-to-implement, cost-effective, environmentally-responsible measures. Document your findings in a memorandum.

**4.8D** The technical literature contains discussions of ways for using tethered kite-mounted wind turbine systems to harvest power from high-altitude winds, including jet streams at elevations from 6 to 15 kilometers (4 to 9 miles). Analysts estimate that if such systems were deployed in sufficient numbers, they could meet a significant share of total U.S. demand for electricity. Critically evaluate the feasibility of such a kite system, selected from the existing literature, to be fully operational by 2025. Consider means for deploying the system to the proper altitude, how the

power developed is transferred to earth, infrastructure requirements, environmental impact, cost, and other pertinent issues. Write a report including at least three references.

**4.9D** Forced-air warming systems involving inflatable thermal blankets commonly are used to prevent subnormal body temperature (hypothermia) during and following surgery. A heater and blower provide a stream of warmed air to the blanket. While the air temperature leaving the heater/blower is monitored by a temperature sensor, the temperature of the air providing warming to patients can vary widely, causing in some instances overheating and localized burning of patients. The object of this project is to develop cost-effective modifications of existing thermal blankets that would control the air temperature and eliminate injurious “hot spots.” The modifications must conform to standards governing the safety of systems involving heating in medical applications. Summarize your conclusions in a report, including sample calculations and at least three references.

**4.10D** Residential *integrated systems* capable of generating electricity and providing space heating and water heating will reduce reliance on electricity supplied from central power plants. For a 2500-ft<sup>2</sup> dwelling in your locale, evaluate two alternative technologies for combined power and heating: a solar energy-based system and a natural gas fuel cell system. For each alternative, specify equipment and evaluate costs, including the initial system cost, installation cost, and operating cost. Compare total cost with that for conventional means for powering and heating the dwelling. Write a report summarizing your

analysis and recommending either or both of the options if they are preferable to conventional means.

**4.11D** Figure P4.11D provides the schematic of a device for producing a combustible fuel gas for transportation from biomass. While several types of solid biomass can be employed in current gasifier designs, wood chips are commonly used. Wood chips are introduced at the top of the gasifier unit. Just below this level, the chips react with oxygen in the combustion air to produce charcoal. At the next depth, the charcoal reacts with hot combustion gases from the charcoal-formation stage to produce a fuel gas consisting mainly of hydrogen, carbon monoxide, and nitrogen from the combustion air. The fuel gas is then cooled, filtered, and ducted to the internal combustion engine served by the gasifier. Critically evaluate the suitability of this technology for transportation use today in the event of a prolonged petroleum shortage in your locale. Document your conclusions in a memorandum.

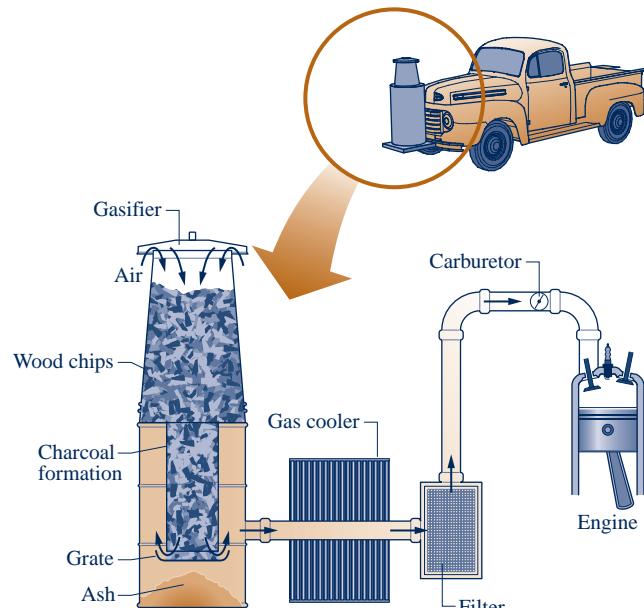


Fig. P4.11D