

SEVENTH EDITION

# Fundamentals of Thermodynamics

BORGNAKKE

|

SONNTAG







# Preface

In this seventh edition we have retained the basic objective of the earlier editions:

- to present a comprehensive and rigorous treatment of classical thermodynamics while retaining an engineering perspective, and in doing so
- to lay the groundwork for subsequent studies in such fields as fluid mechanics, heat transfer, and statistical thermodynamics, and also
- to prepare the student to effectively use thermodynamics in the practice of engineering.

We have deliberately directed our presentation to students. New concepts and definitions are presented in the context where they are first relevant in a natural progression. The first thermodynamic properties to be defined (Chapter 2) are those that can be readily measured: pressure, specific volume, and temperature. In Chapter 3, tables of thermodynamic properties are introduced, but only in regard to these measurable properties. Internal energy and enthalpy are introduced in connection with the first law, entropy with the second law, and the Helmholtz and Gibbs functions in the chapter on thermodynamic relations. Many real world realistic examples have been included in the book to assist the student in gaining an understanding of thermodynamics, and the problems at the end of each chapter have been carefully sequenced to correlate with the subject matter, and are grouped and identified as such. The early chapters in particular contain a much larger number of examples, illustrations and problems than in previous editions, and throughout the book, chapter-end summaries are included, followed by a set of concept/study problems that should be of benefit to the students.

## NEW FEATURES IN THIS EDITION

### In-Text-Concept Question

For this edition we have placed concept questions in the text after major sections of material to allow students to reflect on the material just presented. These questions are intended to be quick self tests for students or used by teachers as wrap up checks for each of the subjects covered. Most of these are straightforward conclusions from the material without being memory facts, but a few will require some extended thoughts and we do provide a short answer in the solution manual. Additional concept questions are placed as homework problems at the end of each chapter.

### End-of-Chapter Engineering Applications

We have added a short section at the end of each chapter that we call engineering applications. These sections present motivating material with informative examples of how the particular chapter material is being used in engineering. The vast majority of these sections do not have any material with equations or developments of theory but they do contain pictures



and explanations about a few real physical systems where the chapter material is relevant for the engineering analysis and design. We have deliberately kept these sections short and we do not try to explain all the details in the devices shown so the reader can get an idea about the applications in a relatively short time. For some of the later chapters where the whole chapter could be characterized as an engineering application this section can be a little involved including formulas and theory. We have placed these sections in the end of the chapters so we do not disrupt the main flow of the presentation, but we do suggest that each instructor try to incorporate some of this material up front as motivation for students to study this particular chapter material.

### Chapter of Power and Refrigeration Cycles Split into Two Chapters

The previous edition Chapter 11 with power and refrigeration systems has been separated into two chapters, one with cycles involving a change of phase for the working substance and one chapter with gas cycles. We added some material to each of the two chapters, but kept the balance between them.

We have added a section about refrigeration cycle configurations and included new substances as alternative refrigerants R-410a and carbon dioxide in the printed B-section tables. This does allow for a more modern treatment and examples with current system design features.

The gas cycles have been augmented by the inclusion of the Atkinson and Miller cycles. These cycles are important for the explanations of the cycle variations that are being used for the new hybrid car engines and this allows us to present material that is relevant to the current state of the art technology.

### Chapter with Compressible Flow

For this edition we have been able to again offer the chapter with compressible flow last printed in the 5th edition. In-Text Concept questions, concept study-guide problems and new homework problems are included to match the rest of the book.

## FEATURES CONTINUED FROM 6TH EDITION

### End-of-Chapter Summaries

The new end-of-chapter summaries provide a short review of the main concepts covered in the chapter, with highlighted key words. To further enhance the summary we have listed the set of skills that the student should have mastered after studying the chapter. These skills are among the outcomes that can be tested with the accompanying set of study-guide problems in addition to the main set of homework problems.

### Main Concepts and Formulas

Main concepts and formulas are included at the end of each chapter, for reference and a collection of these will be available on Wiley's website.

### Study Guide Problems

We have revised the set of study guide problems for each chapter as a quick check of the chapter material. These are selected to be short and directed toward a very specific concept. A student can answer all of these questions to assess their level of understanding, and

determine if any of the subjects need to be studied further. These problems are also suitable to use together with the rest of the homework problems in assignments and included in the solution manual.

## Homework Problems

The number of homework problems has been greatly expanded and now exceeds 2800. A large number of introductory problems have been added to cover all aspects of the chapter material. We have furthermore separated the problems into sections according to subject for easy selection according to the particular coverage given. A number of more comprehensive problems have been retained and grouped in the end as **review problems**.

## Tables

The tables of the substances have been expanded to include **alternative refrigerant R-410a** which is the replacement for R-22 and **carbon dioxide** which is a natural refrigerant. Several more new substance have been included in the software. The ideal gas tables have been printed on a mass basis as well as a mole basis, to reflect their use on mass basis early in the text, and mole basis for the combustion and chemical equilibrium chapters.

## Revisions

In this edition we have incorporated a number of developments and approaches included in our recent textbook, *Introduction to Engineering Thermodynamics*, Richard E. Sonntag and Claus Borgnakke, John Wiley & Sons, Inc. (2001).

In Chapter 3, we first introduce thermodynamic tables, and then note the behavior of superheated vapor at progressively lower densities, which leads to the definition of the ideal gas model. Also to distinguish the different subjects we made separate sections for the compressibility factor, equations of state and the computerized tables.

In Chapter 5, the result of ideal gas energy depending only on temperature follows the examination of steam table values at different temperatures and pressures.

Second law presentation in Chapter 7 is streamlined, with better integration of the concepts of thermodynamic temperature and ideal gas temperature. We have also expanded the discussion about temperature differences in the heat transfer as it influences the heat engine and heat pump cycles and finally added a short listing of historical events related to thermodynamics.

The coverage of entropy in Chapter 8 has been rearranged to have sections with entropy for solids/liquids and ideal gases followed by the polytropic processes before the treatment of the irreversible processes. This completes the presentation of the entropy and its evaluation for different phases and variation in different reversible processes before proceeding to the actual processes. The description of entropy generation in actual processes has been strengthened. It is now more specific with respect to the location of the irreversibilities and clearly connecting this to the selected control volume. We have also added an example to tie the entropy to the concept of chaos at the molecular level giving a real physical meaning to the abstract concept of entropy.

The analysis for the general control volume in Chapter 9 is extended with the presentation of the actual shaft work for the steady state single flow processes leading to the simplified version in the Bernoulli equation. We again here reinforce the concept of entropy generation and where it happens. We have added a new section with a

comprehensive step by step presentation of a control volume analysis which really is the essence of what students should learn.

A revision of the reversible work and exergy in Chapter 10 has reduced the number of equations and focused on the basic idea leading to the concept of reversible work and irreversibility. We emphasize that a specific situation is a simplification of the general analysis and we then show the exergy comes from the reversible work. This makes the final exergy balance equation less abstract and its use is explained in the section with engineering applications.

The previous single chapter with cycles has been separated into two chapters as explained above as a new feature in this edition.

Mixtures and moist air in Chapter 13 is retained but we have added a number of practical air-conditioning systems and components as examples in the section with engineering applications.

The chapter with property relations has been updated to include the modern development of thermodynamic tables. This introduces the fitting of a dimensionless Helmholtz function to experimental data and explains the principles of how the current set of tables are calculated.

Combustion is enhanced with a description of the distillation column and the mentioning of current fuel developments. We have reduced the number examples related to the second law and combustion by mentioning the main effects instead. On the other hand we added a model of the fuel cell to make this subject more interesting and allow some computations of realistic fuel cell performance. Some practical aspects of combustion have been moved into the section with engineering applications.

Chemical equilibrium is made more relevant by a section with coal gasification that relies on some equilibrium processes. We also added a NO<sub>x</sub> formation model in the engineering application section to show how this depends on chemical equilibrium and leads in to more advanced studies of reaction rates in general.

## Expanded Software Included

In this edition we have included access to the extended software **CATT3** that includes a number of additional substances besides those included in the printed tables in Appendix B. (See registration card inside front cover.) The current set of substances for which the software can do the complete tables are:

Water

Refrigerants: R-11, 12, 13, 14, 21, 22, 23, 113, 114, 123, 134a, 152a, 404a, 407c, 410a, 500, 502, 507a and C318

Cryogenics: Ammonia, argon, ethane, ethylene, iso-butane, methane, neon, nitrogen, oxygen and propane

Ideal Gases: air, CO<sub>2</sub>, CO, N, N<sub>2</sub>, NO, NO<sub>2</sub>, H, H<sub>2</sub>, H<sub>2</sub>O, O, O<sub>2</sub>, OH

Some of these are printed in the booklet *Thermodynamic and Transport Properties*, Claus Borgnakke and Richard E. Sonntag, John Wiley and Sons, 1997. Besides the properties of the substances just mentioned the software can do the psychrometric chart and the compressibility and generalized charts using Lee-Keslers equation-of-state including an extension for increased accuracy with the acentric factor. The software can also plot a limited number of processes in the T-s and log P-log v diagrams giving the real process curves instead of the sketches presented in the text material.

## FLEXIBILITY IN COVERAGE AND SCOPE

We have attempted to cover fairly comprehensively the basic subject matter of classical thermodynamics, and believe that the book provides adequate preparation for study of the application of thermodynamics to the various professional fields as well as for study of more advanced topics in thermodynamics, such as those related to materials, surface phenomena, plasmas, and cryogenics. We also recognize that a number of colleges offer a single introductory course in thermodynamics for all departments, and we have tried to cover those topics that the various departments might wish to have included in such a course. However, since specific courses vary considerably in prerequisites, specific objectives, duration, and background of the students, we have arranged the material, particularly in the later chapters, so that there is considerable flexibility in the amount of material that may be covered.

In general we have expanded the number of sections in the material to make it easier to select and choose the coverage.

### Units

Our philosophy regarding units in this edition has been to organize the book so that the course or sequence can be taught entirely in SI units (Le Système International d'Unités). Thus, all the text examples are in SI units, as are the complete problem sets and the thermodynamic tables. In recognition, however, of the continuing need for engineering graduates to be familiar with English Engineering units, we have included an introduction to this system in Chapter 2. We have also repeated a sufficient number of examples, problems, and tables in these units, which should allow for suitable practice for those who wish to use these units. For dealing with English units, the force-mass conversion question between pound mass and pound force is treated simply as a units conversion, without using an explicit conversion constant. Throughout, symbols, units and sign conventions are treated as in previous editions.

### Supplements and Additional Support

Additional support is made available through the website at [www.wiley.com/college/borgnakke](http://www.wiley.com/college/borgnakke). Through this there is access to tutorials and reviews of all the basic material through **Thermonet** also indicated in the main text. This allows students to go through a self-paced study developing the basic skill set associated with the various subjects usually covered in a first course in thermodynamics.

We have tried to include material appropriate and sufficient for a two-semester course sequence, and to provide flexibility for choice of topic coverage. Instructors may want to visit the publisher's Website at [www.wiley.com/college/borgnakke](http://www.wiley.com/college/borgnakke) for information and suggestions on possible course structure and schedules, additional study problem material, and current errata for the book.

## ACKNOWLEDGMENTS

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We also wish to welcome our new editor Mike McDonald and thank him for the encouragement and help during the production of this edition.

Our hope is that this book will contribute to the effective teaching of thermodynamics to students who face very significant challenges and opportunities during their professional careers. Your comments, criticism, and suggestions will also be appreciated and you may channel that through Claus Borgnakke, [claus@umich.edu](mailto:claus@umich.edu).

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# Symbols

$a$	acceleration
$A$	area
$a, A$	specific Helmholtz function and total Helmholtz function
$AF$	air-fuel ratio
$B_S$	adiabatic bulk modulus
$B_T$	isothermal bulk modulus
$c$	velocity of sound
$c$	mass fraction
$C_D$	coefficient of discharge
$C_p$	constant-pressure specific heat
$C_v$	constant-volume specific heat
$C_{po}$	zero-pressure constant-pressure specific heat
$C_{vo}$	zero-pressure constant-volume specific heat
COP	coefficient of performance
CR	compression ratio
$e, E$	specific energy and total energy
EMF	electromotive force
$F$	force
$FA$	fuel-air ratio
$g$	acceleration due to gravity
$g, G$	specific Gibbs function and total Gibbs function
$h, H$	specific enthalpy and total enthalpy
HV	heating value
$i$	electrical current
$I$	irreversibility
$J$	proportionality factor to relate units of work to units of heat
$k$	specific heat ratio: $C_p/C_v$
$K$	equilibrium constant
KE	kinetic energy
$L$	length
$m$	mass
$\dot{m}$	mass flow rate
$M$	molecular mass
$M$	Mach number
$n$	number of moles
$n$	polytropic exponent
$P$	pressure
$P_i$	partial pressure of component $i$ in a mixture
PE	potential energy

	$P_r$	reduced pressure $P/P_c$
	$P_r$	relative pressure as used in gas tables
	$q, Q$	heat transfer per unit mass and total heat transfer
	$\dot{Q}$	rate of heat transfer
	$Q_H, Q_L$	heat transfer with high-temperature body and heat transfer with low-temperature body; sign determined from context
	$R$	gas constant
	$\bar{R}$	universal gas constant
	$s, S$	specific entropy and total entropy
	$S_{\text{gen}}$	entropy generation
	$\dot{S}_{\text{gen}}$	rate of entropy generation
	$t$	time
	$T$	temperature
	$T_r$	reduced temperature $T/T_c$
	$u, U$	specific internal energy and total internal energy
	$v, V$	specific volume and total volume
	$v_r$	relative specific volume as used in gas tables
	$\mathbf{V}$	velocity
	$w, W$	work per unit mass and total work
	$\dot{W}$	rate of work, or power
	$w^{\text{rev}}$	reversible work between two states
	$x$	quality
	$y$	gas-phase mole fraction
	$y$	extraction fraction
	$Z$	elevation
	$Z$	compressibility factor
	$Z$	electrical charge
SCRIPT LETTERS	$\mathcal{E}$	electrical potential
	$\mathcal{S}$	surface tension
	$\mathcal{T}$	tension
GREEK LETTERS	$\alpha$	residual volume
	$\alpha$	dimensionless Helmholtz function $a/RT$
	$\alpha_p$	volume expansivity
	$\beta$	coefficient of performance for a refrigerator
	$\beta'$	coefficient of performance for a heat pump
	$\beta_s$	adiabatic compressibility
	$\beta_T$	isothermal compressibility
	$\delta$	dimensionless density $\rho/\rho_c$
	$\eta$	efficiency
	$\mu$	chemical potential
	$\nu$	stoichiometric coefficient
	$\rho$	density
	$\tau$	dimensionless temperature variable $T_c/T$
	$\tau_0$	dimensionless temperature variable $1 - T_r$
	$\Phi$	equivalence ratio
	$\phi$	relative humidity

	$\phi, \Phi$	exergy or availability for a control mass
	$\psi$	exergy, flow availability
	$\omega$	humidity ratio or specific humidity
	$\omega$	acentric factor
SUBSCRIPTS	$c$	property at the critical point
	c.v.	control volume
	$e$	state of a substance leaving a control volume
	$f$	formation
	$f$	property of saturated liquid
	$fg$	difference in property for saturated vapor and saturated liquid
	$g$	property of saturated vapor
	$i$	state of a substance entering a control volume
	$i$	property of saturated solid
	$if$	difference in property for saturated liquid and saturated solid
	$ig$	difference in property for saturated vapor and saturated solid
	$r$	reduced property
	$s$	isentropic process
	0	property of the surroundings
	0	stagnation property
SUPERSCRIPTS	—	bar over symbol denotes property on a molal basis (over $V, H, S, U, A, G$ , the bar denotes partial molal property)
	°	property at standard-state condition
	*	ideal gas
	*	property at the throat of a nozzle
	irr	irreversible
	r	real gas part
	rev	reversible



*Fundamental Physical Constants*

Avogadro	$N_0 = 6.022\,1415 \times 10^{23} \text{ mol}^{-1}$
Boltzmann	$k = 1.380\,6505 \times 10^{-23} \text{ J K}^{-1}$
Planck	$h = 6.626\,0693 \times 10^{-34} \text{ Js}$
Gas Constant	$\bar{R} = N_0 k = 8.314\,472 \text{ J mol}^{-1} \text{ K}^{-1}$
Atomic Mass Unit	$m_0 = 1.660\,538\,86 \times 10^{-27} \text{ kg}$
Velocity of light	$c = 2.997\,924\,58 \times 10^8 \text{ ms}^{-1}$
Electron Charge	$e = 1.602\,176\,53 \times 10^{-19} \text{ C}$
Electron Mass	$m_e = 9.109\,3826 \times 10^{-31} \text{ kg}$
Proton Mass	$m_p = 1.672\,621\,71 \times 10^{-27} \text{ kg}$
Gravitation (Std.)	$g = 9.806\,65 \text{ ms}^{-2}$
Stefan Boltzmann	$\sigma = 5.670\,400 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$

Mol here is gram mol.

*Prefixes*

$10^{-1}$	deci	d
$10^{-2}$	centi	c
$10^{-3}$	milli	m
$10^{-6}$	micro	$\mu$
$10^{-9}$	nano	n
$10^{-12}$	pico	p
$10^{-15}$	femto	f
$10^1$	deka	da
$10^2$	hecto	h
$10^3$	kilo	k
$10^6$	mega	M
$10^9$	giga	G
$10^{12}$	tera	T
$10^{15}$	peta	P

*Concentration*

$10^{-6}$  parts per million ppm





# Some Introductory Comments

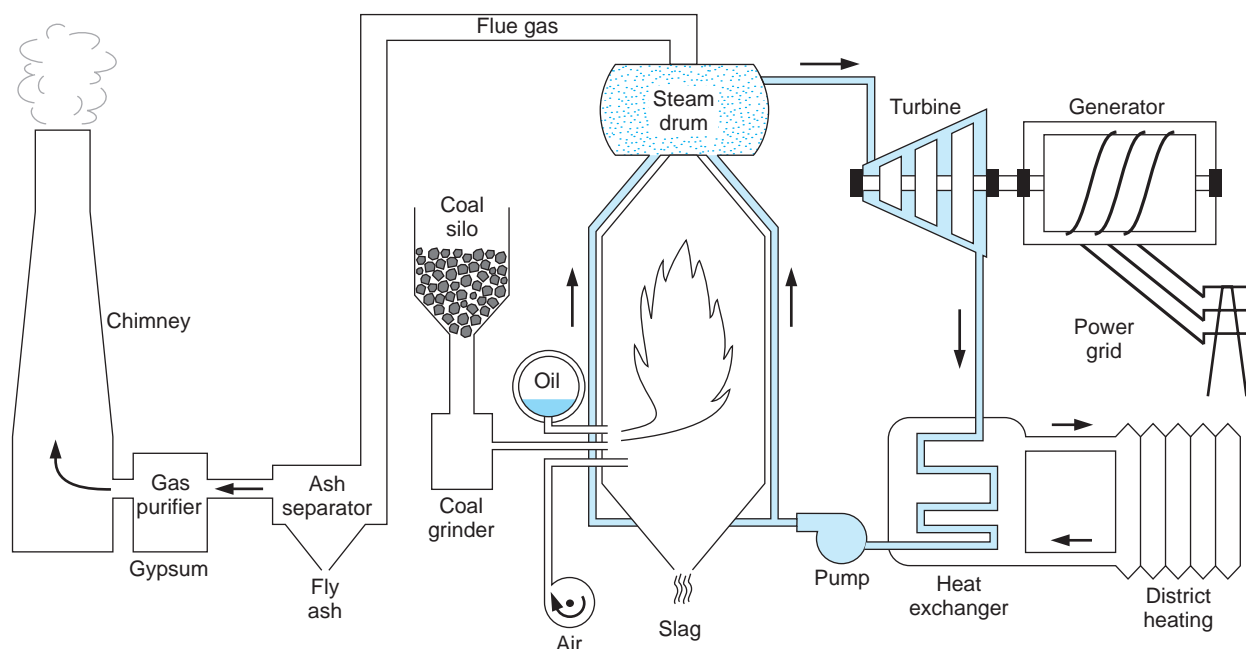
In the course of our study of thermodynamics, a number of the examples and problems presented refer to processes that occur in equipment such as a steam power plant, a fuel cell, a vapor-compression refrigerator, a thermoelectric cooler, a turbine or rocket engine, and an air separation plant. In this introductory chapter, a brief description of this equipment is given. There are at least two reasons for including such a chapter. First, many students have had limited contact with such equipment, and the solution of problems will be more meaningful when they have some familiarity with the actual processes and the equipment. Second, this chapter will provide an introduction to thermodynamics, including the use of certain terms (which will be more formally defined in later chapters), some of the problems to which thermodynamics can be applied, and some of the things that have been accomplished, at least in part, from the application of thermodynamics.

Thermodynamics is relevant to many processes other than those cited in this chapter. It is basic to the study of materials, chemical reactions, and plasmas. The student should bear in mind that this chapter is only a brief and necessarily incomplete introduction to the subject of thermodynamics.

## 1.1 THE SIMPLE STEAM POWER PLANT

A schematic diagram of a recently installed steam power plant is shown in Fig. 1.1. High-pressure superheated steam leaves the steam drum at the top of the boiler, also referred to as a *steam generator*, and enters the turbine. The steam expands in the turbine and in doing so does work, which enables the turbine to drive the electric generator. The steam, now at low pressure, exits the turbine and enters the heat exchanger, where heat is transferred from the steam (causing it to condense) to the cooling water. Since large quantities of cooling water are required, power plants have traditionally been located near rivers or lakes, leading to thermal pollution of those water supplies. More recently, condenser cooling water has been recycled by evaporating a fraction of the water in large cooling towers, thereby cooling the remainder of the water that remains as a liquid. In the power plant shown in Fig. 1.1, the plant is designed to recycle the condenser cooling water by using the heated water for district space heating.

The pressure of the condensate leaving the condenser is increased in the pump, enabling it to return to the steam generator for reuse. In many cases, an economizer or water preheater is used in the steam cycle, and in many power plants, the air that is used for combustion of the fuel may be preheated by the exhaust combustion-product gases. These exhaust gases must also be purified before being discharged to the atmosphere, so there are many complications to the simple cycle.



**FIGURE 1.1** Schematic diagram of a steam power plant.

Figure 1.2 is a photograph of the power plant depicted in Fig. 1.1. The tall building shown at the left is the boiler house, next to which are buildings housing the turbine and other components. Also noted are the tall chimney, or stack, and the coal supply ship at the dock. This particular power plant is located in Denmark, and at the time of its installation it set a world record for efficiency, converting 45% of the 850 MW of coal combustion energy into electricity. Another 47% is reusable for district space heating, an amount that in older plants was simply released to the environment, providing no benefit.

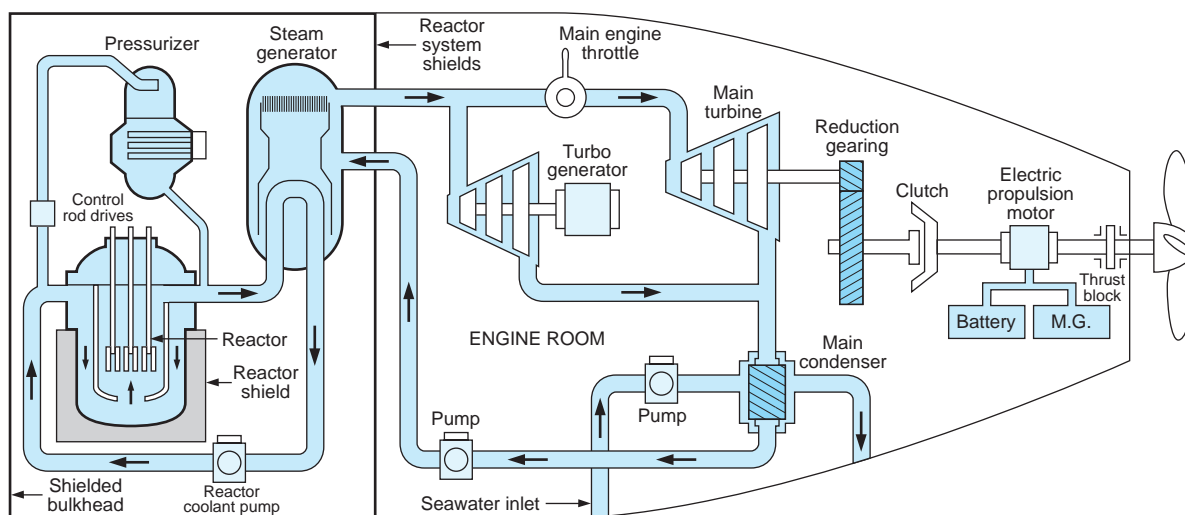
The steam power plant described utilizes coal as the combustion fuel. Other plants use natural gas, fuel oil, or biomass as the fuel. A number of power plants around the world operate on the heat released from nuclear reactions instead of fuel combustion. Figure 1.3 is a schematic diagram of a nuclear marine propulsion power plant. A secondary fluid circulates through the reactor, picking up heat generated by the nuclear reaction inside. This heat is then transferred to the water in the steam generator. The steam cycle processes are the same as in the previous example, but in this application the condenser cooling water is seawater, which is then returned at higher temperature to the sea.

## 1.2 FUEL CELLS

When a conventional power plant is viewed as a whole, as shown in Fig. 1.4, fuel and air enter the power plant and products of combustion leave the unit. In addition, heat is transferred to the cooling water, and work is done in the form of electrical energy leaving the power plant. The overall objective of a power plant is to convert the availability (to do work) of the fuel into work (in the form of electrical energy) in the most efficient manner, taking into consideration cost, space, safety, and environmental concerns.



**FIGURE 1.2** The Esbjerg, Denmark, power station. (Courtesy Vestkraft 1996.)



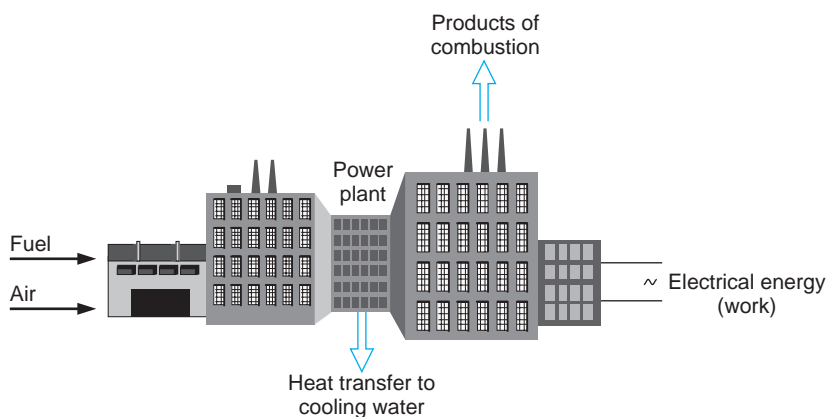
**FIGURE 1.3** Schematic diagram of a shipboard nuclear propulsion system. (Courtesy Babcock & Wilcox Co.)

We might well ask whether all the equipment in the power plant, such as the steam generator, the turbine, the condenser, and the pump, is necessary. Is it possible to produce electrical energy from the fuel in a more direct manner?

The fuel cell accomplishes this objective. Figure 1.5 shows a schematic arrangement of a fuel cell of the ion-exchange membrane type. In this fuel cell, hydrogen and oxygen react to form water. Hydrogen gas enters at the anode side and is ionized at the surface of the ion-exchange membrane, as indicated in Fig. 1.5. The electrons flow through the external circuit to the cathode while the positive hydrogen ions migrate through the membrane to the cathode, where both react with oxygen to form water.

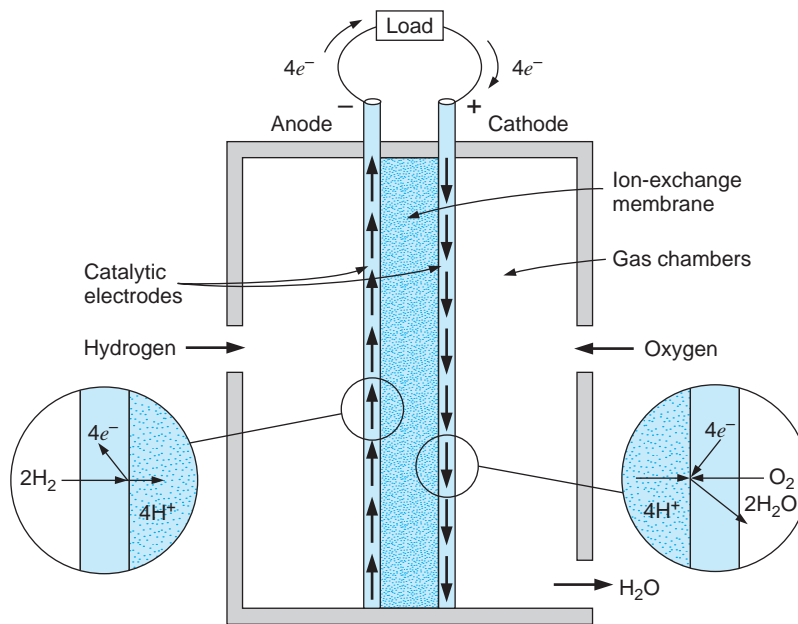
There is a potential difference between the anode and cathode, and thus there is a flow of electricity through a potential difference; this, in thermodynamic terms, is called *work*. There may also be a transfer of heat between the fuel cell and the surroundings.

At the present time, the fuel used in fuel cells is usually either hydrogen or a mixture of gaseous hydrocarbons and hydrogen. The oxidizer is usually oxygen. However, current development is directed toward the production of fuel cells that use hydrogen or hydrocarbon fuels and air. Although the conventional (or nuclear) steam power plant is still used in



**FIGURE 1.4**  
Schematic diagram of a power plant.

**FIGURE 1.5**  
Schematic arrangement  
of an ion-exchange  
membrane type of fuel  
cell.



large-scale power-generating systems, and although conventional piston engines and gas turbines are still used in most transportation power systems, the fuel cell may eventually become a serious competitor. The fuel cell is already being used to produce power for the space program and other special applications.

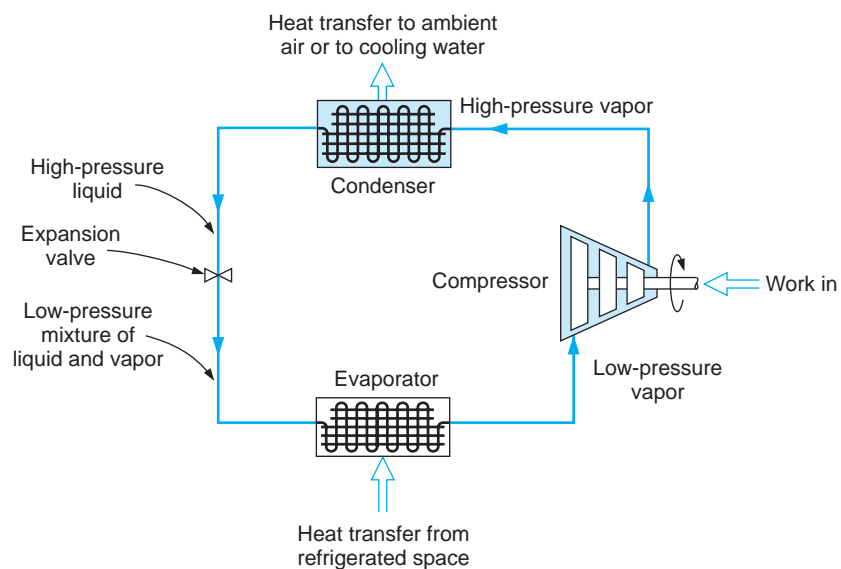
Thermodynamics plays a vital role in the analysis, development, and design of all power-producing systems, including reciprocating internal-combustion engines and gas turbines. Considerations such as the increase in efficiency, improved design, optimum operating conditions, reduced environmental pollution, and alternate methods of power generation involve, among other factors, the careful application of the fundamentals of thermodynamics.

### 1.3 THE VAPOR-COMPRESSION REFRIGERATION CYCLE

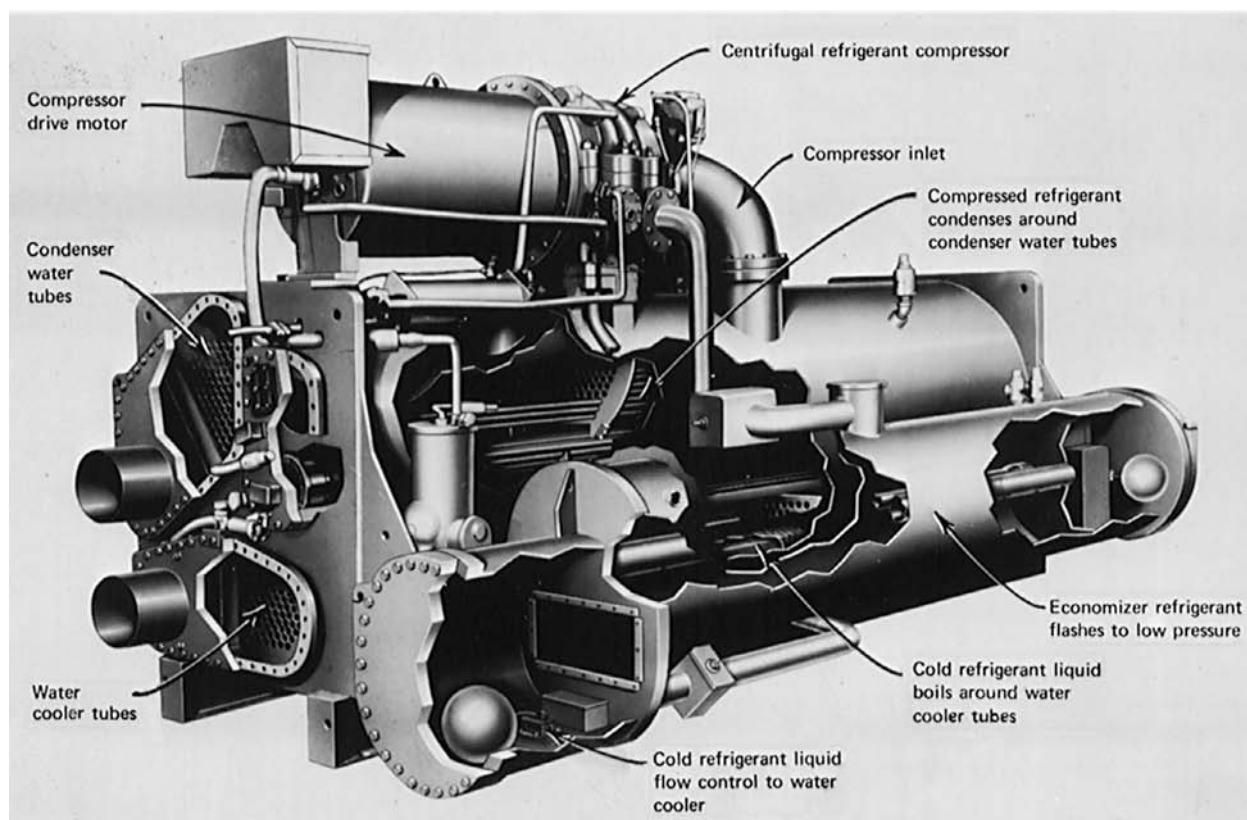
A simple vapor-compression refrigeration cycle is shown schematically in Fig. 1.6. The refrigerant enters the compressor as a slightly superheated vapor at a low pressure. It then leaves the compressor and enters the condenser as a vapor at an elevated pressure, where the refrigerant is condensed as heat is transferred to cooling water or to the surroundings. The refrigerant then leaves the condenser as a high-pressure liquid. The pressure of the liquid is decreased as it flows through the expansion valve, and as a result, some of the liquid flashes into cold vapor. The remaining liquid, now at a low pressure and temperature, is vaporized in the evaporator as heat is transferred from the refrigerated space. This vapor then reenters the compressor.

In a typical home refrigerator the compressor is located at the rear near the bottom of the unit. The compressors are usually hermetically sealed; that is, the motor and compressor are mounted in a sealed housing, and the electric leads for the motor pass through this



**FIGURE 1.6**

Schematic diagram of a simple refrigeration cycle.



**FIGURE 1.7** A refrigeration unit for an air-conditioning system. (Courtesy Carrier Air Conditioning Co.)

housing. This seal prevents leakage of the refrigerant. The condenser is also located at the back of the refrigerator and is arranged so that the air in the room flows past the condenser by natural convection. The expansion valve takes the form of a long capillary tube, and the evaporator is located around the outside of the freezing compartment inside the refrigerator.

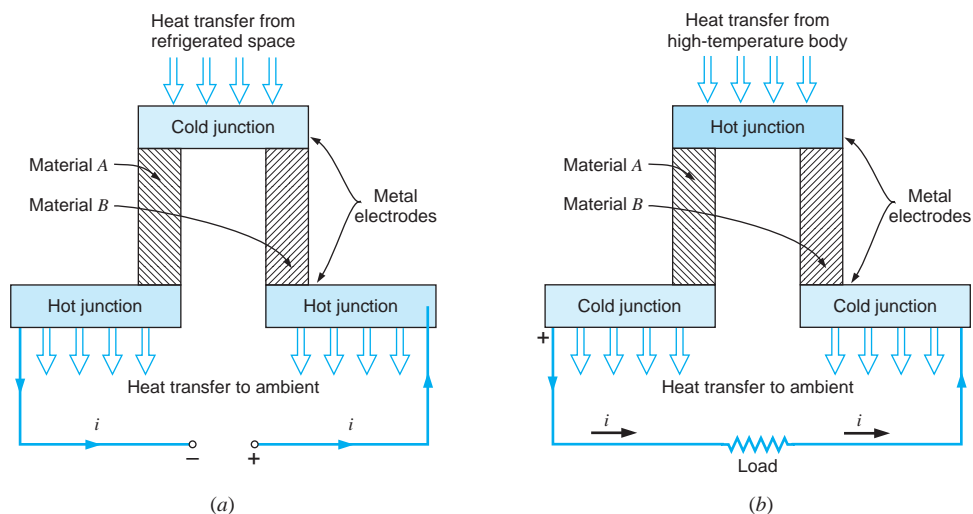
Figure 1.7 shows a large centrifugal unit that is used to provide refrigeration for an air-conditioning unit. In this unit, water is cooled and then circulated to provide cooling where needed.

## 1.4 THE THERMOELECTRIC REFRIGERATOR

We may well ask the same question about the vapor-compression refrigerator that we asked about the steam power plant: is it possible to accomplish our objective in a more direct manner? Is it possible, in the case of a refrigerator, to use the electrical energy (which goes to the electric motor that drives the compressor) to produce cooling in a more direct manner and thereby to avoid the cost of the compressor, condenser, evaporator, and all the related piping?

The thermoelectric refrigerator is such a device. This is shown schematically in Fig. 1.8a. The thermoelectric device, like the conventional thermocouple, uses two dissimilar materials. There are two junctions between these two materials in a thermoelectric refrigerator. One is located in the refrigerated space and the other in ambient surroundings. When a potential difference is applied, as indicated, the temperature of the junction located in the refrigerated space will decrease and the temperature of the other junction will increase. Under steady-state operating conditions, heat will be transferred from the refrigerated space to the cold junction. The other junction will be at a temperature above the ambient, and heat will be transferred from the junction to the surroundings.

A thermoelectric device can also be used to generate power by replacing the refrigerated space with a body that is at a temperature above the ambient. Such a system is shown in Fig. 1.8b.



**FIGURE 1.8** (a) A thermoelectric refrigerator. (b) A thermoelectric power generation device.

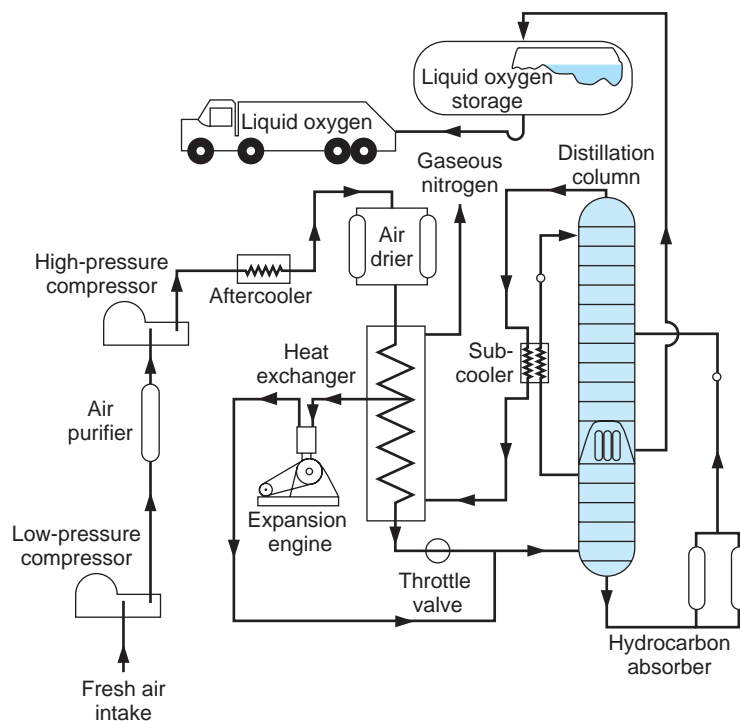


The thermoelectric refrigerator cannot yet compete economically with conventional vapor-compression units. However, in certain special applications, the thermoelectric refrigerator is already in use and, in view of research and development efforts underway in this field, it is quite possible that thermoelectric refrigerators will be much more extensively used in the future.

## 1.5 THE AIR SEPARATION PLANT

One process of great industrial significance is air separation. In an air separation plant, air is separated into its various components. The oxygen, nitrogen, argon, and rare gases so produced are used extensively in various industrial, research, space, and consumer-goods applications. The air separation plant can be considered an example from two major fields: chemical processing and cryogenics. *Cryogenics* is a term applied to technology, processes, and research at very low temperatures (in general, below about  $-125^{\circ}\text{C}$  ( $-193^{\circ}\text{F}$ )). In both chemical processing and cryogenics, thermodynamics is basic to an understanding of many phenomena and to the design and development of processes and equipment.

Air separation plants of many different designs have been developed. Consider Fig. 1.9, a simplified sketch of a type of plant that is frequently used. Air from the atmosphere is compressed to a pressure of 2 to 3 MPa (20 to 30 times normal atmospheric pressure). It is then purified, particularly to remove carbon dioxide (which would plug the flow passages as it solidifies when the air is cooled to its liquefaction temperature). The air is then compressed to a pressure of 15 to 20 MPa, cooled to the ambient temperature in the aftercooler, and dried to remove the water vapor (which would also plug the flow passages as it freezes).



**FIGURE 1.9** A simplified diagram of a liquid oxygen plant.

The basic refrigeration in the liquefaction process is provided by two different processes. In one process the air in the expansion engine expands. During this process the air does work and, as a result, the temperature of the air is reduced. In the other refrigeration process air passes through a throttle valve that is so designed and so located that there is a substantial drop in the pressure of the air and, associated with this, a substantial drop in the temperature of the air.

As shown in Fig. 1.9, the dry, high-pressure air enters a heat exchanger. As the air flows through the heat exchanger, its temperature drops. At some intermediate point in the heat exchanger, part of the air is bled off and flows through the expansion engine. The remaining air flows through the rest of the heat exchanger and through the throttle valve. The two streams join (both are at a pressure of 0.5 to 1 MPa) and enter the bottom of the distillation column, which is referred to as the *high-pressure column*. The function of the distillation column is to separate the air into its various components, principally oxygen and nitrogen. Two streams of different composition flow from the high-pressure column through throttle valves to the upper column (also called the *low-pressure column*). One of these streams is an oxygen-rich liquid that flows from the bottom of the lower column, and the other is a nitrogen-rich stream that flows through the subcooler. The separation is completed in the upper column. Liquid oxygen leaves from the bottom of the upper column, and gaseous nitrogen leaves from the top of the column. The nitrogen gas flows through the subcooler and the main heat exchanger. It is the transfer of heat to this cold nitrogen gas that causes the high-pressure air entering the heat exchanger to become cooler.

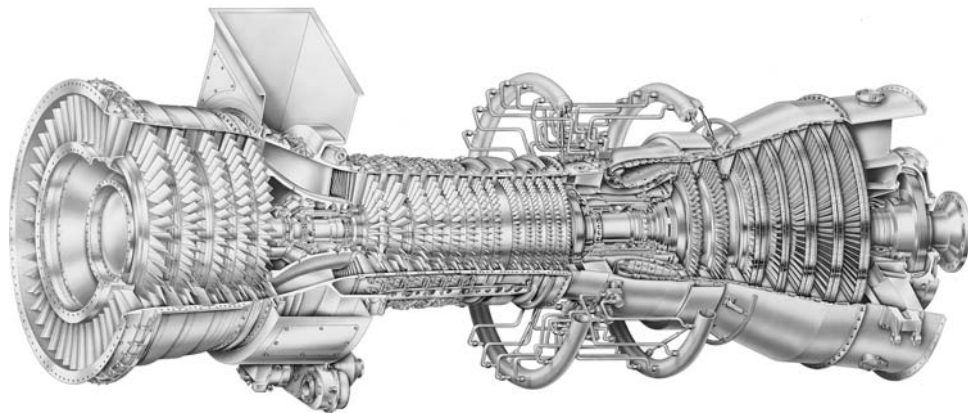
Not only is a thermodynamic analysis essential to the design of the system as a whole, but essentially every component of such a system, including the compressors, the expansion engine, the purifiers and driers, and the distillation column, operates according to the principles of thermodynamics. In this separation process we are also concerned with the thermodynamic properties of mixtures and the principles and procedures by which these mixtures can be separated. This is the type of problem encountered in petroleum refining and many other chemical processes. It should also be noted that cryogenics is particularly relevant to many aspects of the space program, and a thorough knowledge of thermodynamics is essential for creative and effective work in cryogenics.

## 1.6 THE GAS TURBINE

The basic operation of a gas turbine is similar to that of a steam power plant, except that air is used instead of water. Fresh atmospheric air flows through a compressor that brings it to a high pressure. Energy is then added by spraying fuel into the air and igniting it so that the combustion generates a high-temperature flow. This high-temperature, high-pressure gas enters a turbine, where it expands down to the exhaust pressure, producing shaft work output in the process. The turbine shaft work is used to drive the compressor and other devices, such as an electric generator that may be coupled to the shaft. The energy that is not used for shaft work is released in the exhaust gases, so these gases have either a high temperature or a high velocity. The purpose of the gas turbine determines the design so that the most desirable energy form is maximized. An example of a large gas turbine for stationary power generation is shown in Fig. 1.10. The unit has 16 stages of compression and 4 stages in the turbine and is rated at 43 MW (43 000 kW). Notice that since the combustion of fuel uses the oxygen in the air, the exhaust gases cannot be recirculated, as the water is in a steam power plant.

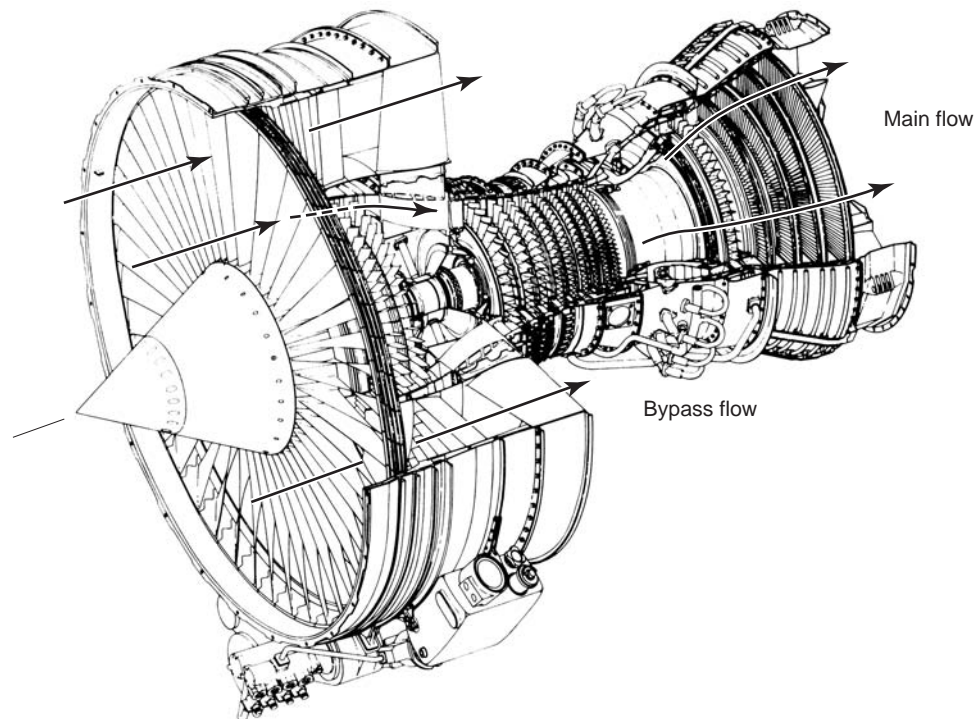
A gas turbine is often the preferred power-generating device where a large amount of power is needed but only a small physical size is possible. Examples are jet engines,

**FIGURE 1.10** A 43 MW gas turbine. (Courtesy General Electric Corporation.)



turbofan jet engines, offshore oilrig power plants, ship engines, helicopter engines, smaller local power plants, or peak-load power generators in larger power plants. Since the gas turbine has relatively high exhaust temperatures, it can also be arranged so that the exhaust gases are used to heat water that runs in a steam power plant before it exhausts to the atmosphere.

In the examples mentioned previously, the jet engine and turboprop applications utilize part of the power to discharge the gases at high velocity. This is what generates the thrust of the engine that moves the airplane forward. The gas turbines in these applications are



**FIGURE 1.11** A turbofan jet engine. (Courtesy General Electric Aircraft Engines.)

therefore designed differently than those for the stationary power plant, where the energy is released as shaft work to an electric generator. An example of a turbofan jet engine used in a commercial airplane is shown in Fig. 1.11. The large front-end fan also blows air past the engine, providing cooling and giving additional thrust.

## 1.7 THE CHEMICAL ROCKET ENGINE

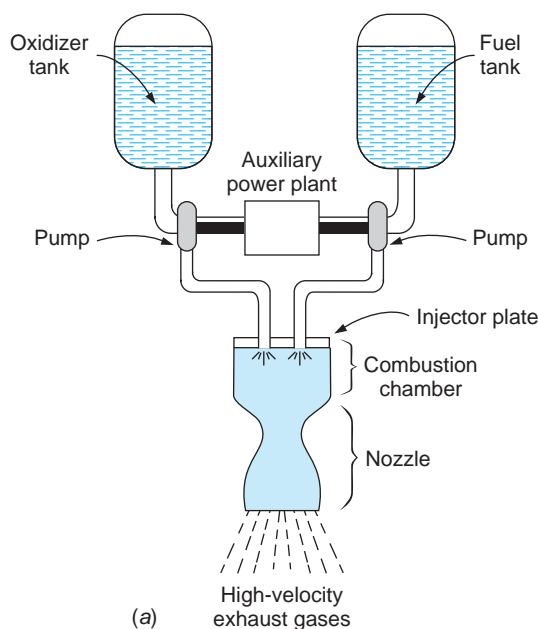
The advent of missiles and satellites brought to prominence the use of the rocket engine as a propulsion power plant. Chemical rocket engines may be classified as either liquid propellant or solid propellant, according to the fuel used.

Figure 1.12 shows a simplified schematic diagram of a liquid-propellant rocket. The oxidizer and fuel are pumped through the injector plate into the combustion chamber, where combustion takes place at high pressure. The high-pressure, high-temperature products of combustion expand as they flow through the nozzle, and as a result they leave the nozzle with a high velocity. The momentum change associated with this increase in velocity gives rise to the forward thrust on the vehicle.

The oxidizer and fuel must be pumped into the combustion chamber, and an auxiliary power plant is necessary to drive the pumps. In a large rocket this auxiliary power plant must be very reliable and have a relatively high power output, yet it must be light in weight. The oxidizer and fuel tanks occupy the largest part of the volume of a rocket, and the range and payload of a rocket are determined largely by the amount of oxidizer and fuel that can be carried. Many different fuels and oxidizers have been considered and tested, and much effort has gone into the development of fuels and oxidizers that will give a higher thrust per unit mass rate of flow of reactants. Liquid oxygen is frequently used as the oxidizer in liquid-propellant rockets, and liquid hydrogen is frequently used as the fuel.

**FIGURE 1.12**

(a) Simplified schematic diagram of a liquid-propellant rocket engine. (b) Photo of the NASA space shuttle's main engine.



Much work has also been done on solid-propellant rockets. They have been successfully used for jet-assisted takeoffs of airplanes, military missiles, and space vehicles. They require much simpler basic equipment for operation and fewer logistic problems are involved in their use, but they are more difficult to control.

## 1.8 OTHER APPLICATIONS AND ENVIRONMENTAL ISSUES

There are many other applications in which thermodynamics is relevant. Many municipal landfill operations are now utilizing the heat produced by the decomposition of biomass waste to produce power, and they also capture the methane gas produced by these chemical reactions for use as a fuel. Geothermal sources of heat are also being utilized, as are solar- and windmill-produced electricity. Sources of fuel are being converted from one form to another, more usable or convenient form, such as in the gasification of coal or the conversion of biomass to liquid fuels. Hydroelectric plants have been in use for many years, as have other applications involving water power. Thermodynamics is also relevant to such processes as the curing of a poured concrete slab, which produces heat, the cooling of electronic equipment, various applications in cryogenics (cryosurgery, food fast-freezing), and many other applications. Several of the topics and applications mentioned in this paragraph will be examined in detail in later chapters of this book.

We must also be concerned with environmental issues related to these many devices and applications of thermodynamics. For example, the construction and operation of the steam power plant creates electricity, which is so deeply entrenched in our society that we take its ready availability for granted. In recent years, however, it has become increasingly apparent that we need to consider seriously the effects of such an operation on our environment. Combustion of hydrocarbon fuels releases carbon dioxide into the atmosphere, where its concentration is increasing. Carbon dioxide, as well as other gases, absorbs infrared radiation from the surface of the earth, holding it close to the planet and creating the greenhouse effect, which in turn causes global warming and critical climatic changes around the earth. Power plant combustion, particularly of coal, releases sulfur dioxide, which is absorbed in clouds and later falls as acid rain in many areas. Combustion processes in power plants, and in gasoline and diesel engines, also generate pollutants other than these two. Species such as carbon monoxide, nitric oxides, and partly burned fuels, together with particulates, all contribute to atmospheric pollution and are regulated by law for many applications. Catalytic converters on automobiles help to minimize the air pollution problem. Figure 1.1 indicates the fly ash and flue gas cleanup processes that are now incorporated in power plants to address these problems. Thermal pollution associated with power plant cooling water requirements was discussed in Section 1.1.

Refrigeration and air-conditioning systems, as well as other industrial processes, have used certain chlorofluorocarbon fluids that eventually find their way to the upper atmosphere and destroy the protective ozone layer. Many countries have already banned the production of some of these compounds, and the search for improved replacement fluids continues.

These are only some of the many environmental problems caused by our efforts to produce goods and effects intended to improve our way of life. During our study of thermodynamics, which is the science of the conversion of energy from one form to another, we must continue to reflect on these issues. We must consider how we can eliminate or at least minimize damaging effects, as well as use our natural resources, efficiently and responsibly.

# Some Concepts and Definitions

## 2

One excellent definition of thermodynamics is that it is the science of energy and entropy. Since we have not yet defined these terms, an alternate definition in already familiar terms is: Thermodynamics is the science that deals with heat and work and those properties of substances that bear a relation to heat and work. As with all sciences, the basis of thermodynamics is experimental observation. In thermodynamics these findings have been formalized into certain basic laws, which are known as the *first*, *second*, and *third laws of thermodynamics*. In addition to these laws, the *zeroth law of thermodynamics*, which in the logical development of thermodynamics precedes the first law, has been set forth.

In the chapters that follow, we will present these laws and the thermodynamic properties related to these laws and apply them to a number of representative examples. The objective of the student should be to gain both a thorough understanding of the fundamentals and an ability to apply them to thermodynamic problems. The examples and problems further this twofold objective. It is not necessary for the student to memorize numerous equations, for problems are best solved by the application of the definitions and laws of thermodynamics. In this chapter, some concepts and definitions basic to thermodynamics are presented.

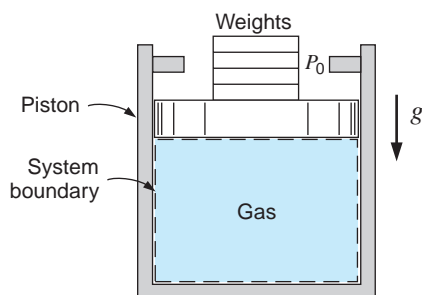
## 2.1 A THERMODYNAMIC SYSTEM AND THE CONTROL VOLUME

A thermodynamic system is a device or combination of devices containing a quantity of matter that is being studied. To define this more precisely, a **control volume** is chosen so that it contains the matter and devices inside a control surface. Everything external to the control volume is the surroundings, with the separation provided by the control surface. The surface may be open or closed to mass flows, and it may have flows of energy in terms of heat transfer and work across it. The boundaries may be movable or stationary. In the case of a control surface that is closed to mass flow, so that no mass can escape or enter the control volume, it is called a **control mass** containing the same amount of matter at all times.

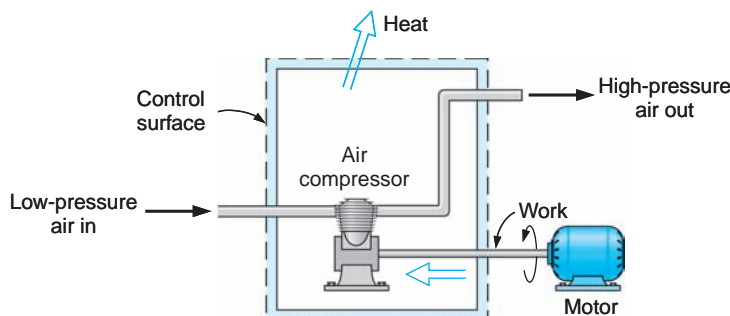
Selecting the gas in the cylinder of Fig. 2.1 as a control volume by placing a control surface around it, we recognize this as a control mass. If a Bunsen burner is placed under the cylinder, the temperature of the gas will increase and the piston will rise. As the piston rises, the boundary of the control mass moves. As we will see later, heat and work cross the boundary of the control mass during this process, but the matter that composes the control mass can always be identified and remains the same.

An isolated system is one that is not influenced in any way by the surroundings. This means that no mass, heat, or work cross the boundary of the system. In many cases, a





**FIGURE 2.1** Example of a control mass.



**FIGURE 2.2** Example of a control volume.

thermodynamic analysis must be made of a device, such as an air compressor, which has a flow of mass into it, out of it, or both, as shown schematically in Fig. 2.2. The procedure followed in such an analysis is to specify a control volume that surrounds the device under consideration. The surface of this control volume is the control surface, which may be crossed by mass momentum, as well as heat and work.



Thus the more general control surface defines a control volume, where mass may flow in or out, with a control mass as the special case of no mass flow in or out. Hence the control mass contains a fixed mass at all times, which explains its name. The difference in the formulation of the analysis is considered in detail in Chapter 6. The terms **closed system** (fixed mass) and **open system** (involving a flow of mass) are sometimes used to make this distinction. Here, we use the term **system** as a more general and loose description for a mass, device, or combination of devices that then is more precisely defined when a control volume is selected. The procedure that will be followed in presenting the first and second laws of thermodynamics is first to present these laws for a control mass and then to extend the analysis to the more general control volume.

## 2.2 MACROSCOPIC VERSUS MICROSCOPIC POINTS OF VIEW

The behavior of a system may be investigated from either a microscopic or macroscopic point of view. Let us briefly describe a system from a microscopic point of view. Consider a system consisting of a cube 25 mm on a side and containing a monatomic gas at atmospheric pressure and temperature. This volume contains approximately  $10^{20}$  atoms. To describe the position of each atom, we need to specify three coordinates; to describe the velocity of each atom, we specify three velocity components.

Thus, to describe completely the behavior of this system from a microscopic point of view, we must deal with at least  $6 \times 10^{20}$  equations. Even with a large digital computer, this is a hopeless computational task. However, there are two approaches to this problem that reduce the number of equations and variables to a few that can be computed relatively easily. One is the statistical approach, in which, on the basis of statistical considerations and probability theory, we deal with average values for all particles under consideration. This is usually done in connection with a model of the atom under consideration. This is the approach used in the disciplines of kinetic theory and statistical mechanics.

The other approach to reducing the number of variables to a few that can be handled is the macroscopic point of view of classical thermodynamics. As the word *macroscopic* implies, we are concerned with the gross or average effects of many molecules. These effects can be perceived by our senses and measured by instruments. However, what we really perceive and measure is the time-averaged influence of many molecules. For example, consider the pressure a gas exerts on the walls of its container. This pressure results from the change in momentum of the molecules as they collide with the wall. From a macroscopic point of view, however, we are concerned not with the action of the individual molecules but with the time-averaged force on a given area, which can be measured by a pressure gauge. In fact, these macroscopic observations are completely independent of our assumptions regarding the nature of matter.

Although the theory and development in this book are presented from a macroscopic point of view, a few supplementary remarks regarding the significance of the microscopic perspective are included as an aid to understanding the physical processes involved. Another book in this series, *Introduction to Thermodynamics: Classical and Statistical*, by R. E. Sonntag and G. J. Van Wylen, includes thermodynamics from the microscopic and statistical point of view.

A few remarks should be made regarding the continuum. From the macroscopic point of view, we are always concerned with volumes that are very large compared to molecular dimensions and, therefore, with systems that contain many molecules. Because we are not concerned with the behavior of individual molecules, we can treat the substance as being continuous, disregarding the action of individual molecules. This **continuum** concept, of course, is only a convenient assumption that loses validity when the mean free path of the molecules approaches the order of magnitude of the dimensions of the vessel, as, for example, in high-vacuum technology. In much engineering work the assumption of a continuum is valid and convenient, going hand in hand with the macroscopic point of view.

## 2.3 PROPERTIES AND STATE OF A SUBSTANCE

If we consider a given mass of water, we recognize that this water can exist in various forms. If it is a liquid initially, it may become a vapor when it is heated or a solid when it is cooled. Thus, we speak of the different phases of a substance. A **phase** is defined as a quantity of matter that is homogeneous throughout. When more than one phase is present, the phases are separated from each other by the phase boundaries. In each phase the substance may exist at various pressures and temperatures or, to use the thermodynamic term, in various **states**. The state may be identified or described by certain observable, macroscopic **properties**; some familiar ones are temperature, pressure, and density. In later chapters, other properties will be introduced. Each of the properties of a substance in a given state has only one definite value, and these properties always have the same value for a given state, regardless of how the





substance arrived at the state. In fact, a property can be defined as any quantity that depends on the state of the system and is independent of the path (that is, the prior history) by which the system arrived at the given state. Conversely, the state is specified or described by the properties. Later we will consider the number of independent properties a substance can have, that is, the minimum number of properties that must be specified to fix the state of the substance.

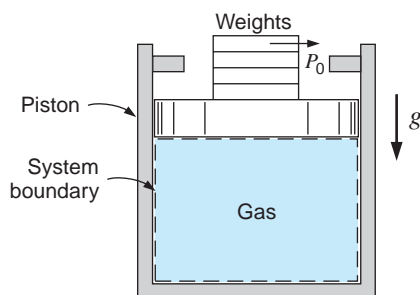
Thermodynamic properties can be divided into two general classes: **intensive** and **extensive**. An intensive property is independent of the mass; the value of an extensive property varies directly with the mass. Thus, if a quantity of matter in a given state is divided into two equal parts, each part will have the same value of intensive properties as the original and half the value of the extensive properties. Pressure, temperature, and density are examples of intensive properties. Mass and total volume are examples of extensive properties. Extensive properties per unit mass, such as specific volume, are intensive properties.

Frequently we will refer not only to the properties of a substance but also to the properties of a system. When we do so, we necessarily imply that the value of the property has significance for the entire system, and this implies equilibrium. For example, if the gas that composes the system (control mass) in Fig. 2.1 is in thermal equilibrium, the temperature will be the same throughout the entire system, and we may speak of the temperature as a property of the system. We may also consider mechanical equilibrium, which is related to pressure. If a system is in mechanical equilibrium, there is no tendency for the pressure at any point to change with time as long as the system is isolated from the surroundings. There will be variation in pressure with elevation because of the influence of gravitational forces, although under equilibrium conditions there will be no tendency for the pressure at any location to change. However, in many thermodynamic problems, this variation in pressure with elevation is so small that it can be neglected. Chemical equilibrium is also important and will be considered in Chapter 16. When a system is in equilibrium regarding all possible changes of state, we say that the system is in **thermodynamic equilibrium**.

## 2.4 PROCESSES AND CYCLES

Whenever one or more of the properties of a system change, we say that a change in state has occurred. For example, when one of the weights on the piston in Fig. 2.3 is removed, the piston rises and a change in state occurs, for the pressure decreases and the specific volume increases. The path of the succession of states through which the system passes is called the **process**.

Let us consider the equilibrium of a system as it undergoes a change in state. The moment the weight is removed from the piston in Fig. 2.3, mechanical equilibrium does not exist; as a result, the piston is moved upward until mechanical equilibrium is restored.



**FIGURE 2.3** Example of a system that may undergo a quasi-equilibrium process.

The question is this: Since the properties describe the state of a system only when it is in equilibrium, how can we describe the states of a system during a process if the actual process occurs only when equilibrium does not exist? One step in finding the answer to this question concerns the definition of an ideal process, which we call a *quasi-equilibrium* process. A quasi-equilibrium process is one in which the deviation from thermodynamic equilibrium is infinitesimal, and all the states the system passes through during a quasi-equilibrium process may be considered equilibrium states. Many actual processes closely approach a quasi-equilibrium process and may be so treated with essentially no error. If the weights on the piston in Fig. 2.3 are small and are taken off one by one, the process could be considered quasi-equilibrium. However, if all the weights are removed at once, the piston will rise rapidly until it hits the stops. This would be a nonequilibrium process, and the system would not be in equilibrium at any time during this change of state.

For nonequilibrium processes, we are limited to a description of the system before the process occurs and after the process is completed and equilibrium is restored. We are unable to specify each state through which the system passes or the rate at which the process occurs. However, as we will see later, we are able to describe certain overall effects that occur during the process.

Several processes are described by the fact that one property remains constant. The prefix *iso-* is used to describe such a process. An isothermal process is a constant-temperature process, an isobaric (sometimes called *isopiestic*) process is a constant-pressure process, and an isochoric process is a constant-volume process.

When a system in a given initial state goes through a number of different changes of state or processes and finally returns to its initial state, the system has undergone a *cycle*. Therefore, at the conclusion of a cycle, all the properties have the same value they had at the beginning. Steam (water) that circulates through a steam power plant undergoes a cycle.

A distinction should be made between a thermodynamic cycle, which has just been described, and a mechanical cycle. A four-stroke-cycle internal-combustion engine goes through a mechanical cycle once every two revolutions. However, the working fluid does not go through a thermodynamic cycle in the engine, since air and fuel are burned and changed to products of combustion that are exhausted to the atmosphere. In this book, the term *cycle* will refer to a thermodynamic cycle unless otherwise designated.



## 2.5 UNITS FOR MASS, LENGTH, TIME, AND FORCE

Since we are considering thermodynamic properties from a macroscopic perspective, we are dealing with quantities that can, either directly or indirectly, be measured and counted. Therefore, the matter of units becomes an important consideration. In the remaining sections of this chapter we will define certain thermodynamic properties and the basic units. Because the relation between force and mass is often difficult for students to understand, it is considered in this section in some detail.

Force, mass, length, and time are related by Newton's second law of motion, which states that the force acting on a body is proportional to the product of the mass and the acceleration in the direction of the force:

$$F \propto ma$$

The concept of time is well established. The basic unit of time is the second (s), which in the past was defined in terms of the solar day, the time interval for one complete revolution of the earth relative to the sun. Since this period varies with the season of the year, an

TABLE 2.1  
Unit Prefixes

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

average value over a 1-year period is called the *mean solar day*, and the mean solar second is 1/86 400 of the mean solar day. (The earth's rotation is sometimes measured relative to a fixed star, in which case the period is called a *sidereal day*.) In 1967, the General Conference of Weights and Measures (CGPM) adopted a definition of the second as the time required for a beam of cesium-133 atoms to resonate 9 192 631 770 cycles in a cesium resonator.

For periods of time less than 1 s, the prefixes *milli*, *micro*, *nano*, or *pico*, as listed in Table 2.1, are commonly used. For longer periods of time, the units minute (min), hour (h), or day (day) are frequently used. It should be pointed out that the prefixes in Table 2.1 are used with many other units as well.

The concept of length is also well established. The basic unit of length is the meter (m). For many years the accepted standard was the International Prototype Meter, the distance between two marks on a platinum–iridium bar under certain prescribed conditions. This bar is maintained at the International Bureau of Weights and Measures in Sevres, France. In 1960, the CGPM adopted a definition of the meter as a length equal to 1 650 763.73 wavelengths in a vacuum of the orange-red line of krypton-86. Then in 1983, the CGPM adopted a more precise definition of the meter in terms of the speed of light (which is now a fixed constant): The meter is the length of the path traveled by light in a vacuum during a time interval of 1/299 792 458 of a second.

The fundamental unit of mass is the kilogram (kg). As adopted by the first CGPM in 1889 and restated in 1901, it is the mass of a certain platinum–iridium cylinder maintained under prescribed conditions at the International Bureau of Weights and Measures. A related unit that is used frequently in thermodynamics is the mole (mol), defined as an amount of substance containing as many elementary entities as there are atoms in 0.012 kg of carbon-12. These elementary entities must be specified; they may be atoms, molecules, electrons, ions, or other particles or specific groups. For example, one mole of diatomic oxygen, having a molecular mass of 32 (compared to 12 for carbon), has a mass of 0.032 kg. The mole is often termed a *gram mole*, since it is an amount of substance in grams numerically equal to the molecular mass. In this book, when using the metric SI system, we will find it preferable to use the kilomole (kmol), the amount of substance in kilograms numerically equal to the molecular mass, rather than the mole.

The system of units in use presently throughout most of the world is the metric International System, commonly referred to as *SI units* (from Le Système International d'Unités). In this system, the second, meter, and kilogram are the basic units for time, length, and mass, respectively, as just defined, and the unit of force is defined directly from Newton's second law.

Therefore, a proportionality constant is unnecessary, and we may write that law as an equality:

$$F = ma \quad (2.1)$$

The unit of force is the newton (N), which by definition is the force required to accelerate a mass of one kilogram at the rate of one meter per second per second:

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

It is worth noting that SI units derived from proper nouns use capital letters for symbols; others use lowercase letters. The liter, with the symbol L, is an exception.

The traditional system of units used in the United States is the English Engineering System. In this system the unit of time is the second, which was discussed earlier. The basic unit of length is the foot (ft), which at present is defined in terms of the meter as

$$1 \text{ ft} = 0.3048 \text{ m}$$

The inch (in.) is defined in terms of the foot:

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

The unit of mass in this system is the pound mass (lbm). It was originally defined as the mass of a certain platinum cylinder kept in the Tower of London, but now it is defined in terms of the kilogram as

$$1 \text{ lbm} = 0.453\,592\,37 \text{ kg}$$

A related unit is the pound mole (lb mol), which is an amount of substance in pounds mass numerically equal to the molecular mass of that substance. It is important to distinguish between a pound mole and a mole (gram mole).

In the English Engineering System of Units, the unit of force is the pound force (lbf), defined as the force with which the standard pound mass is attracted to the earth under conditions of standard acceleration of gravity, which is that at 45° latitude and sea level elevation, 9.806 65 m/s<sup>2</sup> or 32.1740 ft/s<sup>2</sup>. Thus, it follows from Newton's second law that

$$1 \text{ lbf} = 32.174 \text{ lbm ft/s}^2$$

which is a necessary factor for the purpose of units conversion and consistency. Note that we must be careful to distinguish between a lbm and a lbf, and we do not use the term *pound* alone.

The term *weight* is often used with respect to a body and is sometimes confused with mass. Weight is really correctly used only as a force. When we say that a body weighs so much, we mean that this is the force with which it is attracted to the earth (or some other body), that is, the product of its mass and the local gravitational acceleration. The mass of a substance remains constant with elevation, but its weight varies with elevation.

### EXAMPLE 2.1

What is the weight of a 1 kg mass at an altitude where the local acceleration of gravity is 9.75 m/s<sup>2</sup>?

#### Solution

Weight is the force acting on the mass, which from Newton's second law is

$$F = mg = 1 \text{ kg} \times 9.75 \text{ m/s}^2 \times [1 \text{ N s}^2/\text{kg m}] = 9.75 \text{ N}$$

**EXAMPLE 2.1E**

What is the weight of a 1 lbm mass at an altitude where the local acceleration of gravity is  $32.0 \text{ ft/s}^2$ ?

**Solution**

Weight is the force acting on the mass, which from Newton's second law is

$$F = mg = 1 \text{ lbm} \times 32.0 \text{ ft/s}^2 \times [\text{lbf s}^2 / 32.174 \text{ lbm ft}] = 0.9946 \text{ lbf}$$

**2.6 ENERGY**

One very important concept in a study of thermodynamics is energy. Energy is a fundamental concept, such as mass or force, and, as is often the case with such concepts, it is very difficult to define. Energy has been defined as the capability to produce an effect. Fortunately the word **energy** and the basic concept that this word represents are familiar to us in everyday usage, and a precise definition is not essential at this point.

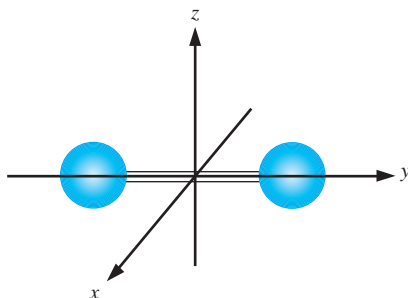
Energy can be stored within a system and can be transferred (as heat, for example) from one system to another. In a study of statistical thermodynamics we would examine, from a molecular point of view, the ways in which energy can be stored. Because it is helpful in a study of classical thermodynamics to have some notion of how this energy is stored, a brief introduction is presented here.

Consider as a system a certain gas at a given pressure and temperature contained within a tank or pressure vessel. Using the molecular point of view, we identify three general forms of energy:

1. Intermolecular potential energy, which is associated with the forces between molecules
2. Molecular kinetic energy, which is associated with the translational velocity of individual molecules
3. Intramolecular energy (that within the individual molecules), which is associated with the molecular and atomic structure and related forces

The first of these forms of energy, intermolecular potential energy, depends on the magnitude of the intermolecular forces and the position of the molecules relative to each other at any instant of time. It is impossible to determine accurately the magnitude of this energy because we do not know either the exact configuration and orientation of the molecules at any time or the exact intermolecular potential function. However, there are two situations for which we can make good approximations. The first situation is at low or moderate densities. In this case the molecules are relatively widely spaced, so that only two-molecule or two- and three-molecule interactions contribute to the potential energy. At these low and moderate densities, techniques are available for determining, with reasonable accuracy, the potential energy of a system composed of fairly simple molecules. The second situation is at very low densities; under these conditions, the average intermolecular distance between molecules is so large that the potential energy may be assumed to be zero. Consequently, we have in this case a system of independent particles (an ideal gas) and, therefore, from a statistical point of view, we are able to concentrate our efforts on evaluating the molecular translational and internal energies.

**FIGURE 2.4** The coordinate system for a diatomic molecule.



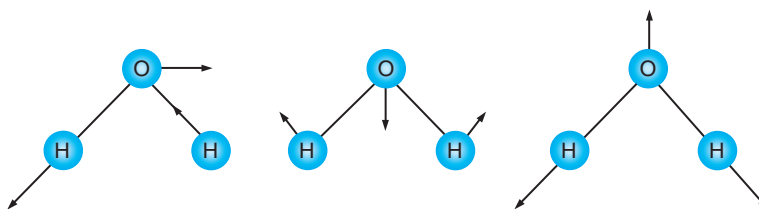
The translational energy, which depends only on the mass and velocities of the molecules, is determined by using the equations of mechanics—either quantum or classical.

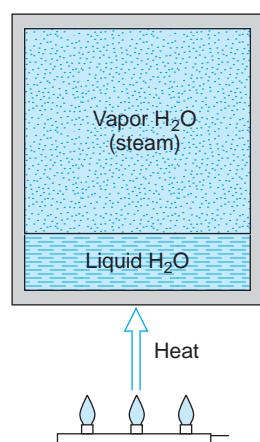
The intramolecular internal energy is more difficult to evaluate because, in general, it may result from a number of contributions. Consider a simple monatomic gas such as helium. Each molecule consists of a helium atom. Such an atom possesses electronic energy as a result of both orbital angular momentum of the electrons about the nucleus and angular momentum of the electrons spinning on their axes. The electronic energy is commonly very small compared with the translational energies. (Atoms also possess nuclear energy, which, except in the case of nuclear reactions, is constant. We are not concerned with nuclear energy at this time.) When we consider more complex molecules, such as those composed of two or three atoms, additional factors must be considered. In addition to having electronic energy, a molecule can rotate about its center of gravity and thus have rotational energy. Furthermore, the atoms may vibrate with respect to each other and have vibrational energy. In some situations there may be an interaction between the rotational and vibrational modes of energy.

In evaluating the energy of a molecule, we often refer to the degree of freedom,  $f$ , of these energy modes. For a monatomic molecule such as helium,  $f = 3$ , which represents the three directions  $x$ ,  $y$ , and  $z$  in which the molecule can move. For a diatomic molecule, such as oxygen,  $f = 6$ . Three of these are the translation of the molecule as a whole in the  $x$ ,  $y$ , and  $z$  directions, and two are for rotation. The reason why there are only two modes of rotational energy is evident from Fig. 2.4, where we take the origin of the coordinate system at the center of gravity of the molecule, and the  $y$ -axis along the molecule's internuclear axis. The molecule will then have an appreciable moment of inertia about the  $x$ -axis and the  $z$ -axis but not about the  $y$ -axis. The sixth degree of freedom of the molecule is vibration, which relates to stretching of the bond joining the atoms.

For a more complex molecule such as  $\text{H}_2\text{O}$ , there are additional vibrational degrees of freedom. Figure 2.5 shows a model of the  $\text{H}_2\text{O}$  molecule. From this diagram, it is evident that there are three vibrational degrees of freedom. It is also possible to have rotational energy about all three axes. Thus, for the  $\text{H}_2\text{O}$  molecule, there are nine degrees of freedom ( $f = 9$ ): three translational, three rotational, and three vibrational.

**FIGURE 2.5** The three principal vibrational modes for the  $\text{H}_2\text{O}$  molecule.





**FIGURE 2.6** Heat transfer to  $\text{H}_2\text{O}$ .

Most complex molecules, such as typical polyatomic molecules, are usually three-dimensional in structure and have multiple vibrational modes, each of which contributes to the energy storage of the molecule. The more complicated the molecule is, the larger the number of degrees of freedom that exist for energy storage. The modes of energy storage and their evaluation are discussed in some detail in Appendix C for those interested in further development of the quantitative effects from a molecular viewpoint.

This general discussion can be summarized by referring to Fig. 2.6. Let heat be transferred to  $\text{H}_2\text{O}$ . During this process the temperature of the liquid and vapor (steam) will increase, and eventually all the liquid will become vapor. From the macroscopic point of view, we are concerned only with the energy that is transferred as heat, the change in properties such as temperature and pressure, and the total amount of energy (relative to some base) that the  $\text{H}_2\text{O}$  contains at any instant. Thus, questions about how energy is stored in the  $\text{H}_2\text{O}$  do not concern us. From a microscopic viewpoint, we are concerned about the way in which energy is stored in the molecules. We might be interested in developing a model of the molecule so that we can predict the amount of energy required to change the temperature a given amount. Although the focus in this book is on the macroscopic or classical viewpoint, it is helpful to keep in mind the microscopic or statistical perspective as well, as the relationship between the two helps us understand basic concepts such as energy.

### In-Text Concept Questions

- Make a control volume around the turbine in the steam power plant in Fig. 1.1 and list the flows of mass and energy located there.
- Take a control volume around your kitchen refrigerator, indicate where the components shown in Fig. 1.6 are located, and show all energy transfers.

## 2.7 SPECIFIC VOLUME AND DENSITY

The **specific volume** of a substance is defined as the volume per unit mass and is given the symbol  $v$ . The **density** of a substance is defined as the mass per unit volume, and it is therefore the reciprocal of the specific volume. Density is designated by the symbol  $\rho$ . Specific volume and density are intensive properties.

The specific volume of a system in a gravitational field may vary from point to point. For example, if the atmosphere is considered a system, the specific volume increases as the elevation increases. Therefore, the definition of specific volume involves the specific volume of a substance at a point in a system.

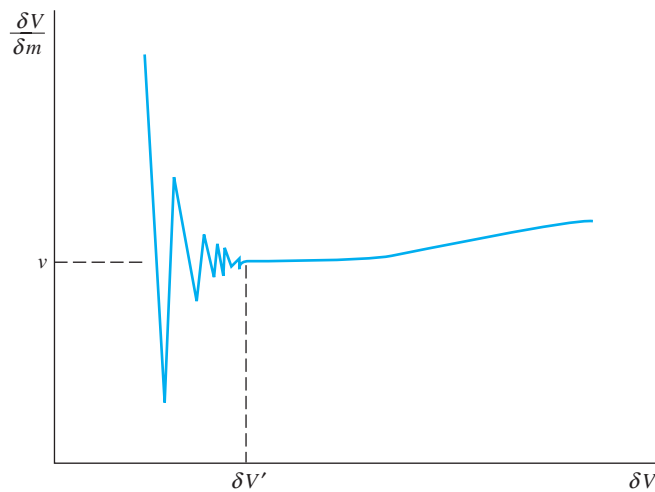
Consider a small volume  $\delta V$  of a system, and let the mass be designated  $\delta m$ . The specific volume is defined by the relation

$$v = \lim_{\delta V \rightarrow \delta V'} \frac{\delta V}{\delta m}$$

where  $\delta V'$  is the smallest volume for which the mass can be considered a continuum. Volumes smaller than this will lead to the recognition that mass is not evenly distributed in space but is concentrated in particles as molecules, atoms, electrons, etc. This is tentatively indicated in Fig. 2.7, where in the limit of a zero volume the specific volume may be infinite (the volume does not contain any mass) or very small (the volume is part of a nucleus).



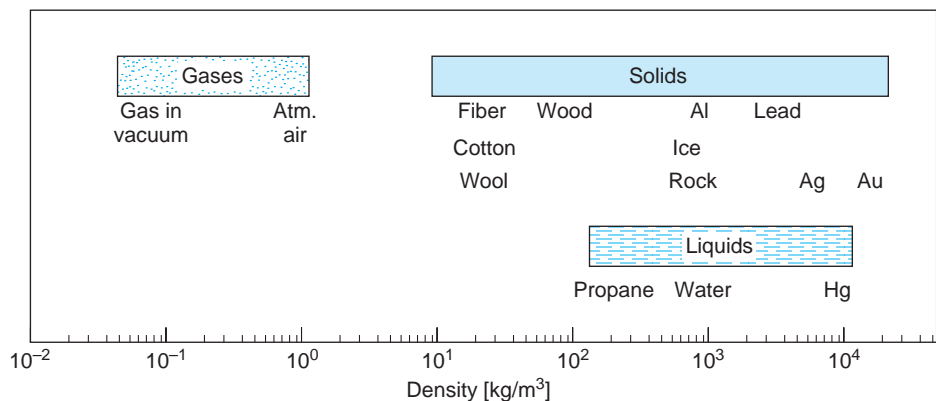
**FIGURE 2.7** The continuum limit for the specific volume.



Thus, in a given system, we should speak of the specific volume or density at a point in the system and recognize that this may vary with elevation. However, most of the systems that we consider are relatively small, and the change in specific volume with elevation is not significant. Therefore, we can speak of one value of specific volume or density for the entire system.

In this book, the specific volume and density will be given either on a mass or a mole basis. A bar over the symbol (lowercase) will be used to designate the property on a mole basis. Thus,  $\bar{v}$  will designate molal specific volume and  $\bar{\rho}$  will designate molal density. In SI units, those for specific volume are  $\text{m}^3/\text{kg}$  and  $\text{m}^3/\text{mol}$  (or  $\text{m}^3/\text{kmol}$ ); for density the corresponding units are  $\text{kg}/\text{m}^3$  and  $\text{mol}/\text{m}^3$  (or  $\text{kmol}/\text{m}^3$ ). In English units, those for specific volume are  $\text{ft}^3/\text{lbm}$  and  $\text{ft}^3/\text{lb mol}$ ; the corresponding units for density are  $\text{lbm}/\text{ft}^3$  and  $\text{lb mol}/\text{ft}^3$ .

Although the SI unit for volume is the cubic meter, a commonly used volume unit is the liter (L), which is a special name given to a volume of 0.001 cubic meters, that is,  $1 \text{ L} = 10^{-3} \text{ m}^3$ . The general ranges of density for some common solids, liquids, and gases are shown in Fig. 2.8. Specific values for various solids, liquids, and gases in SI units are listed in Tables A.3, A.4, and A.5, respectively, and in English units in Tables F.2, F.3, and F.4.



**FIGURE 2.8** Density of common substances.



## EXAMPLE 2.2

A  $1 \text{ m}^3$  container, shown in Fig. 2.9, is filled with  $0.12 \text{ m}^3$  of granite,  $0.15 \text{ m}^3$  of sand, and  $0.2 \text{ m}^3$  of liquid  $25^\circ\text{C}$  water; the rest of the volume,  $0.53 \text{ m}^3$ , is air with a density of  $1.15 \text{ kg/m}^3$ . Find the overall (average) specific volume and density.

**Solution**

From the definition of specific volume and density we have

$$v = V/m \quad \text{and} \quad \rho = m/V = 1/v$$

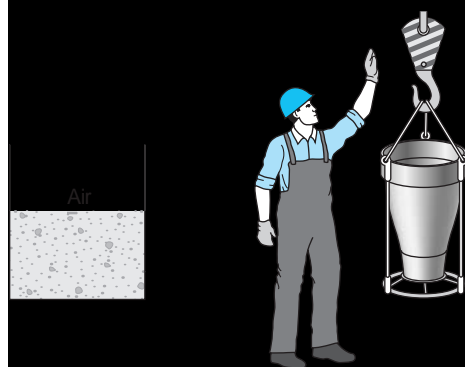
We need to find the total mass, taking density from Tables A.3 and A.4:

$$m_{\text{granite}} = \rho_{\text{granite}} V_{\text{granite}} = 2750 \text{ kg/m}^3 \times 0.12 \text{ m}^3 = 330 \text{ kg}$$

$$m_{\text{sand}} = \rho_{\text{sand}} V_{\text{sand}} = 1500 \text{ kg/m}^3 \times 0.15 \text{ m}^3 = 225 \text{ kg}$$

$$m_{\text{water}} = \rho_{\text{water}} V_{\text{water}} = 997 \text{ kg/m}^3 \times 0.2 \text{ m}^3 = 199.4 \text{ kg}$$

$$m_{\text{air}} = \rho_{\text{air}} V_{\text{air}} = 1.15 \text{ kg/m}^3 \times 0.53 \text{ m}^3 = 0.61 \text{ kg}$$



**FIGURE 2.9** Sketch for Example 2.2.

Now the total mass becomes

$$m_{\text{tot}} = m_{\text{granite}} + m_{\text{sand}} + m_{\text{water}} + m_{\text{air}} = 755 \text{ kg}$$

and the specific volume and density can be calculated:

$$v = V_{\text{tot}}/m_{\text{tot}} = 1 \text{ m}^3/755 \text{ kg} = 0.001325 \text{ m}^3/\text{kg}$$

$$\rho = m_{\text{tot}}/V_{\text{tot}} = 755 \text{ kg}/1 \text{ m}^3 = 755 \text{ kg/m}^3$$

**Remark:** It is misleading to include air in the numbers for  $\rho$  and  $V$ , as the air is separate from the rest of the mass.

### In-Text Concept Questions

- c. Why do people float high in the water when swimming in the Dead Sea as compared with swimming in a freshwater lake?
- d. The density of liquid water is  $\rho = 1008 - T/2 \text{ [kg/m}^3\text{]}$  with  $T$  in  $^\circ\text{C}$ . If the temperature increases, what happens to the density and specific volume?

## 2.8 PRESSURE

When dealing with liquids and gases, we ordinarily speak of pressure; for solids we speak of stresses. The pressure in a fluid at rest at a given point is the same in all directions, and we define **pressure** as the normal component of force per unit area. More specifically, if  $\delta A$  is a small area,  $\delta A'$  is the smallest area over which we can consider the fluid a continuum, and  $\delta F_n$  is the component of force normal to  $\delta A$ , we define pressure,  $P$ , as

$$P = \lim_{\delta A \rightarrow \delta A'} \frac{\delta F_n}{\delta A}$$

where the lower limit corresponds to sizes as mentioned for the specific volume, shown in Fig. 2.7. The pressure  $P$  at a point in a fluid in equilibrium is the same in all directions. In a viscous fluid in motion, the variation in the state of stress with orientation becomes an important consideration. These considerations are beyond the scope of this book, and we will consider pressure only in terms of a fluid in equilibrium.

The unit for pressure in the International System is the force of one newton acting on a square meter area, which is called the pascal (Pa). That is,

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

Two other units, not part of the International System, continue to be widely used. These are the bar, where

$$1 \text{ bar} = 10^5 \text{ Pa} = 0.1 \text{ MPa}$$

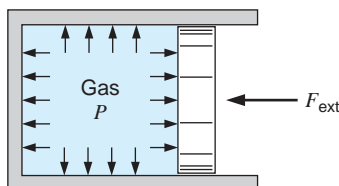
and the standard atmosphere, where

$$1 \text{ atm} = 101\,325 \text{ Pa} = 14.696 \text{ lbf/in.}^2$$

which is slightly larger than the bar. In this book, we will normally use the SI unit, the pascal, and especially the multiples of kilopascal and megapascal. The bar will be utilized often in the examples and problems, but the atmosphere will not be used, except in specifying certain reference points.

Consider a gas contained in a cylinder fitted with a movable piston, as shown in Fig. 2.10. The pressure exerted by the gas on all of its boundaries is the same, assuming that the gas is in an equilibrium state. This pressure is fixed by the external force acting on the piston, since there must be a balance of forces for the piston to remain stationary. Thus, the product of the pressure and the movable piston area must be equal to the external force. If the external force is now changed in either direction, the gas pressure inside must accordingly adjust, with appropriate movement of the piston, to establish a force balance at a new equilibrium state. As another example, if the gas in the cylinder is heated by an outside body, which tends to increase the gas pressure, the piston will move instead, such that the pressure remains equal to whatever value is required by the external force.

**FIGURE 2.10** The balance of forces on a movable boundary relates to inside gas pressure.



## EXAMPLE 2.3

The hydraulic piston/cylinder system shown in Fig. 2.11 has a cylinder diameter of  $D = 0.1$  m with a piston and rod mass of 25 kg. The rod has a diameter of 0.01 m with an outside atmospheric pressure of 101 kPa. The inside hydraulic fluid pressure is 250 kPa. How large a force can the rod push within the upward direction?

## Solution

We will assume a static balance of forces on the piston (positive upward), so

$$\begin{aligned} F_{\text{net}} &= ma = 0 \\ &= P_{\text{cyl}} A_{\text{cyl}} - P_0(A_{\text{cyl}} - A_{\text{rod}}) - F - m_p g \end{aligned}$$

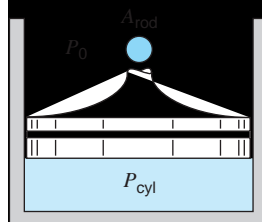


FIGURE 2.11 Sketch for Example 2.3.

Solve for  $F$ :

$$F = P_{\text{cyl}} A_{\text{cyl}} - P_0(A_{\text{cyl}} - A_{\text{rod}}) - m_p g$$

The areas are

$$A_{\text{cyl}} = \pi r^2 = \pi D^2/4 = \frac{\pi}{4} 0.1^2 \text{ m}^2 = 0.007854 \text{ m}^2$$

$$A_{\text{rod}} = \pi r^2 = \pi D^2/4 = \frac{\pi}{4} 0.01^2 \text{ m}^2 = 0.00007854 \text{ m}^2$$

So the force becomes

$$\begin{aligned} F &= [250 \times 0.007854 - 101(0.007854 - 0.00007854)]1000 - 25 \times 9.81 \\ &= 1963.5 - 785.32 - 245.25 \\ &= 932.9 \text{ N} \end{aligned}$$

Note that we must convert kPa to Pa to get units of N.

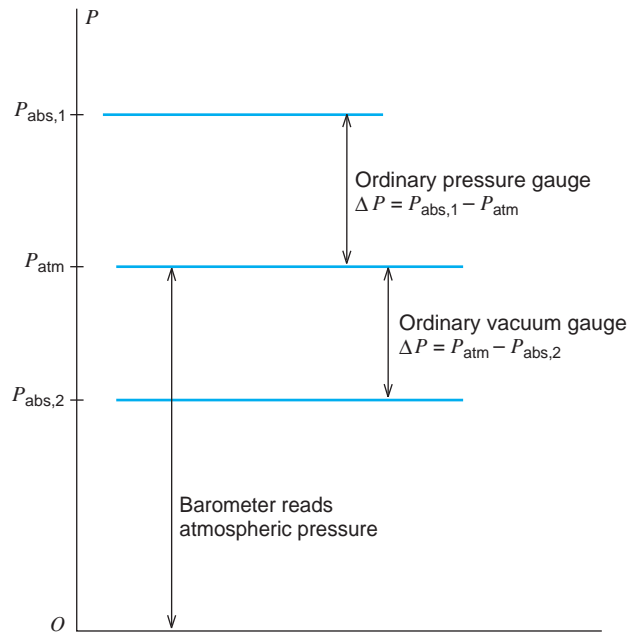
In most thermodynamic investigations we are concerned with absolute pressure. Most pressure and vacuum gauges, however, read the difference between the absolute pressure and the atmospheric pressure existing at the gauge. This is referred to as *gauge pressure*. It is shown graphically in Fig. 2.12, and the following examples illustrate the principles. Pressures below atmospheric and slightly above atmospheric, and pressure differences (for example, across an orifice in a pipe), are frequently measured with a manometer, which contains water, mercury, alcohol, oil, or other fluids.

Consider the column of fluid of height  $H$  standing above point  $B$  in the manometer shown in Fig. 2.13. The force acting downward at the bottom of the column is

$$P_0 A + mg = P_0 A + \rho A g H$$

where  $m$  is the mass of the fluid column,  $A$  is its cross-sectional area, and  $\rho$  is its density. This force must be balanced by the upward force at the bottom of the column, which is  $P_B A$ .

**FIGURE 2.12**  
Illustration of terms  
used in pressure  
measurement.



Therefore,

$$P_B - P_0 = \rho g H$$

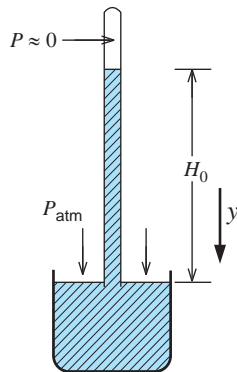
Since points *A* and *B* are at the same elevation in columns of the same fluid, their pressures must be equal (the fluid being measured in the vessel has a much lower density, such that its pressure *P* is equal to *P<sub>A</sub>*). Overall,

$$\Delta P = P - P_0 = \rho g H \quad (2.2)$$

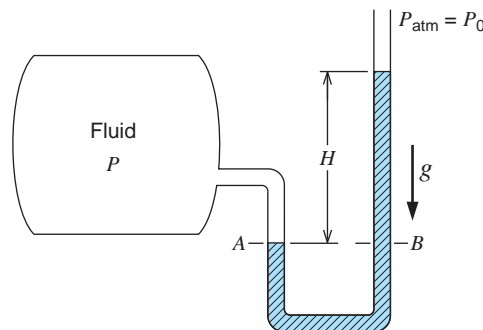
For distinguishing between absolute and gauge pressure in this book, the term *pascal* will always refer to absolute pressure. Any gauge pressure will be indicated as such.

Consider the barometer used to measure atmospheric pressure, as shown in Fig. 2.14. Since there is a near vacuum in the closed tube above the vertical column of fluid, usually mercury, the height of the fluid column gives the atmospheric pressure directly from Eq. 2.2:

$$P_{\text{atm}} = \rho g H_0 \quad (2.3)$$



**FIGURE 2.14**  
Barometer.



**FIGURE 2.13** Example of pressure  
measurement using a column of fluid.

**EXAMPLE 2.4**

A mercury barometer located in a room at 25°C has a height of 750 mm. What is the atmospheric pressure in kPa?

**Solution**

The density of mercury at 25°C is found from Appendix Table A.4 to be 13 534 kg/m<sup>3</sup>. Using Eq. 2.3,

$$\begin{aligned} P_{\text{atm}} &= \rho g H_0 = 13\,534 \times 9.806\,65 \times 0.750/1000 \\ &= 99.54 \text{ kPa} \end{aligned}$$

**EXAMPLE 2.5**

A mercury (Hg) manometer is used to measure the pressure in a vessel as shown in Fig. 2.13. The mercury has a density of 13 590 kg/m<sup>3</sup>, and the height difference between the two columns is measured to be 24 cm. We want to determine the pressure inside the vessel.

**Solution**

The manometer measures the gauge pressure as a pressure difference. From Eq. 2.2,

$$\begin{aligned} \Delta P &= P_{\text{gauge}} = \rho g H = 13\,590 \times 9.806\,65 \times 0.24 \\ &= 31\,985 \frac{\text{kg}}{\text{m}^3} \frac{\text{m}}{\text{s}^2} = 31\,985 \text{ Pa} = 31.985 \text{ kPa} \\ &= 0.316 \text{ atm} \end{aligned}$$

To get the absolute pressure inside the vessel, we have

$$P_A = P_{\text{vessel}} = P_B = \Delta P + P_{\text{atm}}$$

We need to know the atmospheric pressure measured by a barometer (absolute pressure). Assume that this pressure is known to be 750 mm Hg. The absolute pressure in the vessel becomes

$$\begin{aligned} P_{\text{vessel}} &= \Delta P + P_{\text{atm}} = 31\,985 + 13\,590 \times 0.750 \times 9.806\,65 \\ &= 31\,985 + 99\,954 = 131\,940 \text{ Pa} = 1.302 \text{ atm} \end{aligned}$$

**EXAMPLE 2.5E**

A mercury (Hg) manometer is used to measure the pressure in a vessel as shown in Fig. 2.13. The mercury has a density of 848 lbf/ft<sup>3</sup>, and the height difference between the two columns is measured to be 9.5 in. We want to determine the pressure inside the vessel.

**Solution**

The manometer measures the gauge pressure as a pressure difference. From Eq. 2.2,

$$\begin{aligned} \Delta P &= P_{\text{gauge}} = \rho g H \\ &= 848 \frac{\text{lbf}}{\text{ft}^3} \times 32.174 \frac{\text{ft}}{\text{s}^2} \times 9.5 \text{ in.} \times \frac{1}{1728} \frac{\text{ft}^3}{\text{in.}^3} \times \left[ \frac{1 \text{ lbf s}^2}{32.174 \text{ lbf ft}} \right] \\ &= 4.66 \text{ lbf/in.}^2 \end{aligned}$$

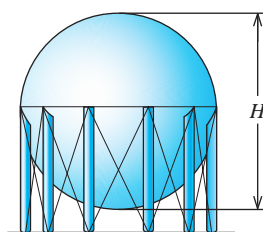
To get the absolute pressure inside the vessel, we have

$$P_A = P_{\text{vessel}} = P_0 = \Delta P + P_{\text{atm}}$$

We need to know the atmospheric pressure measured by a barometer (absolute pressure). Assume that this pressure is known to be 29.5 in. Hg. The absolute pressure in the vessel becomes

$$\begin{aligned} P_{\text{vessel}} &= \Delta P + P_{\text{atm}} \\ &= 848 \times 32.174 \times 29.5 \times \frac{1}{1728} \times \left( \frac{1}{32.174} \right) + 4.66 \\ &= 19.14 \text{ lbf/in.}^2 \end{aligned}$$

### EXAMPLE 2.6



**FIGURE 2.15** Sketch for Example 2.6.

What is the pressure at the bottom of the 7.5-m-tall storage tank of fluid at 25°C shown in Fig. 2.15? Assume that the fluid is gasoline with atmospheric pressure 101 kPa on the top surface. Repeat the question for the liquid refrigerant R-134a when the top surface pressure is 1 MPa.

#### Solution

The densities of the liquids are listed in Table A.4:

$$\rho_{\text{gasoline}} = 750 \text{ kg/m}^3; \quad \rho_{\text{R-134a}} = 1206 \text{ kg/m}^3$$

The pressure difference due to gravity is, from Eq. 2.2,

$$\Delta P = \rho g H$$

The total pressure is

$$P = P_{\text{top}} + \Delta P$$

For the gasoline we get

$$\Delta P = \rho g H = 750 \text{ kg/m}^3 \times 9.807 \text{ m/s}^2 \times 7.5 \text{ m} = 55\,164 \text{ Pa}$$

Now convert all pressures to kPa:

$$P = 101 + 55.164 = 156.2 \text{ kPa}$$

For the R-134a we get

$$\Delta P = \rho g H = 1206 \text{ kg/m}^3 \times 9.807 \text{ m/s}^2 \times 7.5 \text{ m} = 88\,704 \text{ Pa}$$

Now convert all pressures to kPa:

$$P = 1000 + 88.704 = 1089 \text{ kPa}$$

### EXAMPLE 2.7

A piston/cylinder with a cross-sectional area of 0.01 m<sup>2</sup> is connected with a hydraulic line to another piston/cylinder with a cross-sectional area of 0.05 m<sup>2</sup>. Assume that both chambers and the line are filled with hydraulic fluid of density 900 kg/m<sup>3</sup> and the larger second piston/cylinder is 6 m higher up in elevation. The telescope arm and the buckets have hydraulic piston/cylinders moving them, as seen in Fig. 2.16. With an outside atmospheric pressure of 100 kPa and a net force of 25 kN on the smallest piston, what is the balancing force on the second larger piston?



FIGURE 2.16 Sketch for Example 2.7.

**Solution**

When the fluid is stagnant and at the same elevation, we have the same pressure throughout the fluid. The force balance on the smaller piston is then related to the pressure (we neglect the rod area) as

$$F_1 + P_0 A_1 = P_1 A_1$$

from which the fluid pressure is

$$P_1 = P_0 + F_1/A_1 = 100 \text{ kPa} + 25 \text{ kN}/0.01 \text{ m}^2 = 2600 \text{ kPa}$$

The pressure at the higher elevation in piston/cylinder 2 is, from Eq. 2.2,

$$\begin{aligned} P_2 &= P_1 - \rho g H = 2600 \text{ kPa} - 900 \text{ kg/m}^3 \times 9.81 \text{ m/s}^2 \times 6 \text{ m}/(1000 \text{ Pa/kPa}) \\ &= 2547 \text{ kPa} \end{aligned}$$

where the second term is divided by 1000 to convert from Pa to kPa. Then the force balance on the second piston gives

$$F_2 + P_0 A_2 = P_2 A_2$$

$$F_2 = (P_2 - P_0) A_2 = (2547 - 100) \text{ kPa} \times 0.05 \text{ m}^2 = 122.4 \text{ kN}$$

**In-Text Concept Questions**

- e. A car tire gauge indicates 195 kPa; what is the air pressure inside?
- f. Can I always neglect  $\Delta P$  in the fluid above location A in Fig. 2.13? What circumstances does that depend on?
- g. A U tube manometer has the left branch connected to a box with a pressure of 110 kPa and the right branch open. Which side has a higher column of fluid?

**2.9 EQUALITY OF TEMPERATURE**

Although temperature is a familiar property, defining it exactly is difficult. We are aware of temperature first of all as a sense of hotness or coldness when we touch an object. We also learn early that when a hot body and a cold body are brought into contact, the hot body becomes cooler and the cold body becomes warmer. If these bodies remain in contact for

some time, they usually appear to have the same hotness or coldness. However, we also realize that our sense of hotness or coldness is very unreliable. Sometimes very cold bodies may seem hot, and bodies of different materials that are at the same temperature appear to be at different temperatures.

Because of these difficulties in defining temperature, we define [equality of temperature](#). Consider two blocks of copper, one hot and the other cold, each of which is in contact with a mercury-in-glass thermometer. If these two blocks of copper are brought into thermal communication, we observe that the electrical resistance of the hot block decreases with time and that of the cold block increases with time. After a period of time has elapsed, however, no further changes in resistance are observed. Similarly, when the blocks are first brought in thermal communication, the length of a side of the hot block decreases with time but the length of a side of the cold block increases with time. After a period of time, no further change in length of either block is perceived. In addition, the mercury column of the thermometer in the hot block drops at first and that in the cold block rises, but after a period of time no further changes in height are observed. We may say, therefore, that two bodies have equality of temperature if, when they are in thermal communication, no change in any observable property occurs.

## 2.10 THE ZEROth LAW OF THERMODYNAMICS

Now consider the same two blocks of copper and another thermometer. Let one block of copper be brought into contact with the thermometer until equality of temperature is established, and then remove it. Then let the second block of copper be brought into contact with the thermometer. Suppose that no change in the mercury level of the thermometer occurs during this operation with the second block. We then can say that both blocks are in thermal equilibrium with the given thermometer.

The zeroth law of thermodynamics states that when two bodies have equality of temperature with a third body, they in turn have equality of temperature with each other. This seems obvious to us because we are so familiar with this experiment. Because the principle is not derivable from other laws, and because it precedes the first and second laws of thermodynamics in the logical presentation of thermodynamics, it is called the [zeroth law of thermodynamics](#). This law is really the basis of temperature measurement. Every time a body has equality of temperature with the thermometer, we can say that the body has the temperature we read on the thermometer. The problem remains of how to relate temperatures that we might read on different mercury thermometers or obtain from different temperature-measuring devices, such as thermocouples and resistance thermometers. This observation suggests the need for a standard scale for temperature measurements.

## 2.11 TEMPERATURE SCALES

Two scales are commonly used for measuring temperature, namely, the Fahrenheit (after Gabriel Fahrenheit, 1686–1736) and the Celsius. The Celsius scale was formerly called the centigrade scale but is now designated the Celsius scale after Anders Celsius (1701–1744), the Swedish astronomer who devised this scale.

The Fahrenheit temperature scale is used with the English Engineering system of units and the Celsius scale with the SI unit system. Until 1954 both of these scales



were based on two fixed, easily duplicated points: the ice point and the steam point. The temperature of the ice point is defined as the temperature of a mixture of ice and water that is in equilibrium with saturated air at a pressure of 1 atm. The temperature of the steam point is the temperature of water and steam, which are in equilibrium at a pressure of 1 atm. On the Fahrenheit scale these two points are assigned the numbers 32 and 212, respectively, and on the Celsius scale the points are 0 and 100, respectively. Why Fahrenheit chose these numbers is an interesting story. In searching for an easily reproducible point, Fahrenheit selected the temperature of the human body and assigned it the number 96. He assigned the number 0 to the temperature of a certain mixture of salt, ice, and salt solution. On this scale the ice point was approximately 32. When this scale was slightly revised and fixed in terms of the ice point and steam point, the normal temperature of the human body was found to be 98.6 F.

In this book the symbols F and °C will denote the Fahrenheit and Celsius scales, respectively (the Celsius scale symbol includes the degree symbol since the letter C alone denotes Coulomb, the unit of electrical charge in the SI system of units). The symbol  $T$  will refer to temperature on all temperature scales.

At the tenth CGPM in 1954, the Celsius scale was redefined in terms of a single fixed point and the ideal-gas temperature scale. The single fixed point is the triple point of water (the state in which the solid, liquid, and vapor phases of water exist together in equilibrium). The magnitude of the degree is defined in terms of the ideal-gas temperature scale, which is discussed in Chapter 7. The essential features of this new scale are a single fixed point and a definition of the magnitude of the degree. The triple point of water is assigned the value of 0.01°C. On this scale the steam point is experimentally found to be 100.00°C. Thus, there is essential agreement between the old and new temperature scales.

We have not yet considered an absolute scale of temperature. The possibility of such a scale comes from the second law of thermodynamics and is discussed in Chapter 7. On the basis of the second law of thermodynamics, a temperature scale that is independent of any thermometric substance can be defined. This absolute scale is usually referred to as the *thermodynamic scale of temperature*. However, it is difficult to use this scale directly; therefore, a more practical scale, the International Temperature Scale, which closely represents the thermodynamic scale, has been adopted.

The absolute scale related to the Celsius scale is the Kelvin scale (after William Thomson, 1824–1907, who is also known as Lord Kelvin), and is designated K (without the degree symbol). The relation between these scales is

$$K = ^\circ C + 273.15 \quad (2.4)$$

In 1967, the CGPM defined the kelvin as 1/273.16 of the temperature at the triple point of water. The Celsius scale is now defined by this equation instead of by its earlier definition.

The absolute scale related to the Fahrenheit scale is the Rankine scale and is designated R. The relation between these scales is

$$R = F + 459.67 \quad (2.5)$$

A number of empirically based temperature scales, to standardize temperature measurement and calibration, have been in use during the last 70 years. The most recent of these is the International Temperature Scale of 1990, or ITS-90. It is based on a number of fixed and easily reproducible points that are assigned definite numerical values of temperature, and on specified formulas relating temperature to the readings on certain temperature-measuring instruments for the purpose of interpolation between the defining fixed points. Details of the

ITS-90 are not considered further in this book. This scale is a practical means for establishing measurements that conform closely to the absolute thermodynamic temperature scale.

## 2.12 ENGINEERING APPLICATIONS

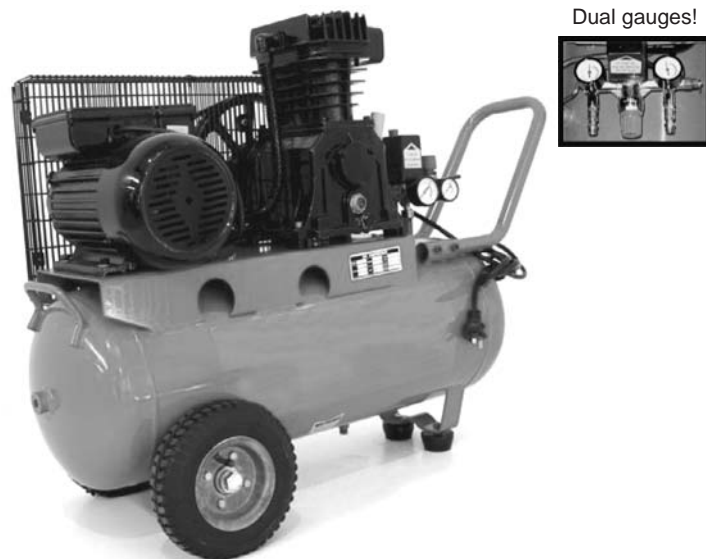
Pressure is used in applications for process control or limit control for safety reasons. In most cases, this is the gauge pressure. For instance a storage tank has a pressure indicator to show how close it is to being full, but it may also have a pressure-sensitive safety valve that will open and let material escape if the pressure exceeds a preset value. An air tank with a compressor on top is shown in Fig. 2.17; as a portable unit, it is used to drive air tools, such as nailers. A pressure gauge will activate a switch to start the compressor when the pressure drops below a preset value, and it will disengage the compressor when a preset high value is reached.

Tire pressure gauges, shown in Fig. 2.18, are connected to the valve stem on the tire. Some gauges have a digital readout. The tire pressure is important for the safety and durability of automobile tires. Too low a pressure causes large deflections and the tire may overheat; too high a pressure leads to excessive wear in the center.

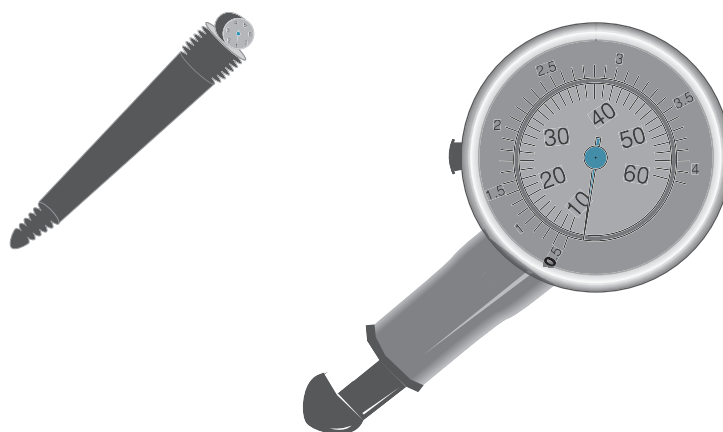
A spring-loaded pressure relief valve is shown in Fig. 2.19. With the cap the spring can be compressed to make the valve open at a higher pressure, or the opposite. This valve is used for pneumatic systems.

When a throttle plate in an intake system for an automotive engine restricts the flow (Fig. 2.20), it creates a vacuum behind it that is measured by a pressure gauge sending a signal to the computer control. The smallest absolute pressure (highest vacuum) occurs when the engine idles and the highest pressure (smallest vacuum) occurs when the engine is at full throttle. In Fig. 2.20, the throttle is shown completely closed.

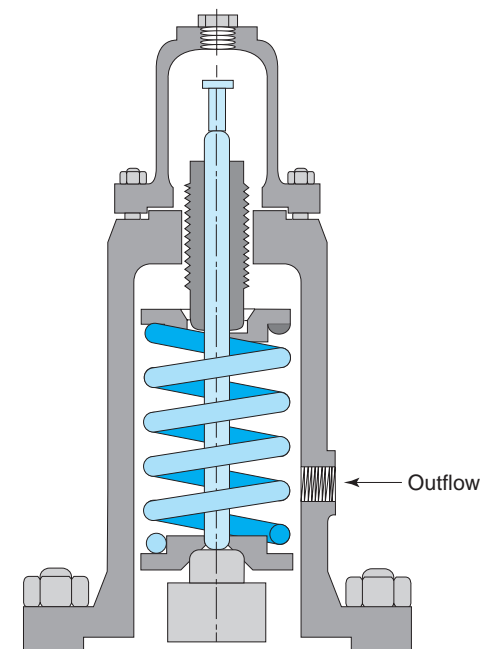
A pressure difference,  $\Delta P$ , can be used to measure flow velocity indirectly, as shown schematically in Fig. 2.21 (this effect is felt when you hold your hand out of a car window, with a higher pressure on the side facing forward and a lower pressure on the other side,



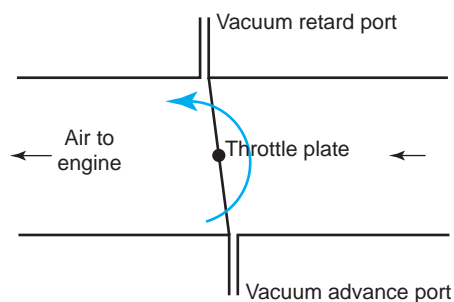
**FIGURE 2.17** Air compressor with tank.



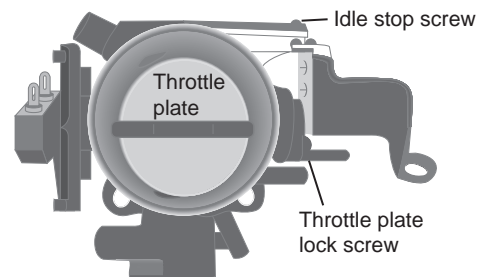
**FIGURE 2.18**  
Automotive tire pressure gauges.

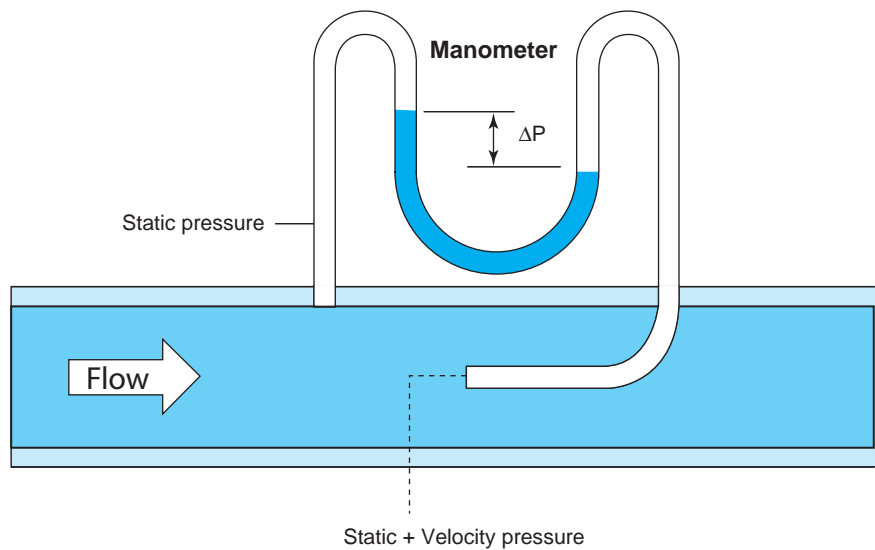


**FIGURE 2.19**  
Schematic of a pressure relief valve.



**FIGURE 2.20**  
Automotive engine intake throttle.



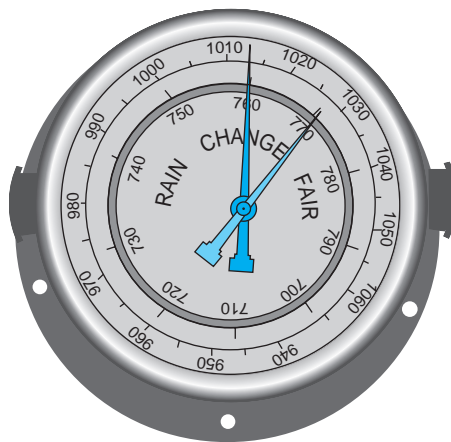


**FIGURE 2.21**  
Schematic of flow  
velocity measurement.

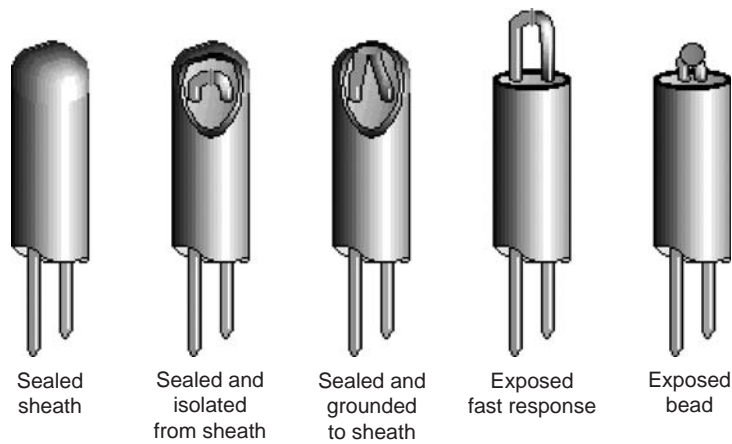
giving a net force on your hand). The engineering analysis of such processes is developed and presented in Chapter 9. In a speedboat, a small pipe has its end pointing forward, feeling the higher pressure due to the relative velocity between the boat and the water. The other end goes to a speedometer transmitting the pressure signal to an indicator.

An aneroid barometer, shown in Fig. 2.22, measures the absolute pressure used for weather predictions. It consists of a thin metal capsule or bellows that expands or contracts with atmospheric pressure. Measurement is by a mechanical pointer or by a change in electrical capacitance with distance between two plates.

Numerous types of devices are used to measure temperature. Perhaps the most familiar of these is the liquid-in-glass thermometer, in which the liquid is commonly mercury. Since the density of the liquid decreases with temperature, the height of the liquid column rises accordingly. Other liquids are also used in such thermometers, depending on the range of temperature to be measured.

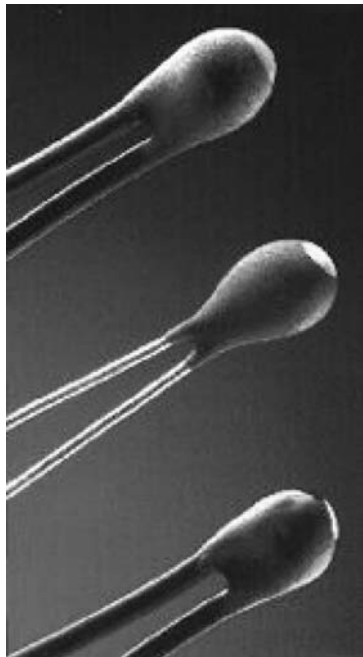


**FIGURE 2.22** Aneroid  
barometer.



**FIGURE 2.23**  
Thermocouples.

Two types of devices commonly used in temperature measurement are thermocouples and thermistors, examples of which are shown in Figs. 2.23 and 2.24, respectively. A thermocouple consists of a pair of junctions of two dissimilar metals that creates an electrical potential (voltage) that increases with the temperature difference between the junctions. One junction is maintained at a known reference temperature (for example, in an ice bath), such that the voltage measured indicates the temperature of the other junction. Different material combinations are used for different temperature ranges, and the size of the junction is kept small to have a short response time. Thermistors change their electrical resistance with temperature, so if a known current is passed through the thermistor, the voltage across it becomes proportional to the resistance. The output signal is improved if this is arranged in an electrical bridge that provides input to an instrument. The small signal from these sensors is amplified and scaled so that a meter can show the temperature or the signal can



**FIGURE 2.24**  
Thermistors.

be sent to a computer or a control system. High-precision temperature measurements are made in a similar manner using a platinum resistance thermometer. A large portion of the ITS-90 (13.8033 K to 1234.93 K) is measured in such a manner. Higher temperatures are determined from visible-spectrum radiation intensity observations.

It is also possible to measure temperature indirectly by certain pressure measurements. If the vapor pressure, discussed in Chapter 3, is accurately known as a function of temperature, then this value can be used to indicate the temperature. Also, under certain conditions, a constant-volume gas thermometer, discussed in Chapter 7, can be used to determine temperature by a series of pressure measurements.

## SUMMARY

We introduce a thermodynamic system as a **control volume**, which for a fixed mass is a **control mass**. Such a system can be **isolated**, exchanging neither mass, momentum, nor energy with its surroundings. A **closed** system versus an **open** system refers to the ability of mass exchange with the surroundings. If properties for a substance change, the **state** changes and a **process** occurs. When a substance has gone through several processes, returning to the same initial state, it has completed a **cycle**.

Basic **units** for thermodynamic and physical properties are mentioned, and most are covered in Table A.1. Thermodynamic properties such as **density**  $\rho$ , **specific volume**  $v$ , **pressure**  $P$ , and **temperature**  $T$  are introduced together with units for these properties. Properties are classified as **intensive**, independent of mass (like  $v$ ), or **extensive**, proportional to mass (like  $V$ ). Students should already be familiar with other concepts from physics such as force  $F$ , velocity  $\mathbf{V}$ , and acceleration  $a$ . Application of Newton's law of motion leads to the variation of static pressure in a column of fluid and the measurements of pressure (absolute and gauge) by barometers and manometers. The normal temperature scale and the absolute temperature scale are introduced.

You should have learned a number of skills and acquired abilities from studying this chapter that will allow you to

- Define (choose) a control volume (C.V.) around some matter; sketch the content and identify storage locations for mass; and identify mass and energy flows crossing the C.V. surface.
- Know properties  $P$ ,  $T$ ,  $v$ , and  $\rho$  and their units.
- Know how to look up conversion of units in Table A.1.
- Know that energy is stored as kinetic, potential, or internal (in molecules).
- Know that energy can be transferred.
- Know the difference between  $(v, \rho)$  and  $(V, m)$  intensive and extensive.
- Apply a force balance to a given system and relate it to pressure  $P$ .
- Know the difference between relative (gauge) and absolute pressure  $P$ .
- Understand the working of a manometer or a barometer and derive  $\Delta P$  or  $P$  from height  $H$ .
- Know the difference between a relative and an absolute temperature  $T$ .
- Be familiar with magnitudes  $(v, \rho, P, T)$ .

Most of these concepts will be repeated and reinforced in the following chapters, such as properties in Chapter 3, energy transfer as heat and work in Chapter 4, and internal energy in Chapter 5, together with their applications.

## KEY CONCEPTS AND FORMULAS

Control volume	everything inside a control surface
Pressure definition	$P = \frac{F}{A}$ (mathematical limit for small $A$ )
Specific volume	$v = \frac{V}{m}$
Density	$\rho = \frac{m}{V}$ (Tables A.3, A.4, A.5, F.2, F.3, and F.4)
Static pressure variation	$\Delta P = \rho g H$ (depth $H$ in fluid of density $\rho$ )
Absolute temperature	$T[\text{K}] = T[^\circ\text{C}] + 273.15$ $T[\text{R}] = T[\text{F}] + 459.67$
Units	Table A.1
<b>Concepts from Physics</b>	
Newton's law of motion	$F = ma$
Acceleration	$a = \frac{d^2x}{dt^2} = \frac{d\mathbf{V}}{dt}$
Velocity	$\mathbf{V} = \frac{dx}{dt}$

## CONCEPT-STUDY GUIDE PROBLEMS

- 2.1** Make a control volume around the whole power plant in Fig. 1.2 and, with the help of Fig. 1.1, list the flows of mass and energy in or out and any storage of energy. Make sure you know what is inside and what is outside your chosen control volume.
- 2.2** Make a control volume around the rocket engine in Fig. 1.12. Identify the mass flows and show where you have significant kinetic energy and where storage changes.
- 2.3** Make a control volume that includes the steam flow in the main turbine loop in the nuclear propulsion system in Fig. 1.3. Identify mass flows (hot or cold) and energy transfers that enter or leave the control volume.
- 2.4** Separate the list  $P$ ,  $F$ ,  $V$ ,  $v$ ,  $\rho$ ,  $T$ ,  $a$ ,  $m$ ,  $L$ ,  $t$ , and  $\mathbf{V}$  into intensive properties, extensive properties, and non-properties.
- 2.5** An electric dip heater is put into a cup of water and heats it from  $20^\circ\text{C}$  to  $80^\circ\text{C}$ . Show the energy flow(s) and storage and explain what changes.
- 2.6** Water in nature exists in three different phases: solid, liquid, and vapor (gas). Indicate the relative magnitude of density and the specific volume for the three phases.
- 2.7** Is density a unique measure of mass distribution in a volume? Does it vary? If so, on what kind of scale (distance)?
- 2.8** The overall density of fibers, rock wool insulation, foams, and cotton is fairly low. Why?
- 2.9** What is the approximate mass of 1 L of engine oil? Atmospheric air?
- 2.10** Can you carry  $1 \text{ m}^3$  of liquid water?
- 2.11** A heavy cabinet has four adjustable feet. What feature of the feet will ensure that they do not make dents in the floor?
- 2.12** The pressure at the bottom of a swimming pool is evenly distributed. Consider a stiff steel plate lying on the ground. Is the pressure below it just as evenly distributed?
- 2.13** Two divers swim at a depth of 20 m. One of them swims directly under a supertanker; the other avoids the tanker. Who feels greater pressure?
- 2.14** A manometer with water shows a  $\Delta P$  of  $P_0/10$ ; what is the column height difference?



- 2.15** A water skier does not sink too far down in the water if the speed is high enough. What makes that situation different from our static pressure calculations?
- 2.16** What is the lowest temperature in degrees Celsius? In degrees Kelvin?
- 2.17** Convert the formula for water density in concept problem d to be for  $T$  in degrees Kelvin.
- 2.18** A thermometer that indicates the temperature with a liquid column has a bulb with a larger volume of liquid. Why?

## HOMEWORK PROBLEMS

### Properties and Units

- 2.19** An apple “weighs” 60 g and has a volume of 75 cm<sup>3</sup> in a refrigerator at 8°C. What is the apple’s density? List three intensive and two extensive properties of the apple.
- 2.20** A steel cylinder of mass 2 kg contains 4 L of water at 25°C at 200 kPa. Find the total mass and volume of the system. List two extensive and three intensive properties of the water.
- 2.21** A storage tank of stainless steel contains 7 kg of oxygen gas and 5 kg of nitrogen gas. How many kmoles are in the tank?
- 2.22** One kilopond (1 kp) is the weight of 1 kg in the standard gravitational field. What is the weight of 1 kg in Newtons (N)?

### Force and Energy

- 2.23** The standard acceleration (at sea level and 45° latitude) due to gravity is 9.806 65 m/s<sup>2</sup>. What is the force needed to hold a mass of 2 kg at rest in this gravitational field? How much mass can a force of 1 N support?
- 2.24** A steel piston of 2.5 kg is in the standard gravitational field, where a force of 25 N is applied vertically up. Find the acceleration of the piston.
- 2.25** When you move up from the surface of the earth, the gravitation is reduced as  $g = 9.807 - 3.32 \times 10^{-6} z$ , with  $z$  being the elevation in meters. By what percentage is the weight of an airplane reduced when it cruises at 11 000 m?
- 2.26** A model car rolls down an incline with a slope such that the gravitational “pull” in the direction of motion is one-third of the standard gravitational force (see Problem 2.23). If the car has a mass of 0.06 kg, find the acceleration.
- 2.27** A van is driven at 60 km/h and is brought to a full stop with constant deceleration in 5 s. If the total mass of the van and driver is 2075 kg, find the necessary force.

- 2.28** An escalator brings four people whose total mass is 300 kg, 25 m up in a building. Explain what happens with respect to energy transfer and stored energy.
- 2.29** A car of mass 1775 kg travels with a velocity of 100 km/h. Find the kinetic energy. How high should the car be lifted in the standard gravitational field to have a potential energy that equals the kinetic energy?
- 2.30** A 1500 kg car moving at 20 km/h is accelerated at a constant rate of 4 m/s<sup>2</sup> up to a speed of 75 km/h. What are the force and total time required?
- 2.31** On the moon the gravitational acceleration is approximately one-sixth that on the surface of the earth. A 5-kg mass is “weighed” with a beam balance on the surface of the moon. What is the expected reading? If this mass is weighed with a spring scale that reads correctly for standard gravity on earth (see Problem 2.23), what is the reading?
- 2.32** The escalator cage in Problem 2.28 has a mass of 500 kg in addition to the mass of the people. How much force should the cable pull up with to have an acceleration of 1 m/s<sup>2</sup> in the upward direction?
- 2.33** A bucket of concrete with a total mass of 200 kg is raised by a crane with an acceleration of 2 m/s<sup>2</sup> relative to the ground at a location where the local gravitational acceleration is 9.5 m/s<sup>2</sup>. Find the required force.
- 2.34** A bottle of 12 kg steel has 1.75 kmoles of liquid propane. It accelerates horizontally at a rate of 3 m/s<sup>2</sup>. What is the needed force?

### Specific Volume

- 2.35** A 15-kg steel gas tank holds 300 L of liquid gasoline with a density of 800 kg/m<sup>3</sup>. If the system is decelerated with 2g, what is the needed force?
- 2.36** A power plant that separates carbon dioxide from the exhaust gases compresses it to a density of 110 kg/m<sup>3</sup> and stores it in an unminable coal seam with



a porous volume of  $100\,000\text{ m}^3$ . Find the mass that can be stored.

- 2.37** A  $1\text{-m}^3$  container is filled with 400 kg of granite stone, 200 kg of dry sand, and  $0.2\text{ m}^3$  of liquid  $25^\circ\text{C}$  water. Using properties from Tables A.3 and A.4, find the average specific volume and density of the masses when you exclude air mass and volume.
- 2.38** One kilogram of diatomic oxygen ( $\text{O}_2$ , molecular weight of 32) is contained in a 500-L tank. Find the specific volume on both a mass and a mole basis ( $v$  and  $\bar{v}$ ).
- 2.39** A tank has two rooms separated by a membrane. Room A has 1 kg of air and a volume of  $0.5\text{ m}^3$ ; room B has  $0.75\text{ m}^3$  of air with density  $0.8\text{ kg/m}^3$ . The membrane is broken, and the air comes to a uniform state. Find the final density of the air.
- 2.40** A  $5\text{-m}^3$  container is filled with 900 kg of granite (density of  $2400\text{ kg/m}^3$ ). The rest of the volume is air, with density equal to  $1.15\text{ kg/m}^3$ . Find the mass of air and the overall (average) specific volume.

### Pressure

- 2.41** The hydraulic lift in an auto-repair shop has a cylinder diameter of 0.2 m. To what pressure should the hydraulic fluid be pumped to lift 40 kg of piston/arms and 700 kg of a car?
- 2.42** A valve in the cylinder shown in Fig. P2.42 has a cross-sectional area of  $11\text{ cm}^2$  with a pressure of 735 kPa inside the cylinder and 99 kPa outside. How large a force is needed to open the valve?

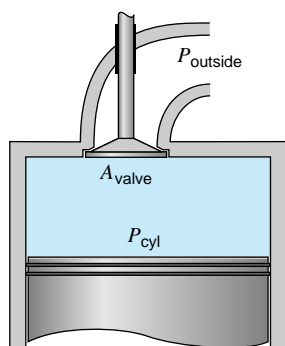


FIGURE P2.42

- 2.43** A hydraulic lift has a maximum fluid pressure of 500 kPa. What should the piston/cylinder diameter be in order to lift a mass of 850 kg?

- 2.44** A laboratory room has a vacuum of 0.1 kPa. What net force does that put on the door of size 2 m by 1 m?
- 2.45** A vertical hydraulic cylinder has a 125-mm-diameter piston with hydraulic fluid inside the cylinder and an ambient pressure of 1 bar. Assuming standard gravity, find the piston mass that will create an inside pressure of 1500 kPa.
- 2.46** A piston/cylinder with a cross-sectional area of  $0.01\text{ m}^2$  has a piston mass of 100 kg resting on the stops, as shown in Fig. P2.46. With an outside atmospheric pressure of 100 kPa, what should the water pressure be to lift the piston?

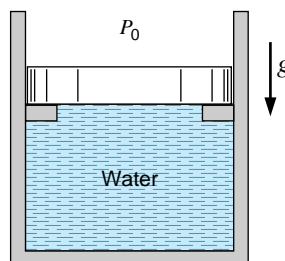


FIGURE P2.46

- 2.47** A 5-kg cannonball acts as a piston in a cylinder with a diameter of 0.15 m. As the gunpowder is burned, a pressure of 7 MPa is created in the gas behind the ball. What is the acceleration of the ball if the cylinder (cannon) is pointing horizontally?
- 2.48** Repeat the previous problem for a cylinder (cannon) pointing  $40^\circ$  up relative to the horizontal direction.
- 2.49** A large exhaust fan in a laboratory room keeps the pressure inside at 10 cm of water relative vacuum to the hallway. What is the net force on the door measuring 1.9 m by 1.1 m?
- 2.50** A tornado rips off a  $100\text{-m}^2$  roof with a mass of 1000 kg. What is the minimum vacuum pressure needed to do that if we neglect the anchoring forces?
- 2.51** A 2.5-m-tall steel cylinder has a cross-sectional area of  $1.5\text{ m}^2$ . At the bottom, with a height of 0.5 m, is liquid water, on top of which is a 1-m-high layer of gasoline. This is shown in Fig. P2.51. The gasoline surface is exposed to atmospheric air at 101 kPa. What is the highest pressure in the water?

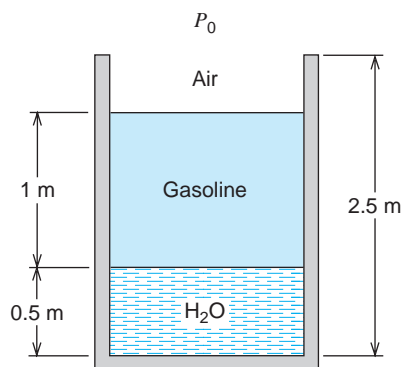


FIGURE P2.51

- 2.52** What is the pressure at the bottom of a 5-m-tall column of fluid with atmospheric pressure of 101 kPa on the top surface if the fluid is
- water at 20°C?
  - glycerine at 25°C?
  - gasoline at 25°C?
- 2.53** At the beach, atmospheric pressure is 1025 mbar. You dive 15 m down in the ocean and you later climb a hill up to 250 m in elevation. Assume that the density of water is about 1000 kg/m<sup>3</sup> and the density of air is 1.18 kg/m<sup>3</sup>. What pressure do you feel at each place?
- 2.54** A steel tank of cross-sectional area 3 m<sup>2</sup> and height 16 m weighs 10 000 kg and is open at the top, as shown in Fig. P2.54. We want to float it in the ocean so that it is positioned 10 m straight down by pouring concrete into its bottom. How much concrete should we use?

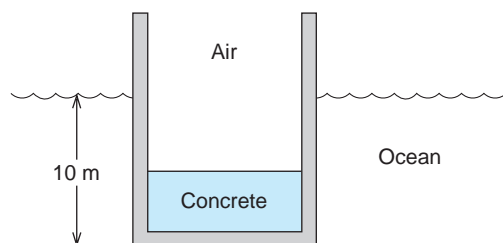


FIGURE P2.54

- 2.55** A piston,  $m_p = 5$  kg, is fitted in a cylinder,  $A = 15$  cm<sup>2</sup>, that contains a gas. The setup is in a centrifuge that creates an acceleration of 25 m/s<sup>2</sup> in the direction of piston motion toward the gas. Assuming standard atmospheric pressure outside the cylinder, find the gas pressure.

- 2.56** Liquid water with density  $\rho$  is filled on top of a thin piston in a cylinder with cross-sectional area  $A$  and total height  $H$ , as shown in Fig. P2.56. Air is let in under the piston so that it pushes up, causing the water to spill over the edge. Derive the formula for the air pressure as a function of piston elevation from the bottom,  $h$ .

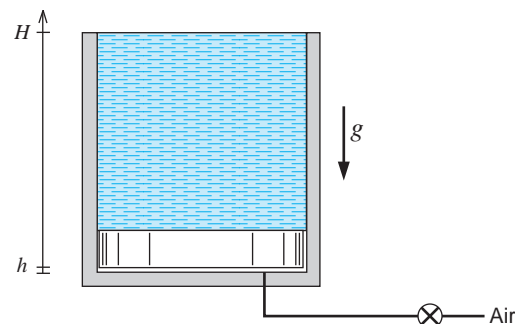


FIGURE P2.56

### Manometers and Barometers

- 2.57** You dive 5 m down in the ocean. What is the absolute pressure there?
- 2.58** A barometer to measure absolute pressure shows a mercury column height of 725 mm. The temperature is such that the density of the mercury is 13 550 kg/m<sup>3</sup>. Find the ambient pressure.
- 2.59** The density of atmospheric air is about 1.15 kg/m<sup>3</sup>, which we assume is constant. How large an absolute pressure will a pilot encounter when flying 2000 m above ground level, where the pressure is 101 kPa?
- 2.60** A differential pressure gauge mounted on a vessel shows 1.25 MPa, and a local barometer gives atmospheric pressure as 0.96 bar. Find the absolute pressure inside the vessel.
- 2.61** A manometer shows a pressure difference of 1 m of liquid mercury. Find  $\Delta P$  in kPa.
- 2.62** Blue manometer fluid of density 925 kg/m<sup>3</sup> shows a column height difference of 3 cm vacuum with one end attached to a pipe and the other open to  $P_0 = 101$  kPa. What is the absolute pressure in the pipe?
- 2.63** What pressure difference does a 10-m column of atmospheric air show?
- 2.64** The absolute pressure in a tank is 85 kPa and the local ambient absolute pressure is 97 kPa. If a U-tube with mercury (density = 13 550 kg/m<sup>3</sup>) is attached to

the tank to measure the vacuum, what column height difference will it show?

**2.65** The pressure gauge on an air tank shows 75 kPa when the diver is 10 m down in the ocean. At what depth will the gauge pressure be zero? What does that mean?

**2.66** An exploration submarine should be able to descend 4000 m down in the ocean. If the ocean density is  $1020 \text{ kg/m}^3$ , what is the maximum pressure on the submarine hull?

**2.67** A submarine maintains an internal pressure of 101 kPa and dives 240 m down in the ocean, which has an average density of  $1030 \text{ kg/m}^3$ . What is the pressure difference between the inside and the outside of the submarine hull?

**2.68** Assume that we use a pressure gauge to measure the air pressure at street level and at the roof of a tall building. If the pressure difference can be determined with an accuracy of 1 mbar (0.001 bar), what uncertainty in the height estimate does that correspond to?

**2.69** A barometer measures 760 mm Hg at street level and 735 mm Hg on top of a building. How tall is the building if we assume air density of  $1.15 \text{ kg/m}^3$ ?

**2.70** An absolute pressure gauge attached to a steel cylinder shows 135 kPa. We want to attach a manometer using liquid water on a day that  $P_{\text{atm}} = 101 \text{ kPa}$ . How high a fluid level difference must we plan for?

**2.71** A U-tube manometer filled with water (density =  $1000 \text{ kg/m}^3$ ) shows a height difference of 25 cm. What is the gauge pressure? If the right branch is tilted to make an angle of  $30^\circ$  with the horizontal, as shown in Fig. P2.71, what should the length of the column in the tilted tube be relative to the U-tube?

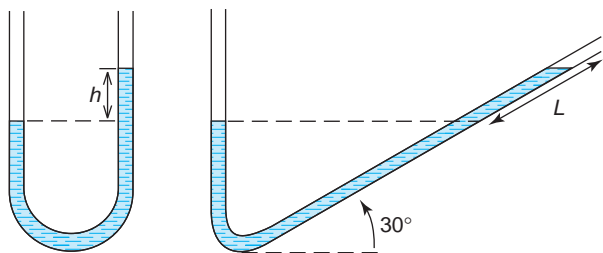


FIGURE P2.71

**2.72** A pipe flowing light oil has a manometer attached, as shown in Fig. P2.72. What is the absolute pressure in the pipe flow?

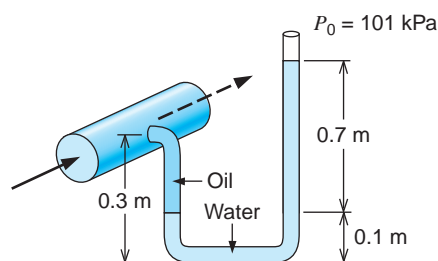


FIGURE P2.72

**2.73** The difference in height between the columns of a manometer is 200 mm, with a fluid of density  $900 \text{ kg/m}^3$ . What is the pressure difference? What is the height difference if the same pressure difference is measured using mercury (density =  $13\,600 \text{ kg/m}^3$ ) as manometer fluid?

**2.74** Two cylinders are filled with liquid water,  $\rho \simeq 1000 \text{ kg/m}^3$ , and connected by a line with a closed valve, as shown in Fig. P2.74. A has 100 kg and B has 500 kg of water, their cross-sectional areas are  $A_A = 0.1 \text{ m}^2$  and  $A_B = 0.25 \text{ m}^2$ , and the height  $h$  is 1 m. Find the pressure on either side of the valve. The valve is opened and water flows to an equilibrium. Find the final pressure at the valve location.

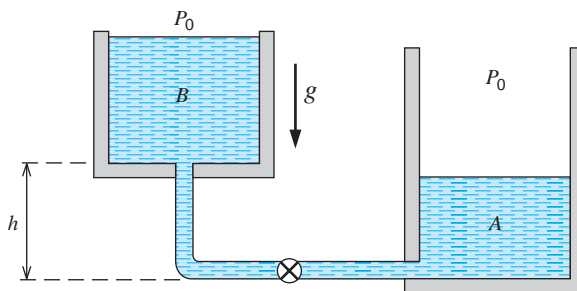


FIGURE P2.74

**2.75** Two piston/cylinder arrangements, A and B, have their gas chambers connected by a pipe, as shown in Fig. P2.75. The cross-sectional areas are  $A_A = 75 \text{ cm}^2$  and  $A_B = 25 \text{ cm}^2$ , with the piston mass in A being  $m_A = 25 \text{ kg}$ . Assume an outside pressure of 100 kPa and standard gravitation. Find the mass  $m_B$  so that none of the pistons have to rest on the bottom.

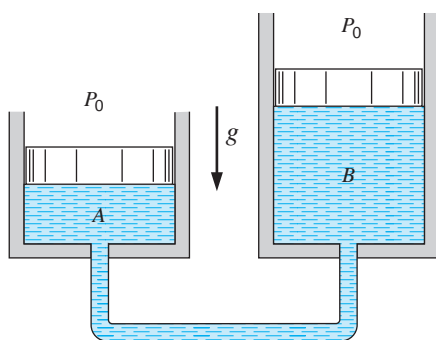


FIGURE P2.75

- 2.76** Two hydraulic piston/cylinders are of the same size and setup as in Problem 2.75, but with negligible piston masses. A single point force of 250 N presses down on piston A. Find the needed extra force on piston B so that none of the pistons have to move.
- 2.77** A piece of experimental apparatus, Fig. P2.77, is located where  $g = 9.5 \text{ m/s}^2$  and the temperature is  $5^\circ\text{C}$ . Air flow inside the apparatus is determined by measuring the pressure drop across an orifice with a mercury manometer (see Problem 2.79 for density) showing a height difference of 200 mm. What is the pressure drop in kPa?

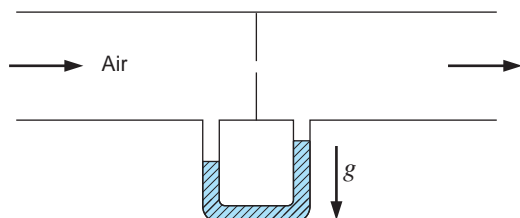


FIGURE P2.77

### Temperature

- 2.78** What is a temperature of  $-5^\circ\text{C}$  in degrees Kelvin?
- 2.79** The density of mercury changes approximately linearly with temperature as

$$\rho_{\text{Hg}} = 13\,595 - 2.5 T \text{ kg/m}^3 \quad (T \text{ in Celsius})$$

so the same pressure difference will result in a manometer reading that is influenced by temperature. If a pressure difference of 100 kPa is measured in the summer at  $35^\circ\text{C}$  and in the winter at  $-15^\circ\text{C}$ , what is the difference in column height between the two measurements?

- 2.80** A mercury thermometer measures temperature by measuring the volume expansion of a fixed mass of

liquid mercury due to a change in density (see Problem 2.79). Find the relative change (%) in volume for a change in temperature from  $10^\circ\text{C}$  to  $20^\circ\text{C}$ .

- 2.81** The density of liquid water is  $\rho = 1008 - T/2 \text{ [kg/m}^3\text{]}$  with  $T$  in  $^\circ\text{C}$ . If the temperature increases  $10^\circ\text{C}$ , how much deeper does a 1 m layer of water become?
- 2.82** Using the freezing and boiling point temperatures for water on both the Celsius and Fahrenheit scales, develop a conversion formula between the scales. Find the conversion formula between the Kelvin and Rankine temperature scales.
- 2.83** The atmosphere becomes colder at higher elevations. As an average, the standard atmospheric absolute temperature can be expressed as  $T_{\text{atm}} = 288 - 6.5 \times 10^{-3} z$ , where  $z$  is the elevation in meters. How cold is it outside an airplane cruising at 12 000 m, expressed in degrees Kelvin and Celsius?

### Review Problems

- 2.84** Repeat Problem 2.77 if the flow inside the apparatus is liquid water ( $\rho \simeq 1000 \text{ kg/m}^3$ ) instead of air. Find the pressure difference between the two holes flush with the bottom of the channel. You cannot neglect the two unequal water columns.
- 2.85** A dam retains a lake 6 m deep, as shown in Fig. P2.85. To construct a gate in the dam, we need to know the net horizontal force on a 5-m-wide, 6-m-tall port section that then replaces a 5-m section of the dam. Find the net horizontal force from the water on one side and air on the other side of the port.

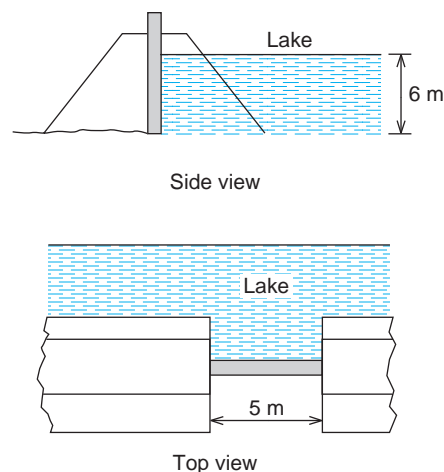


FIGURE P2.85

- 2.86** In the city water tower, water is pumped up to a level 25 m aboveground in a pressurized tank with air at 125 kPa over the water surface. This is illustrated in Fig. P2.86. Assuming water density of  $1000 \text{ kg/m}^3$  and standard gravity, find the pressure required to pump more water in at ground level.

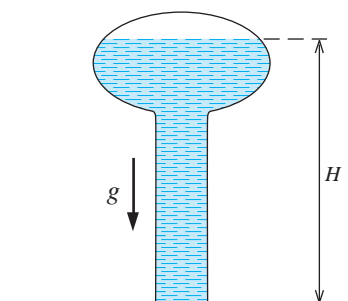


FIGURE P2.86

- 2.87** The main waterline into a tall building has a pressure of 600 kPa at 5 m elevation below ground level. The building is shown in Fig. P2.87. How much extra pressure does a pump need to add to ensure a waterline pressure of 200 kPa at the top floor 150 m aboveground?

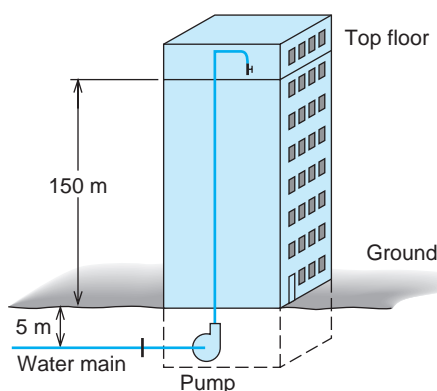


FIGURE P2.87

- 2.88** Two cylinders are connected by a piston, as shown in Fig. P2.88. Cylinder A is used as a hydraulic lift and pumped up to 500 kPa. The piston mass is 25 kg, and there is standard gravity. What is the gas pressure in cylinder B?

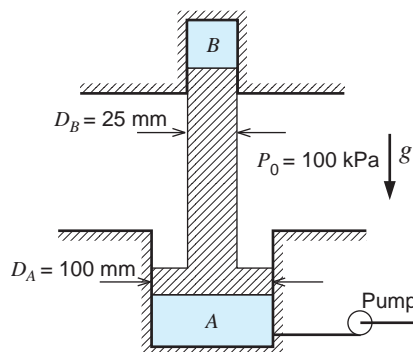


FIGURE P2.88

- 2.89** A 5-kg piston in a cylinder with diameter of 100 mm is loaded with a linear spring and the outside atmospheric pressure is 100 kPa, as shown in Fig. P2.89. The spring exerts no force on the piston when it is at the bottom of the cylinder, and for the state shown, the pressure is 400 kPa with volume 0.4 L. The valve is opened to let some air in, causing the piston to rise 2 cm. Find the new pressure.

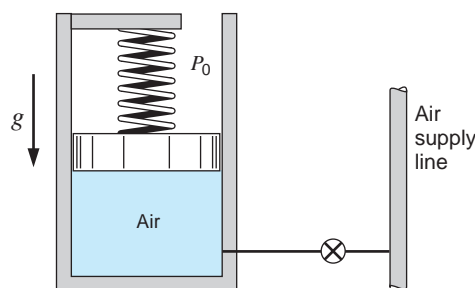


FIGURE P2.89

## ENGLISH UNIT PROBLEMS

### English Unit Concept Problems

- 2.90E** A mass of 2 lbm has an acceleration of  $5 \text{ ft/s}^2$ . What is the needed force in lbf?
- 2.91E** How much mass is in 0.25 gal of engine oil? Atmospheric air?

- 2.92E** Can you easily carry a 1-gal bar of solid gold?
- 2.93E** What is the temperature of  $-5 \text{ F}$  in degrees Rankine?
- 2.94E** What is the lowest possible temperature in degrees Fahrenheit? In degrees Rankine?

- 2.95E** What is the relative magnitude of degree Rankine to degree Kelvin?

### English Unit Problems

- 2.96E** An apple weighs 0.2 lbm and has a volume of 6 in.<sup>3</sup> in a refrigerator at 38 F. What is the apple's density? List three intensive and two extensive properties of the apple.
- 2.97E** A steel piston of mass 5 lbm is in the standard gravitational field, where a force of 10 lbf is applied vertically up. Find the acceleration of the piston.
- 2.98E** A 2500-lbm car moving at 15 mi/h is accelerated at a constant rate of 15 ft/s<sup>2</sup> up to a speed of 50 mi/h. What are the force and total time required?
- 2.99E** An escalator brings four people with a total mass of 600 lbm and a 1000 lbm cage up with an acceleration of 3 ft/s<sup>2</sup>. What is the needed force in the cable?
- 2.100E** One pound mass of diatomic oxygen (O<sub>2</sub> molecular mass 32) is contained in a 100-gal tank. Find the specific volume on both a mass and a mole basis ( $v$  and  $\bar{v}$ ).
- 2.101E** A 30-lbm steel gas tank holds 10 ft<sup>3</sup> of liquid gasoline having a density of 50 lbm/ft<sup>3</sup>. What force is needed to accelerate this combined system at a rate of 15 ft/s<sup>2</sup>?
- 2.102E** A power plant that separates carbon dioxide from the exhaust gases compresses it to a density of 8 lbm/ft<sup>3</sup> and stores it in an unminable coal seam with a porous volume of 3 500 000 ft<sup>3</sup>. Find the mass that can be stored.
- 2.103E** A laboratory room keeps a vacuum of 4 in. of water due to the exhaust fan. What is the net force on a door of size 6 ft by 3 ft?
- 2.104E** A valve in a cylinder has a cross-sectional area of 2 in.<sup>2</sup> with a pressure of 100 psia inside the cylinder and 14.7 psia outside. How large a force is needed to open the valve?
- 2.105E** A manometer shows a pressure difference of 1 ft of liquid mercury. Find  $\Delta P$  in psi.
- 2.106E** A tornado rips off a 1000-ft<sup>2</sup> roof with a mass of 2000 lbm. What is the minimum vacuum pressure needed to do that if we neglect the anchoring forces?
- 2.107E** A 7-ft-m tall steel cylinder has a cross-sectional area of 15 ft<sup>2</sup>. At the bottom, with a height of 2 ft, is liquid water, on top of which is a 4-ft-high layer of gasoline. The gasoline surface is exposed to atmospheric air at 14.7 psia. What is the highest pressure in the water?
- 2.108E** A U-tube manometer filled with water, density 62.3 lbm/ft<sup>3</sup>, shows a height difference of 10 in. What is the gauge pressure? If the right branch is tilted to make an angle of 30° with the horizontal, as shown in Fig. P2.71, what should the length of the column in the tilted tube be relative to the U-tube?
- 2.109E** A piston/cylinder with a cross-sectional area of 0.1 ft<sup>2</sup> has a piston mass of 200 lbm resting on the stops, as shown in Fig. P2.46. With an outside atmospheric pressure of 1 atm, what should the water pressure be to lift the piston?
- 2.110E** The main waterline into a tall building has a pressure of 90 psia at 16 ft elevation below ground level. How much extra pressure does a pump need to add to ensure a waterline pressure of 30 psia at the top floor 450 ft above ground?
- 2.111E** A piston,  $m_p = 10$  lbm, is fitted in a cylinder,  $A = 2.5$  in.<sup>2</sup>, that contains a gas. The setup is in a centrifuge that creates an acceleration of 75 ft/s<sup>2</sup>. Assuming standard atmospheric pressure outside the cylinder, find the gas pressure.
- 2.112E** The atmosphere becomes colder at higher elevations. As an average, the standard atmospheric absolute temperature can be expressed as  $T_{\text{atm}} = 518 - 3.84 \times 10^{-3} z$ , where  $z$  is the elevation in feet. How cold is it outside an airplane cruising at 32 000 ft expressed in degrees Rankine and Fahrenheit?
- 2.113E** The density of mercury changes approximately linearly with temperature as

$$\rho_{\text{Hg}} = 851.5 - 0.086 T \quad \text{lbm/ft}^3 \quad (T \text{ in degrees Fahrenheit})$$

so the same pressure difference will result in a manometer reading that is influenced by temperature. If a pressure difference of 14.7 lbf/in.<sup>2</sup> is measured in the summer at 95 F and in the winter at 5 F, what is the difference in column height between the two measurements?



## COMPUTER, DESIGN AND OPEN-ENDED PROBLEMS

- 2.114** Write a program to list corresponding temperatures in °C, K, F, and R from  $-50^{\circ}\text{C}$  to  $100^{\circ}\text{C}$  in increments of 10 degrees.
- 2.115** Write a program that will input pressure in kPa, atm, or lbf/in.<sup>2</sup> and write the pressure in kPa, atm, bar, and lbf/in.<sup>2</sup>
- 2.116** Write a program to do the temperature correction on a mercury barometer reading (see Problem 2.64). Input the reading and temperature and output the corrected reading at  $20^{\circ}\text{C}$  and pressure in kPa.
- 2.117** Make a list of different weights and scales that are used to measure mass directly or indirectly. Investigate the ranges of mass and the accuracy that can be obtained.
- 2.118** Thermometers are based on several principles. Expansion of a liquid with a rise in temperature is used in many applications. Electrical resistance, thermistors, and thermocouples are common in instrumentation and remote probes. Investigate a variety of thermometers and list their range, accuracy, advantages, and disadvantages.
- 2.119** Collect information for a resistance-, thermistor-, and thermocouple-based thermometer suitable for the range of temperatures from  $0^{\circ}\text{C}$  to  $200^{\circ}\text{C}$ . For each of the three types, list the accuracy and response of the transducer (output per degree change). Is any calibration or correction necessary when it is used in an instrument?
- 2.120** A thermistor is used as a temperature transducer. Its resistance changes with temperature approximately as

$$R = R_0 \exp[\alpha(1/T - 1/T_0)]$$

where it has resistance  $R_0$  at temperature  $T_0$ . Select the constants as  $R_0 = 3000\ \Omega$  and  $T_0 = 298\ \text{K}$ ,

and compute  $\alpha$  so that it has a resistance of  $200\ \Omega$  at  $100^{\circ}\text{C}$ . Write a program to convert a measured resistance,  $R$ , into information about the temperature. Find information for actual thermistors and plot the calibration curves with the formula given in this problem and the recommended correction given by the manufacturer.

- 2.121** Investigate possible transducers for the measurement of temperature in a flame with temperatures near  $1000\ \text{K}$ . Are any transducers available for a temperature of  $2000\ \text{K}$ ?
- 2.122** Devices to measure pressure are available as differential or absolute pressure transducers. Make a list of five different differential pressure transducers to measure pressure differences in order of  $100\ \text{kPa}$ . Note their accuracy, response (linear ?), and price.
- 2.123** Blood pressure is measured with a sphygmomanometer while the sound from the pulse is checked. Investigate how this works, list the range of pressures normally recorded as the systolic (high) and diastolic (low) pressures, and present your findings in a short report.
- 2.124** A micromanometer uses a fluid with density  $1000\ \text{kg/m}^3$ , and it is able to measure height difference with an accuracy of  $\pm 0.5\ \text{mm}$ . Its range is a maximum height difference of  $0.5\ \text{m}$ . Investigate if any transducers are available to replace the micromanometer.
- 2.125** An experiment involves the measurements of temperature and pressure of a gas flowing in a pipe at  $300^{\circ}\text{C}$  and  $250\ \text{kPa}$ . Write a report with a suggested set of transducers (at least two alternatives for each) and give the expected accuracy and cost.

# Properties of a Pure Substance

## 3

In the previous chapter we considered three familiar properties of a substance: specific volume, pressure, and temperature. We now turn our attention to pure substances and consider some of the phases in which a pure substance may exist, the number of independent properties a pure substance may have, and methods of presenting thermodynamic properties.

Properties and the behavior of substances are very important for our studies of devices and thermodynamic systems. The steam power plant in Fig. 1.1 and the nuclear propulsion system in Fig. 1.3 have very similar processes, using water as the working substance. Water vapor (steam) is made by boiling at high pressure in the steam generator followed by expansion in the turbine to a lower pressure, cooling in the condenser, and a return to the boiler by a pump that raises the pressure. We must know the properties of water to properly size equipment such as the burners or heat exchangers, turbine, and pump for the desired transfer of energy and the flow of water. As the water is transformed from liquid to vapor, we need to know the temperature for the given pressure, and we must know the density or specific volume so that the piping can be properly dimensioned for the flow. If the pipes are too small, the expansion creates excessive velocities, leading to pressure losses and increased friction, and thus demanding a larger pump and reducing the turbine's work output.

Another example is a refrigerator, shown in Fig. 1.6, where we need a substance that will boil from liquid to vapor at a low temperature, say  $-20^{\circ}\text{C}$ . This absorbs energy from the cold space, keeping it cold. Inside the black grille in the back or at the bottom, the now hot substance is cooled by air flowing around the grille, so it condenses from vapor to liquid at a temperature slightly higher than room temperature. When such a system is designed, we need to know the pressures at which these processes take place and the amount of energy, covered in Chapter 5, that is involved. We also need to know how much volume the substance occupies, that is, the specific volume, so that the piping diameters can be selected as mentioned for the steam power plant. The substance is selected so that the pressure is reasonable during these processes; it should not be too high, due to leakage and safety concerns, and not too low, as air might leak into the system.

A final example of a system where we need to know the properties of the substance is the gas turbine and a variation thereof, namely, the jet engine shown in Fig. 1.11. In these systems, the working substance is a gas (very similar to air) and no phase change takes place. A combustion process burns fuel and air, freeing a large amount of energy, which heats the gas so that it expands. We need to know how hot the gas gets and how large the expansion is so that we can analyze the expansion process in the turbine and the exit nozzle of the jet engine. In this device, large velocities are needed inside the turbine section and for the exit of the jet engine. This high-velocity flow pushes on the blades in the turbine to create shaft work or pushes on the jet engine (called *thrust*) to move the aircraft forward.



These are just a few examples of complete thermodynamic systems where a substance goes through several processes involving changes of its thermodynamic state and therefore its properties. As your studies progress, many other examples will be used to illustrate the general subjects.

### 3.1 THE PURE SUBSTANCE

A **pure substance** is one that has a homogeneous and invariable chemical composition. It may exist in more than one phase, but the chemical composition is the same in all phases. Thus, liquid water, a mixture of liquid water and water vapor (steam), and a mixture of ice and liquid water are all pure substances; every phase has the same chemical composition. In contrast, a mixture of liquid air and gaseous air is not a pure substance because the composition of the liquid phase is different from that of the vapor phase.

Sometimes a mixture of gases, such as air, is considered a pure substance as long as there is no change of phase. Strictly speaking, this is not true. As we will see later, we should say that a mixture of gases such as air exhibits some of the characteristics of a pure substance as long as there is no change of phase.

In this book the emphasis will be on simple **compressible** substances. This term designates substances whose surface effects, magnetic effects, and electrical effects are insignificant when dealing with the substances. But changes in volume, such as those associated with the expansion of a gas in a cylinder, are very important. Reference will be made, however, to other substances for which surface, magnetic, and electrical effects are important. We will refer to a system consisting of a simple compressible substance as a *simple compressible system*.

### 3.2 VAPOR–LIQUID–SOLID-PHASE EQUILIBRIUM IN A PURE SUBSTANCE



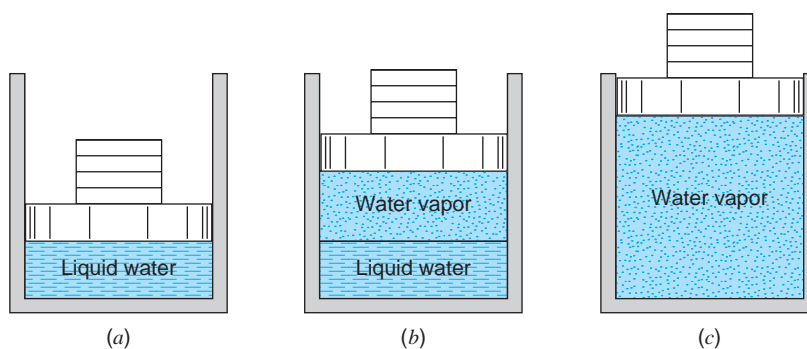
Consider as a system 1 kg of water contained in the piston/cylinder arrangement shown in Fig. 3.1*a*. Suppose that the piston and weight maintain a pressure of 0.1 MPa in the cylinder and that the initial temperature is 20°C. As heat is transferred to the water, the temperature increases appreciably, the specific volume increases slightly, and the pressure remains constant. When the temperature reaches 99.6°C, additional heat transfer results in a change of phase, as indicated in Fig. 3.1*b*. That is, some of the liquid becomes vapor, and during this process both the temperature and pressure remain constant, but the specific volume increases considerably. When the last drop of liquid has vaporized, further transfer of heat results in an increase in both the temperature and specific volume of the vapor, as shown in Fig. 3.1*c*.

The term **saturation temperature** designates the temperature at which vaporization takes place at a given pressure. This pressure is called the **saturation pressure** for the given temperature. Thus, for water at 99.6°C the saturation pressure is 0.1 MPa, and for water at 0.1 MPa the saturation temperature is 99.6°C. For a pure substance there is a definite relation between saturation pressure and saturation temperature. A typical curve, called the *vapor-pressure curve*, is shown in Fig. 3.2.

If a substance exists as liquid at the saturation temperature and pressure, it is called a **saturated liquid**. If the temperature of the liquid is lower than the saturation temperature for

**FIGURE 3.1**

Constant-pressure change from liquid to vapor phase for a pure substance.



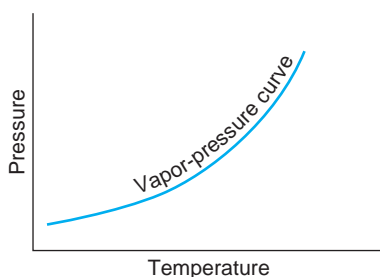
the existing pressure, it is called either a **subcooled liquid** (implying that the temperature is lower than the saturation temperature for the given pressure) or a **compressed liquid** (implying that the pressure is greater than the saturation pressure for the given temperature). Either term may be used, but the latter term will be used in this book.

When a substance exists as part liquid and part vapor at the saturation temperature, its **quality** is defined as the ratio of the mass of vapor to the total mass. Thus, in Fig. 3.1*b*, if the mass of the vapor is 0.2 kg and the mass of the liquid is 0.8 kg, the quality is 0.2 or 20%. The quality may be considered an intensive property and has the symbol  $x$ . Quality has meaning only when the substance is in a saturated state, that is, at saturation pressure and temperature.

If a substance exists as vapor at the saturation temperature, it is called **saturated vapor**. (Sometimes the term *dry saturated vapor* is used to emphasize that the quality is 100%.) When the vapor is at a temperature greater than the saturation temperature, it is said to exist as **superheated vapor**. The pressure and temperature of superheated vapor are independent properties, since the temperature may increase while the pressure remains constant. Actually, the substances we call gases are highly superheated vapors.

Consider Fig. 3.1 again. Let us plot on the temperature–volume diagram of Fig. 3.3 the constant-pressure line that represents the states through which the water passes as it is heated from the initial state of 0.1 MPa and 20°C. Let state *A* represent the initial state, *B* the saturated-liquid state (99.6°C), and line *AB* the process in which the liquid is heated from the initial temperature to the saturation temperature. Point *C* is the saturated-vapor state, and line *BC* is the constant-temperature process in which the change of phase from liquid to vapor occurs. Line *CD* represents the process in which the steam is superheated at constant pressure. Temperature and volume both increase during this process.

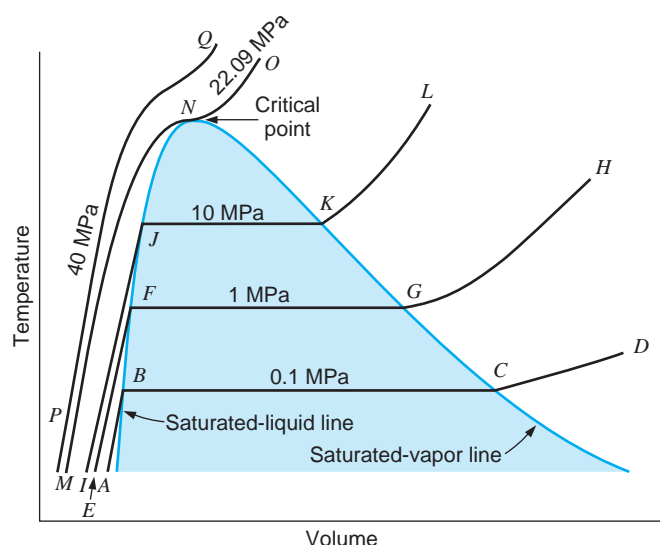
Now let the process take place at a constant pressure of 1 MPa, starting from an initial temperature of 20°C. Point *E* represents the initial state, in which the specific volume

**FIGURE 3.2**

Vapor-pressure curve of a pure substance.

**FIGURE 3.3**

Temperature–volume diagram for water showing liquid and vapor phases (not to scale).



is slightly less than that at 0.1 MPa and 20°C. Vaporization begins at point *F*, where the temperature is 179.9°C. Point *G* is the saturated-vapor state, and line *GH* is the constant-pressure process in which the steam is superheated.

In a similar manner, a constant pressure of 10 MPa is represented by line *IKL*, for which the saturation temperature is 311.1°C.

At a pressure of 22.09 MPa, represented by line *MNO*, we find, however, that there is no constant-temperature vaporization process. Instead, point *N* is a point of inflection with a zero slope. This point is called the **critical point**. At the critical point the saturated-liquid and saturated-vapor states are identical. The temperature, pressure, and specific volume at the critical point are called the *critical temperature*, *critical pressure*, and *critical volume*. The critical-point data for some substances are given in Table 3.1. More extensive data are given in Table A.2 in Appendix A.

A constant-pressure process at a pressure greater than the critical pressure is represented by line *PQ*. If water at 40 MPa and 20°C is heated in a constant-pressure process in a cylinder, as shown in Fig. 3.1, two phases will never be present and the state shown in Fig. 3.1*b* will never exist. Instead, there will be a continuous change in density, and at all times only one phase will be present. The question then is, when do we have a liquid and when do we have a vapor? The answer is that this is not a valid question at supercritical pressures. We simply call the substance a *fluid*. However, rather arbitrarily, at temperatures below the

**TABLE 3.1**

*Some Critical-Point Data*

	Critical Temperature, °C	Critical Pressure, MPa	Critical Volume, m <sup>3</sup> /kg
Water	374.14	22.09	0.003 155
Carbon dioxide	31.05	7.39	0.002 143
Oxygen	−118.35	5.08	0.002 438
Hydrogen	−239.85	1.30	0.032 192

critical temperature we usually refer to it as a *compressed liquid* and at temperatures above the critical temperature as a *superheated vapor*. It should be emphasized, however, that at pressures above the critical pressure a liquid phase and a vapor phase of a pure substance never exist in equilibrium.

In Fig. 3.3, line *NJFB* represents the saturated-liquid line and line *NKGC* represents the saturated-vapor line.

By convention, the subscript *f* is used to designate a property of a saturated liquid and the subscript *g* a property of a saturated vapor (the subscript *g* being used to denote saturation temperature and pressure). Thus, a saturation condition involving part liquid and part vapor, such as that shown in Fig. 3.1*b*, can be shown on *T*–*v* coordinates, as in Fig. 3.4. All of the liquid present is at state *f* with specific volume  $v_f$  and all of the vapor present is at state *g* with  $v_g$ . The total volume is the sum of the liquid volume and the vapor volume, or

$$V = V_{\text{liq}} + V_{\text{vap}} = m_{\text{liq}}v_f + m_{\text{vap}}v_g$$

The average specific volume of the system *v* is then

$$v = \frac{V}{m} = \frac{m_{\text{liq}}}{m} v_f + \frac{m_{\text{vap}}}{m} v_g = (1 - x)v_f + xv_g \quad (3.1)$$

in terms of the definition of quality  $x = m_{\text{vap}}/m$ .

Using the definition

$$v_{fg} = v_g - v_f$$

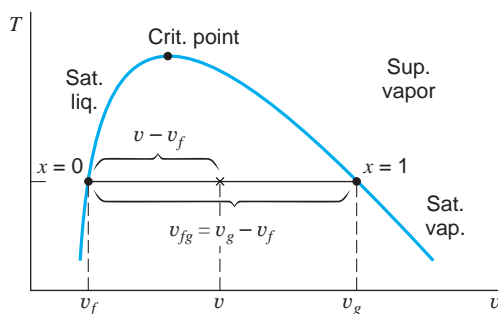
Eq. 3.1 can also be written as

$$v = v_f + xv_{fg} \quad (3.2)$$

Now the quality *x* can be viewed as the fraction  $(v - v_f)/v_{fg}$  of the distance between saturated liquid and saturated vapor, as indicated in Fig. 3.4.

Let us now consider another experiment with the piston/cylinder arrangement. Suppose that the cylinder contains 1 kg of ice at  $-20^\circ\text{C}$ , 100 kPa. When heat is transferred to the ice, the pressure remains constant, the specific volume increases slightly, and the temperature increases until it reaches  $0^\circ\text{C}$ , at which point the ice melts and the temperature remains constant. In this state the ice is called a *saturated solid*. For most substances the specific volume increases during this melting process, but for water the specific volume of the liquid is less than the specific volume of the solid. When all the ice has melted, further heat transfer causes an increase in the temperature of the liquid.

If the initial pressure of the ice at  $-20^\circ\text{C}$  is 0.260 kPa, heat transfer to the ice results in an increase in temperature to  $-10^\circ\text{C}$ . At this point, however, the ice passes directly from



**FIGURE 3.4** *T*–*v* diagram for the two-phase liquid–vapor region showing the quality–specific volume relation.

TABLE 3.2  
Some Solid–Liquid–Vapor Triple-Point Data

	Temperature, °C	Pressure, kPa
Hydrogen (normal)	−259	7.194
Oxygen	−219	0.15
Nitrogen	−210	12.53
Carbon dioxide	−56.4	520.8
Mercury	−39	0.000 000 13
Water	0.01	0.6113
Zinc	419	5.066
Silver	961	0.01
Copper	1083	0.000 079

the solid phase to the vapor phase in the process known as **sublimation**. Further heat transfer results in superheating of the vapor.

Finally, consider an initial pressure of the ice of 0.6113 kPa and a temperature of  $-20^{\circ}\text{C}$ . Through heat transfer, let the temperature increase until it reaches  $0.01^{\circ}\text{C}$ . At this point, however, further heat transfer may cause some of the ice to become vapor and some to become liquid, for at this point it is possible to have the three phases in equilibrium. This point is called the **triple point**, defined as the state in which all three phases may be present in equilibrium. The pressure and temperature at the triple point for a number of substances are given in Table 3.2.

This whole matter is best summarized by Fig. 3.5, which shows how the solid, liquid, and vapor phases may exist together in equilibrium. Along the **sublimation line** the solid

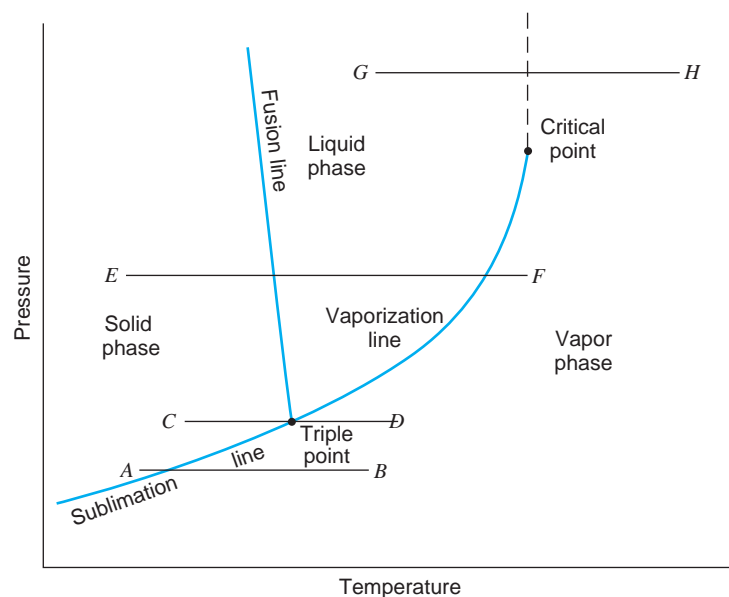


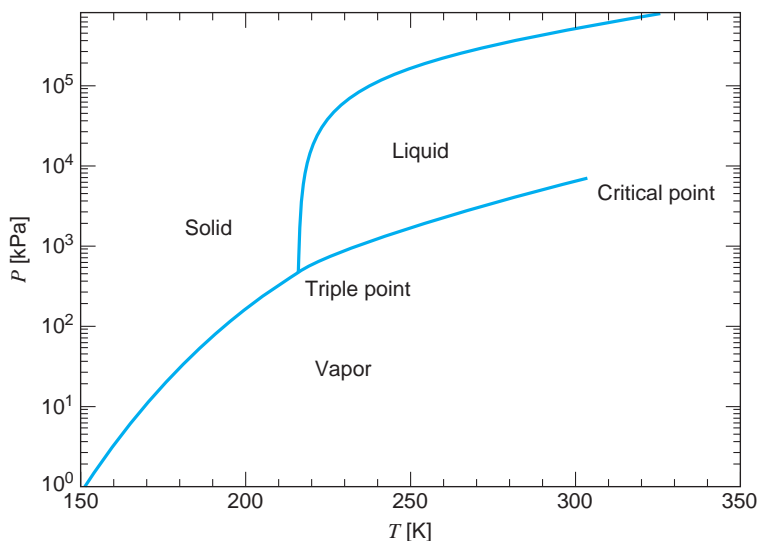
FIGURE 3.5  $P$ – $T$   
diagram for a substance  
such as water.

and vapor phases are in equilibrium, along the **fusion line** the solid and liquid phases are in equilibrium, and along the **vaporization line** the liquid and vapor phases are in equilibrium. The only point at which all three phases may exist in equilibrium is the triple point. The vaporization line ends at the critical point because there is no distinct change from the liquid phase to the vapor phase above the critical point.

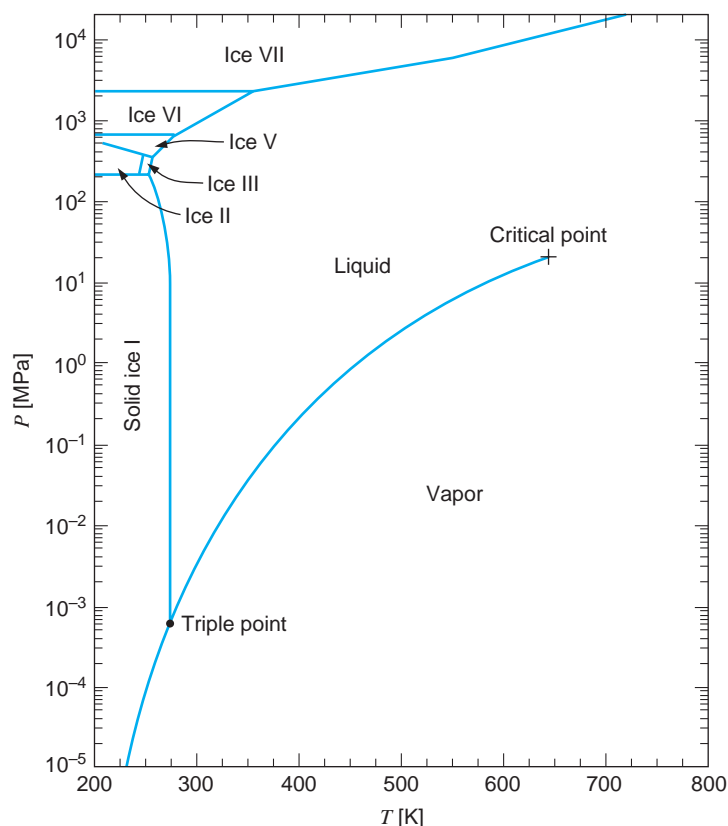
Consider a solid in state *A*, as shown in Fig. 3.5. When the temperature increases but the pressure (which is less than the triple-point pressure) is constant, the substance passes directly from the solid to the vapor phase. Along the constant-pressure line *EF*, the substance passes from the solid to the liquid phase at one temperature and then from the liquid to the vapor phase at a higher temperature. The constant-pressure line *CD* passes through the triple point, and it is only at the triple point that the three phases may exist together in equilibrium. At a pressure above the critical pressure, such as *GH*, there is no sharp distinction between the liquid and vapor phases.

Although we have made these comments with specific reference to water (only because of our familiarity with water), all pure substances exhibit the same general behavior. However, the triple-point temperature and critical temperature vary greatly from one substance to another. For example, the critical temperature of helium, as given in Table A.2, is 5.3 K. Therefore, the absolute temperature of helium at ambient conditions is over 50 times greater than the critical temperature. In contrast, water has a critical temperature of 374.14°C (647.29 K), and at ambient conditions the temperature of water is less than half the critical temperature. Most metals have a much higher critical temperature than water. When we consider the behavior of a substance in a given state, it is often helpful to think of this state in relation to the critical state or triple point. For example, if the pressure is greater than the critical pressure, it is impossible to have a liquid phase and a vapor phase in equilibrium. Or, to consider another example, the states at which vacuum melting a given metal is possible can be ascertained by a consideration of the properties at the triple point. Iron at a pressure just above 5 Pa (the triple-point pressure) would melt at a temperature of about 1535°C (the triple-point temperature).

Figure 3.6 shows the three-phase diagram for carbon dioxide, in which it is seen (see also Table 3.2) that the triple-point pressure is greater than normal atmospheric pressure,



**FIGURE 3.6** Carbon dioxide phase diagram.



**FIGURE 3.7** Water phase diagram.

which is very unusual. Therefore, the commonly observed phase transition under conditions of atmospheric pressure of about 100 kPa is a sublimation from solid directly to vapor, without passing through a liquid phase, which is why solid carbon dioxide is commonly referred to as *dry ice*. We note from Fig. 3.6 that this phase transformation at 100 kPa occurs at a temperature below 200 K.

Finally, it should be pointed out that a pure substance can exist in a number of different solid phases. A transition from one solid phase to another is called an **allotropic transformation**. Figure 3.7 shows a number of solid phases for water. A pure substance can have a number of triple points, but only one triple point has a solid, liquid, and vapor equilibrium. Other triple points for a pure substance can have two solid phases and a liquid phase, two solid phases and a vapor phase, or three solid phases.

### In-Text Concept Questions

- If the pressure is smaller than  $P_{\text{sat}}$  at a given  $T$ , what is the phase?
- An external water tap has the valve activated by a long spindle, so the closing mechanism is located well inside the wall. Why?
- What is the lowest temperature (approximately) at which water can be liquid?

### 3.3 INDEPENDENT PROPERTIES OF A PURE SUBSTANCE

One important reason for introducing the concept of a pure substance is that the state of a simple compressible pure substance (that is, a pure substance in the absence of motion, gravity, and surface, magnetic, or electrical effects) is defined by two **independent properties**. For example, if the specific volume and temperature of superheated steam are specified, the state of the steam is determined.

To understand the significance of the term *independent property*, consider the saturated-liquid and saturated-vapor states of a pure substance. These two states have the same pressure and the same temperature, but they are definitely not the same state. In a saturation state, therefore, pressure and temperature are not independent properties. Two independent properties, such as pressure and specific volume or pressure and quality, are required to specify a saturation state of a pure substance.

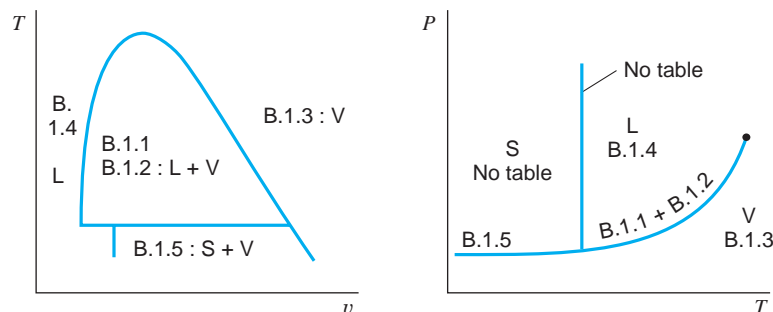
The reason for mentioning previously that a mixture of gases, such as air, has the same characteristics as a pure substance as long as only one phase is present concerns precisely this point. The state of air, which is a mixture of gases of definite composition, is determined by specifying two properties as long as it remains in the gaseous phase. Air then can be treated as a pure substance.

### 3.4 TABLES OF THERMODYNAMIC PROPERTIES

Tables of thermodynamic properties of many substances are available, and in general, all these tables have the same form. In this section we will refer to the steam tables. The steam tables are selected both because they are a vehicle for presenting thermodynamic tables and because steam is used extensively in power plants and industrial processes. Once the steam tables are understood, other thermodynamic tables can be readily used.

Several different versions of steam tables have been published over the years. The set included in Table B.1 in Appendix B is a summary based on a complicated fit to the behavior of water. It is very similar to the *Steam Tables* by Keenan, Keyes, Hill, and Moore, published in 1969 and 1978. We will concentrate here on the three properties already discussed in Chapter 2 and in Section 3.2, namely,  $T$ ,  $P$ , and  $v$ , and note that the other properties listed in the set of Tables B.1— $u$ ,  $h$ , and  $s$ —will be introduced later.

The steam tables in Appendix B consist of five separate tables, as indicated in Fig. 3.8. The region of superheated vapor in Fig. 3.5 is given in Table B.1.3, and that of compressed



**FIGURE 3.8** Listing of the steam tables.



liquid is given in Table B.1.4. The compressed-solid region shown in Fig. 3.5 is not presented in Appendix B. The saturated-liquid and saturated-vapor region, as seen in Fig. 3.3 (and as the vaporization line in Fig. 3.5), is listed according to the values of  $T$  in Table B.1.1 and according to the values of  $P$  ( $T$  and  $P$  are not independent in the two-phase regions) in Table B.1.2. Similarly, the saturated-solid and saturated-vapor region is listed according to  $T$  in Table B.1.5, but the saturated-solid and saturated-liquid region, the third phase boundary line shown in Fig. 3.5, is not listed in Appendix B.

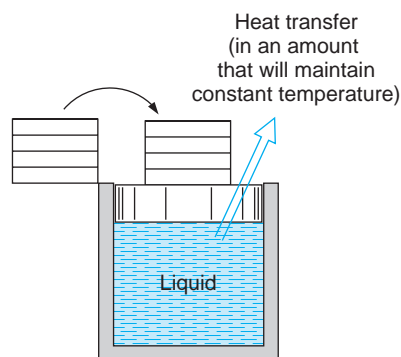
In Table B.1.1, the first column after the temperature gives the corresponding saturation pressure in kilopascals. The next three columns give the specific volume in cubic meters per kilogram. The first of these columns gives the specific volume of the saturated liquid,  $v_f$ ; the third column gives the specific volume of the saturated vapor,  $v_g$ ; and the second column gives the difference between the two,  $v_{fg}$ , as defined in Section 3.2. Table B.1.2 lists the same information as Table B.1.1, but the data are listed according to pressure, as mentioned earlier.

As an example, let us calculate the specific volume of saturated steam at  $200^\circ\text{C}$  having a quality of 70%. Using Eq. 3.1 gives

$$\begin{aligned} v &= 0.3(0.001\,156) + 0.7(0.127\,36) \\ &= 0.0895\,\text{m}^3/\text{kg} \end{aligned}$$

Table B.1.3 gives the properties of superheated vapor. In the superheated region, pressure and temperature are independent properties; therefore, for each pressure a large number of temperatures are given, and for each temperature four thermodynamic properties are listed, the first one being specific volume. Thus, the specific volume of steam at a pressure of 0.5 MPa and  $200^\circ\text{C}$  is  $0.4249\,\text{m}^3/\text{kg}$ .

Table B.1.4 gives the properties of the compressed liquid. To demonstrate the use of this table, consider a piston and a cylinder (as shown in Fig. 3.9) that contains 1 kg of saturated-liquid water at  $100^\circ\text{C}$ . Its properties are given in Table B.1.1, and we note that the pressure is 0.1013 MPa and the specific volume is  $0.001\,044\,\text{m}^3/\text{kg}$ . Suppose the pressure is increased to 10 MPa while the temperature is held constant at  $100^\circ\text{C}$  by the necessary transfer of heat,  $Q$ . Since water is slightly compressible, we would expect a slight decrease in specific volume during this process. Table B.1.4 gives this specific volume as  $0.001\,039\,\text{m}^3/\text{kg}$ . This is only a slight decrease, and only a small error would be made if one assumed that the volume of a compressed liquid is equal to the specific volume of the saturated liquid at the same temperature. In many situations this is the most convenient procedure, particularly when compressed-liquid data are not available. It is very important to note, however, that the specific volume of saturated liquid at the given pressure, 10 MPa, does



**FIGURE 3.9**

Illustration of the compressed-liquid state.

not give a good approximation. This value, from Table B.1.2, at a temperature of 311.1°C, is 0.001 452 m<sup>3</sup>/kg, which is in error by almost 40%.

Table B.1.5 of the steam tables gives the properties of saturated solid and saturated vapor that are in equilibrium. The first column gives the temperature, and the second column gives the corresponding saturation pressure. As would be expected, all these pressures are less than the triple-point pressure. The next two columns give the specific volume of the saturated solid and saturated vapor.

Appendix B also includes thermodynamic tables for several other substances; refrigerant fluids R-134a and R-410a, ammonia and carbon dioxide, and the cryogenic fluids nitrogen and methane. In each case, only two tables are given: saturated liquid-vapor listed by temperature (equivalent to Table B.1.1 for water) and superheated vapor (equivalent to Table B.1.3).

Let us now consider a number of examples to illustrate the use of thermodynamic tables for water and for the other substances listed in Appendix B.

### EXAMPLE 3.1

Determine the phase for each of the following water states using the tables in Appendix B and indicate the relative position in the  $P$ - $v$ ,  $T$ - $v$ , and  $P$ - $T$  diagrams.

- 120°C, 500 kPa
- 120°C, 0.5 m<sup>3</sup>/kg

#### Solution

- Enter Table B.1.1 with 120°C. The saturation pressure is 198.5 kPa, so we have a compressed liquid, point  $a$  in Fig. 3.10. That is above the saturation line for 120°C. We could also have entered Table B.1.2 with 500 kPa and found the saturation temperature as 151.86°C, so we would say that it is a subcooled liquid. That is to the left of the saturation line for 500 kPa, as seen in the  $P$ - $T$  diagram.

- Enter Table B.1.1 with 120°C and notice that

$$v_f = 0.00106 < v < v_g = 0.89186 \text{ m}^3/\text{kg}$$

so the state is a two-phase mixture of liquid and vapor, point  $b$  in Fig. 3.10. The state is to the left of the saturated vapor state and to the right of the saturated liquid state, both seen in the  $T$ - $v$  diagram.

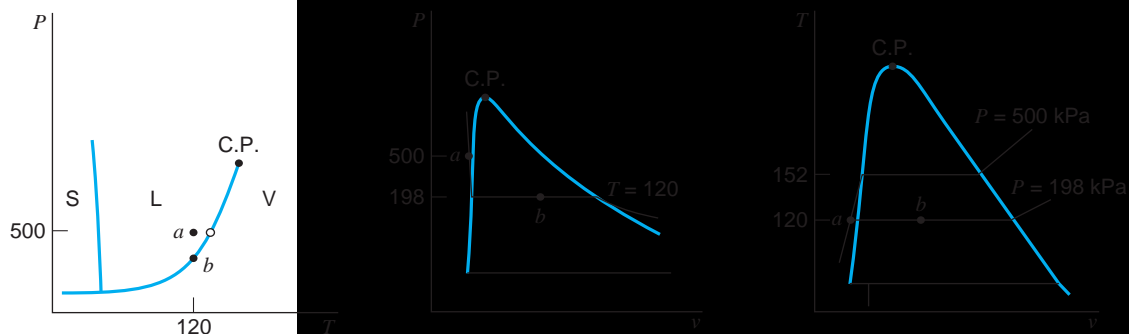


FIGURE 3.10 Diagram for Example 3.1.

**EXAMPLE 3.2**

Determine the phase for each of the following states using the tables in Appendix B and indicate the relative position in the  $P$ - $v$ ,  $T$ - $v$ , and  $P$ - $T$  diagrams, as in Figs. 3.11 and 3.12.

a. Ammonia 30°C, 1000 kPa

b. R-134a 200 kPa, 0.125 m<sup>3</sup>/kg

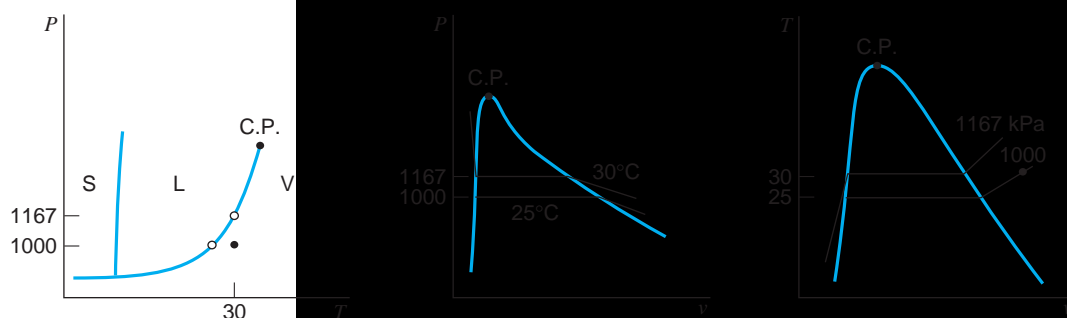
**Solution**

a. Enter Table B.2.1 with 30°C. The saturation pressure is 1167 kPa. As we have a lower  $P$ , it is a superheated vapor state. We could also have entered with 1000 kPa and found a saturation temperature of slightly less than 25°C, so we have a state that is superheated about 5°C.

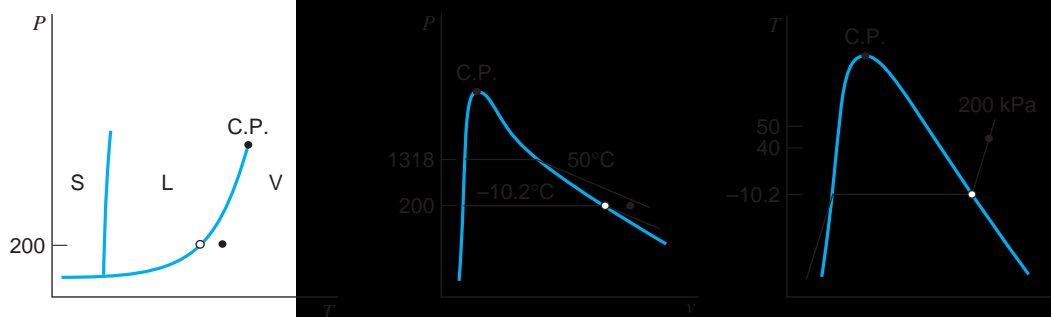
b. Enter Table B.5.2 (or B.5.1) with 200 kPa and notice that

$$v > v_g = 0.1000 \text{ m}^3/\text{kg}$$

so from the  $P$ - $v$  diagram the state is superheated vapor. We can find the state in Table B.5.2 between 40 and 50°C.



**FIGURE 3.11** Diagram for Example 3.2a.



**FIGURE 3.12** Diagram for Example 3.2b.

**EXAMPLE 3.3**

Determine the temperature and quality (if defined) for water at a pressure of 300 kPa and at each of these specific volumes:

- a.  $0.5 \text{ m}^3/\text{kg}$
- b.  $1.0 \text{ m}^3/\text{kg}$

**Solution**

For each state, it is necessary to determine what phase or phases are present in order to know which table is the appropriate one to find the desired state information. That is, we must compare the given information with the appropriate phase boundary values. Consider a  $T$ - $v$  diagram (or a  $P$ - $v$  diagram) such as the one in Fig. 3.8. For the constant-pressure line of 300 kPa shown in Fig. 3.13, the values for  $v_f$  and  $v_g$  shown there are found from the saturation table, Table B.1.2.

- a. By comparison with the values in Fig. 3.13, the state at which  $v$  is  $0.5 \text{ m}^3/\text{kg}$  is seen to be in the liquid-vapor two-phase region, at which  $T = 133.6^\circ\text{C}$ , and the quality  $x$  is found from Eq. 3.2 as

$$0.5 = 0.001073 + x(0.60475), \quad x = 0.825$$

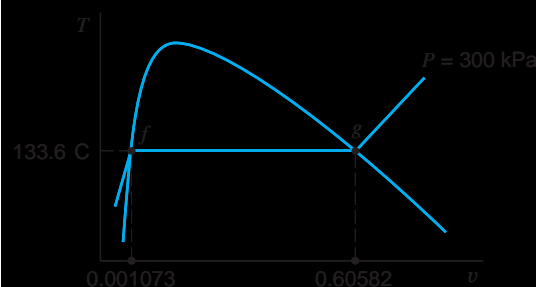
Note that if we did not have Table B.1.2 (as would be the case with the other substances listed in Appendix B), we could have interpolated in Table B.1.1 between the  $130^\circ\text{C}$  and  $135^\circ\text{C}$  entries to get the  $v_f$  and  $v_g$  values for 300 kPa.

- b. By comparison with the values in Fig. 3.13, the state at which  $v$  is  $1.0 \text{ m}^3/\text{kg}$  is seen to be in the superheated vapor region, in which quality is undefined and the temperature for which is found from Table B.1.3. In this case,  $T$  is found by linear interpolation between the 300 kPa specific-volume values at  $300^\circ\text{C}$  and  $400^\circ\text{C}$ , as shown in Fig. 3.14. This is an approximation for  $T$ , since the actual relation along the 300 kPa constant-pressure line is not exactly linear.

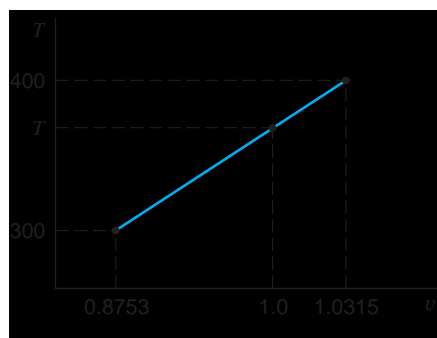
From the figure we have

$$\text{slope} = \frac{T - 300}{1.0 - 0.8753} = \frac{400 - 300}{1.0315 - 0.8753}$$

Solving this gives  $T = 379.8^\circ\text{C}$ .



**FIGURE 3.13** A  $T$ - $v$  diagram for water at 300 kPa.



**FIGURE 3.14**  $T$  and  $v$  values for superheated vapor water at 300 kPa.

### EXAMPLE 3.4

A closed vessel contains  $0.1 \text{ m}^3$  of saturated liquid and  $0.9 \text{ m}^3$  of saturated vapor R-134a in equilibrium at  $30^\circ\text{C}$ . Determine the percent vapor on a mass basis.

#### Solution

Values of the saturation properties for R-134a are found from Table B.5.1. The mass–volume relations then give

$$V_{\text{liq}} = m_{\text{liq}} v_f, \quad m_{\text{liq}} = \frac{0.1}{0.000843} = 118.6 \text{ kg}$$

$$V_{\text{vap}} = m_{\text{vap}} v_g, \quad m_{\text{vap}} = \frac{0.9}{0.02671} = 33.7 \text{ kg}$$

$$m = 152.3 \text{ kg}$$

$$x = \frac{m_{\text{vap}}}{m} = \frac{33.7}{152.3} = 0.221$$

That is, the vessel contains 90% vapor by volume but only 22.1% vapor by mass.

### EXAMPLE 3.4E

A closed vessel contains  $0.1 \text{ ft}^3$  of saturated liquid and  $0.9 \text{ ft}^3$  of saturated vapor R-134a in equilibrium at  $90^\circ\text{F}$ . Determine the percent vapor on a mass basis.

#### Solution

Values of the saturation properties for R-134a are found from Table F.10. The mass–volume relations then give

$$V_{\text{liq}} = m_{\text{liq}} v_f, \quad m_{\text{liq}} = \frac{0.1}{0.0136} = 7.353 \text{ lbm}$$

$$V_{\text{vap}} = m_{\text{vap}} v_g, \quad m_{\text{vap}} = \frac{0.9}{0.4009} = 2.245 \text{ lbm}$$

$$m = 9.598 \text{ lbm}$$

$$x = \frac{m_{\text{vap}}}{m} = \frac{2.245}{9.598} = 0.234$$

That is, the vessel contains 90% vapor by volume but only 23.4% vapor by mass.

**EXAMPLE 3.5**

A rigid vessel contains saturated ammonia vapor at 20°C. Heat is transferred to the system until the temperature reaches 40°C. What is the final pressure?

**Solution**

Since the volume does not change during this process, the specific volume also remains constant. From the ammonia tables, Table B.2.1, we have

$$v_1 = v_2 = 0.14922 \text{ m}^3/\text{kg}$$

Since  $v_g$  at 40°C is less than 0.14922 m<sup>3</sup>/kg, it is evident that in the final state the ammonia is superheated vapor. By interpolating between the 800- and 1000-kPa columns of Table B.2.2, we find that

$$P_2 = 945 \text{ kPa}$$

**EXAMPLE 3.5E**

A rigid vessel contains saturated ammonia vapor at 70 F. Heat is transferred to the system until the temperature reaches 120 F. What is the final pressure?

**Solution**

Since the volume does not change during this process, the specific volume also remains constant. From the ammonia table, Table F.8,

$$v_1 = v_2 = 2.311 \text{ ft}^3/\text{lbm}$$

Since  $v_g$  at 120 F is less than 2.311 ft<sup>3</sup>/lbm, it is evident that in the final state the ammonia is superheated vapor. By interpolating between the 125- and 150-lbf/in.<sup>2</sup> columns of Table F.8, we find that

$$P_2 = 145 \text{ lbf/in.}^2$$

**EXAMPLE 3.6**

Determine the missing property of  $P$ – $v$ – $T$  and  $x$  if applicable for the following states.

- Nitrogen: –53.2°C, 600 kPa
- Nitrogen: 100 K, 0.008 m<sup>3</sup>/kg

**Solution**

For nitrogen the properties are listed in Table B.6 with temperature in Kelvin.

- Enter in Table B.6.1 with  $T = 273.2 - 53.2 = 220 \text{ K}$ , which is higher than the critical  $T$  in the last entry. Then proceed to the superheated vapor tables. We would also have realized this by looking at the critical properties in Table A.2. From Table B.6.2 in the subsection for 600 kPa ( $T_{\text{sat}} = 96.37 \text{ K}$ )

$$v = 0.10788 \text{ m}^3/\text{kg}$$

shown as point  $a$  in Fig. 3.15.

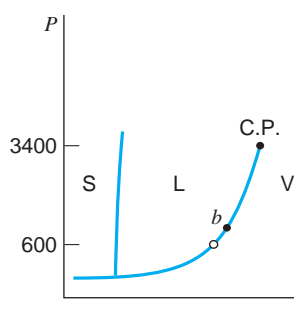
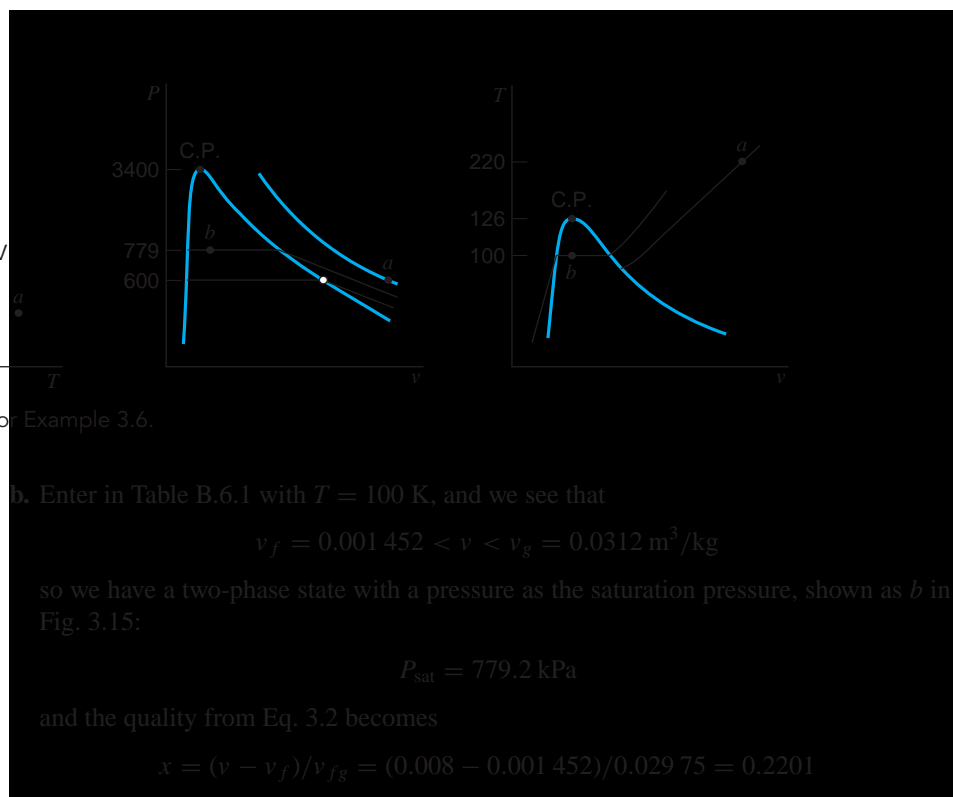


FIGURE 3.15 Diagram for Example 3.6.



### EXAMPLE 3.7

Determine the pressure for water at  $200^\circ\text{C}$  with  $v = 0.4 \text{ m}^3/\text{kg}$ .

#### Solution

Start in Table B.1.1 with  $200^\circ\text{C}$  and note that  $v > v_g = 0.12736 \text{ m}^3/\text{kg}$ , so we have superheated vapor. Proceed to Table B.1.3 at any subsection with  $200^\circ\text{C}$ ; suppose we start at 200 kPa. There  $v = 1.08034$ , which is too large, so the pressure must be higher. For 500 kPa,  $v = 0.42492$ , and for 600 kPa,  $v = 0.35202$ , so it is bracketed. This is shown in Fig. 3.16.

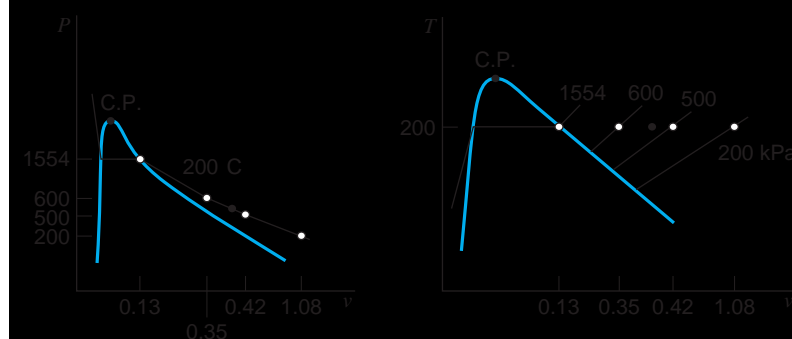
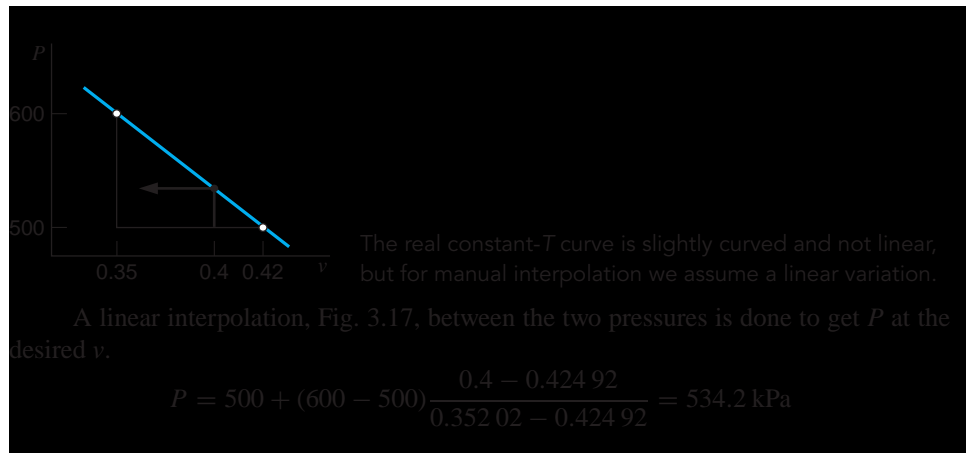


FIGURE 3.16

Diagram for Example 3.7.

**FIGURE 3.17** Linear interpolation for Example 3.7.



### In-Text Concept Questions

- d. Some tools should be cleaned in liquid water at  $150^{\circ}\text{C}$ . How high a  $P$  is needed?
- e. Water at 200 kPa has a quality of 50%. Is the volume fraction  $V_g/V_{\text{tot}} < 50\%$  or  $> 50\%$ ?
- f. Why are most of the compressed liquid or solid regions not included in the printed tables?
- g. Why is it not typical to find tables for argon, helium, neon, or air in a B-section table?
- h. What is the percent change in volume as liquid water freezes? Mention some effects the volume change can have in nature and in our households.

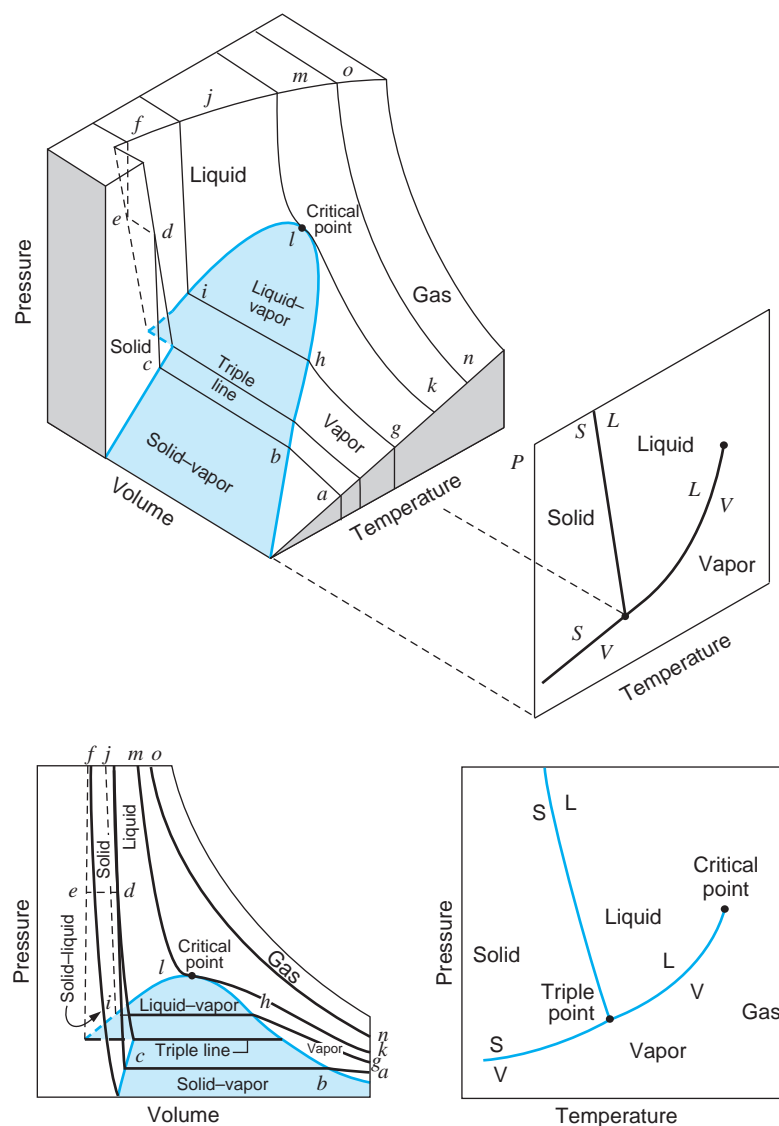
## 3.5 THERMODYNAMIC SURFACES

The matter discussed to this point can be well summarized by consideration of a **pressure-specific volume-temperature surface**. Two such surfaces are shown in Figs. 3.18 and 3.19. Figure 3.18 shows a substance such as water, in which the specific volume increases during freezing. Figure 3.19 shows a substance in which the specific volume decreases during freezing.

In these diagrams the pressure, specific volume, and temperature are plotted on mutually perpendicular coordinates, and each possible equilibrium state is thus represented by a point on the surface. This follows directly from the fact that a pure substance has only two independent intensive properties. All points along a quasi-equilibrium process lie on the  $P$ - $v$ - $T$  surface, since such a process always passes through equilibrium states.

The regions of the surface that represent a single phase—the solid, liquid, and vapor phases—are indicated. These surfaces are curved. The two-phase regions—the solid-liquid, solid-vapor, and liquid-vapor regions—are ruled surfaces. By this we understand that they are made up of straight lines parallel to the specific-volume axis. This, of course, follows from the fact that in the two-phase region, lines of constant pressure are also lines of constant temperature, although the specific volume may change. The triple point actually appears as the triple line on the  $P$ - $v$ - $T$  surface, since the pressure and temperature of the triple point are fixed, but the specific volume may vary, depending on the proportion of each phase.

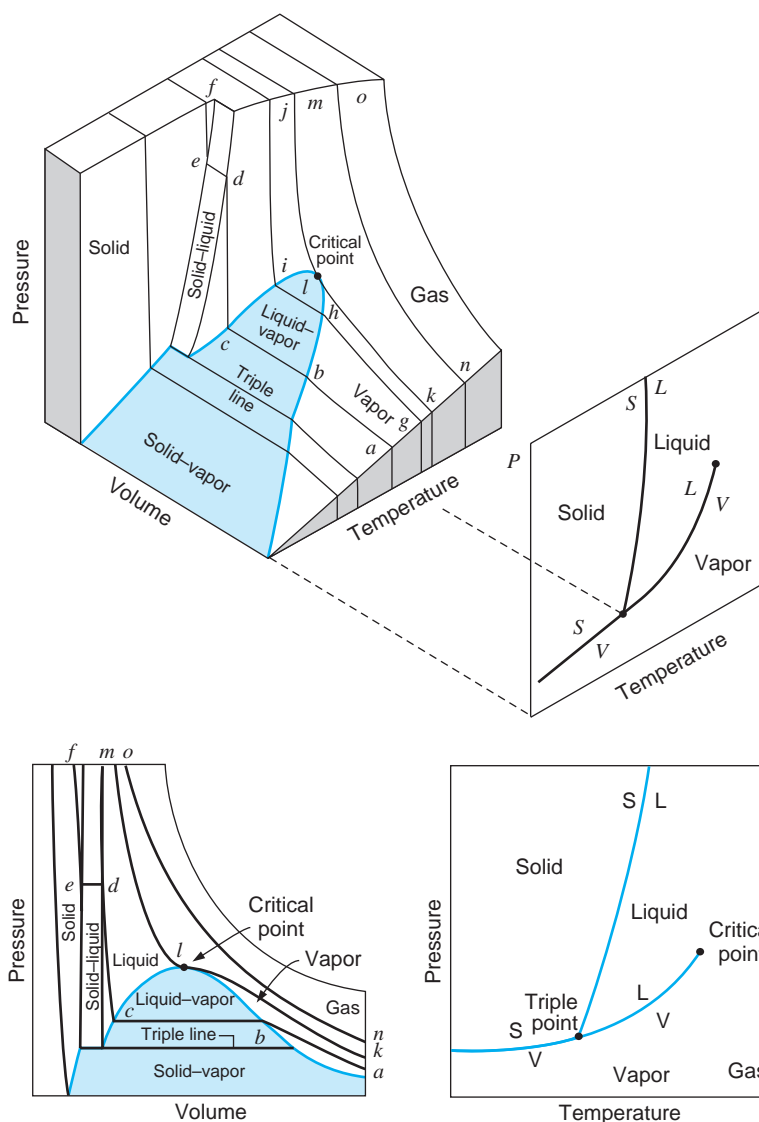




**FIGURE 3.18**  $P$ - $v$ - $T$  surface for a substance that expands on freezing.

It is also of interest to note the pressure–temperature and pressure–volume projections of these surfaces. We have already considered the pressure–temperature diagram for a substance such as water. It is on this diagram that we observe the triple point. Various lines of constant temperature are shown on the pressure–volume diagram, and the corresponding constant-temperature sections are lettered identically on the  $P$ - $v$ - $T$  surface. The critical isotherm has a point of inflection at the critical point.

Notice that for a substance such as water, which expands on freezing, the freezing temperature decreases with an increase in pressure. For a substance that contracts on freezing, the freezing temperature increases as the pressure increases. Thus, as the pressure of vapor is increased along the constant-temperature line  $abcdef$  in Fig. 3.18, a substance that



**FIGURE 3.19**  $P$ - $V$ - $T$  surface for a substance that contracts on freezing.

expands on freezing first becomes solid and then liquid. For the substance that contracts on freezing, the corresponding constant-temperature line (Fig. 3.19) indicates that as the pressure on the vapor is increased, it first becomes liquid and then solid.

### 3.6 THE $P$ - $V$ - $T$ BEHAVIOR OF LOW- AND MODERATE-DENSITY GASES

One form of energy possession by a system discussed in Section 2.6 is intermolecular (IM) potential energy, that energy associated with the forces between molecules. It was stated there that at very low densities the average distance between molecules is so large that the

IM potential energy may effectively be neglected. In such a case, the particles would be independent of one another, a situation referred to as an **ideal gas**. Under this approximation, it has been observed experimentally that, to a close approximation, a very-low-density gas behaves according to the ideal-gas equation of state

$$PV = n\bar{R}T, \quad P\bar{v} = \bar{R}T \quad (3.3)$$

in which  $n$  is the number of kmol of gas, or

$$n = \frac{m}{M} \frac{\text{kg}}{\text{kg/kmol}} \quad (3.4)$$

In Eq. 3.3,  $\bar{R}$  is the universal gas constant, the value of which is, for any gas,

$$\bar{R} = 8.3145 \frac{\text{kN m}}{\text{kmol K}} = 8.3145 \frac{\text{kJ}}{\text{kmol K}}$$

and  $T$  is the absolute (ideal-gas scale) temperature in kelvins (i.e.,  $T(\text{K}) = T(^{\circ}\text{C}) + 273.15$ ). It is important to note that  $T$  must always be the absolute temperature whenever it is being used to multiply or divide in an equation. The ideal-gas absolute temperature scale will be discussed in more detail in Chapter 7. In the English Engineering System,

$$\bar{R} = 1545 \frac{\text{ft lbf}}{\text{lb mol } R}$$

Substituting Eq. 3.4 into Eq. 3.3 and rearranging, we find that the ideal-gas equation of state can be written conveniently in the form

$$PV = mRT, \quad P\bar{v} = RT \quad (3.5)$$

where

$$R = \frac{\bar{R}}{M} \quad (3.6)$$

in which  $R$  is a different constant for each particular gas. The value of  $R$  for a number of substances is given in Table A.5 and in English units in Table F.4.

### EXAMPLE 3.8

What is the mass of air contained in a room  $6 \text{ m} \times 10 \text{ m} \times 4 \text{ m}$  if the pressure is 100 kPa and the temperature is  $25^{\circ}\text{C}$ ?

#### Solution

Assume air to be an ideal gas. By using Eq. 3.5 and the value of  $R$  from Table A.5, we have

$$m = \frac{PV}{RT} = \frac{100 \text{ kN/m}^2 \times 240 \text{ m}^3}{0.287 \text{ kN m/kg K} \times 298.2 \text{ K}} = 280.5 \text{ kg}$$

**EXAMPLE 3.9**

A tank has a volume of  $0.5 \text{ m}^3$  and contains  $10 \text{ kg}$  of an ideal gas having a molecular mass of  $24$ . The temperature is  $25^\circ\text{C}$ . What is the pressure?

**Solution**

The gas constant is determined first:

$$R = \frac{\bar{R}}{M} = \frac{8.3145 \text{ kJ m/kmol K}}{24 \text{ kg/kmol}} \\ = 0.34644 \text{ kJ m/kg K}$$

We now solve for  $P$ :

$$P = \frac{mRT}{V} = \frac{10 \text{ kg} \times 0.34644 \text{ kJ m/kg K} \times 298.2 \text{ K}}{0.5 \text{ m}^3} \\ = 2066 \text{ kPa}$$

**EXAMPLE 3.9E**

A tank has a volume of  $15 \text{ ft}^3$  and contains  $20 \text{ lbm}$  of an ideal gas having a molecular mass of  $24$ . The temperature is  $80^\circ\text{F}$ . What is the pressure?

**Solution**

The gas constant is determined first:

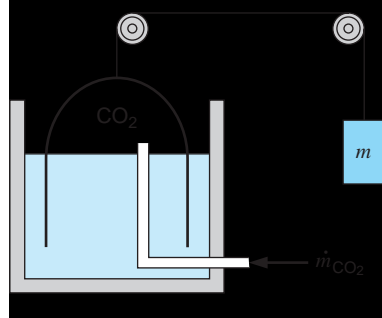
$$R = \frac{\bar{R}}{M} = \frac{1545 \text{ ft lbf/lb mol R}}{24 \text{ lbm/lb mol}} = 64.4 \text{ ft lbf/lbm R}$$

We now solve for  $P$ :

$$P = \frac{mRT}{V} = \frac{20 \text{ lbm} \times 64.4 \text{ ft lbf/lbm R} \times 540 \text{ R}}{144 \text{ in.}^2/\text{ft}^2 \times 15 \text{ ft}^3} = 321 \text{ lbf/in.}^2$$

**EXAMPLE 3.10**

A gas bell is submerged in liquid water, with its mass counterbalanced with rope and pulleys, as shown in Fig. 3.20. The pressure inside is measured carefully to be  $105 \text{ kPa}$ , and the temperature is  $21^\circ\text{C}$ . A volume increase is measured to be  $0.75 \text{ m}^3$  over a period of  $185 \text{ s}$ . What is the volume flow rate and the mass flow rate of the flow into the bell, assuming it is carbon dioxide gas?



**FIGURE 3.20** Sketch for Example 3.10.

### Solution

The volume flow rate is

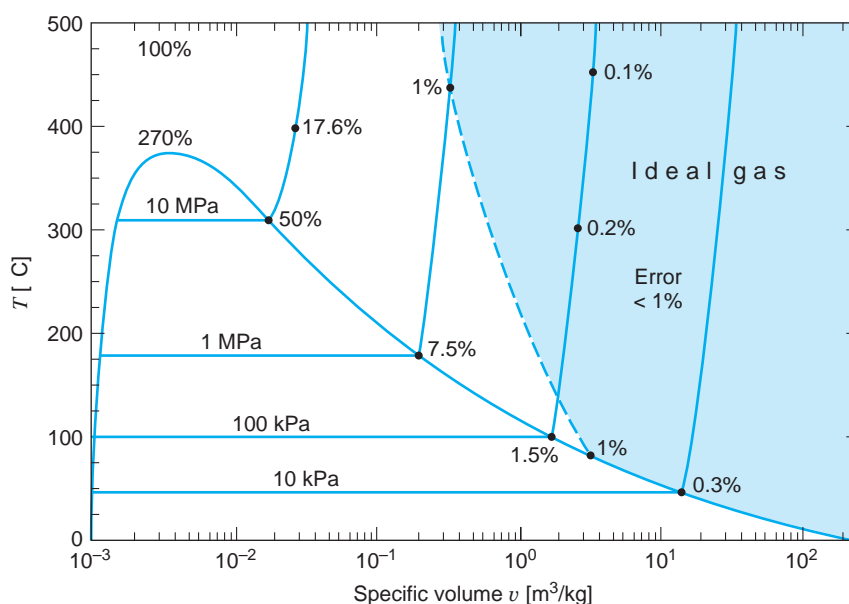
$$\dot{V} = \frac{dV}{dt} = \frac{\Delta V}{\Delta t} = \frac{0.75}{185} = 0.04054 \text{ m}^3/\text{s}$$

and the mass flow rate is  $\dot{m} = \rho \dot{V} = \dot{V}/v$ . At close to room conditions the carbon dioxide is an ideal gas, so  $PV = mRT$  or  $v = RT/P$ , and from Table A.5 we have the ideal-gas constant  $R = 0.1889 \text{ kJ/kg} \cdot \text{K}$ . The mass flow rate becomes

$$\dot{m} = \frac{P \dot{V}}{RT} = \frac{105 \times 0.04054}{0.1889(273.15 + 21)} \frac{\text{kPa m}^3/\text{s}}{\text{kJ/kg}} = 0.0766 \text{ kg/s}$$

Because of its simplicity, the ideal-gas equation of state is very convenient to use in thermodynamic calculations. However, two questions are now appropriate. The ideal-gas equation of state is a good approximation at low density. But what constitutes low density? In other words, over what range of density will the ideal-gas equation of state hold with accuracy? The second question is, how much does an actual gas at a given pressure and temperature deviate from ideal-gas behavior?

One specific example in response to these questions is shown in Fig. 3.21, a  $T$ - $v$  diagram for water that indicates the error in assuming ideal gas for saturated vapor and for superheated vapor. As would be expected, at very low pressure or high temperature the error is small, but it becomes severe as the density increases. The same general trend would occur in referring to Figs. 3.18 or 3.19. As the state becomes further removed from the saturation region (i.e., high  $T$  or low  $P$ ), the behavior of the gas becomes closer to that of the ideal-gas model.



**FIGURE 3.21**

Temperature-specific volume diagram for water.

### 3.7 THE COMPRESSIBILITY FACTOR

A more quantitative study of the question of the ideal-gas approximation can be conducted by introducing the **compressibility factor**  $Z$ , defined as

$$Z = \frac{Pv}{RT}$$

or

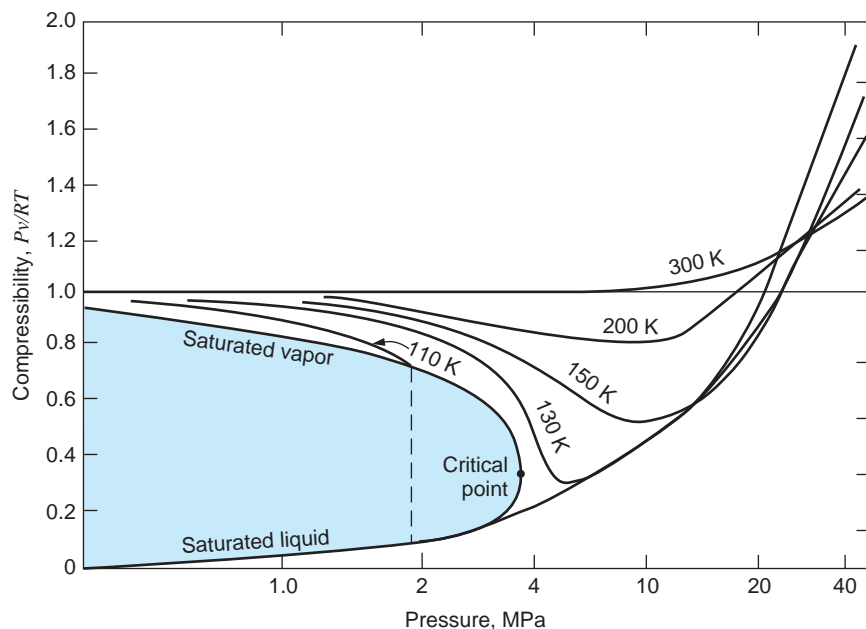
$$Pv = ZRT \quad (3.7)$$

Note that for an ideal gas  $Z = 1$ , and the deviation of  $Z$  from unity is a measure of the deviation of the actual relation from the ideal-gas equation of state.

Figure 3.22 shows a skeleton compressibility chart for nitrogen. From this chart we make three observations. The first is that at all temperatures  $Z \rightarrow 1$  as  $P \rightarrow 0$ . That is, as the pressure approaches zero, the  $P$ - $v$ - $T$  behavior closely approaches that predicted by the ideal-gas equation of state. Second, at temperatures of 300 K and above (that is, room temperature and above), the compressibility factor is near unity up to a pressure of about 10 MPa. This means that the ideal-gas equation of state can be used for nitrogen (and, as it happens, air) over this range with considerable accuracy.

Third, at lower temperatures or at very high pressures, the compressibility factor deviates significantly from the ideal-gas value. Moderate-density forces of attraction tend to pull molecules together, resulting in a value of  $Z < 1$ , whereas very-high-density forces of repulsion tend to have the opposite effect.

If we examine compressibility diagrams for other pure substances, we find that the diagrams are all similar in the characteristics described above for nitrogen, at least in a qualitative sense. Quantitatively the diagrams are all different, since the critical temperatures and pressures of different substances vary over wide ranges, as indicated by the values listed



**FIGURE 3.22**  
Compressibility of  
nitrogen.

in Table A.2. Is there a way we can put all of these substances on a common basis? To do so, we “reduce” the properties with respect to the values at the critical point. The reduced properties are defined as

$$\begin{aligned}\text{reduced pressure} &= P_r = \frac{P}{P_c}, & P_c &= \text{critical pressure} \\ \text{reduced temperature} &= T_r = \frac{T}{T_c}, & T_c &= \text{critical temperature}\end{aligned}\quad (3.8)$$

These equations state that the reduced property for a given state is the value of this property in this state divided by the value of this same property at the critical point.

If lines of constant  $T_r$  are plotted on a  $Z$  versus  $P_r$  diagram, a plot such as that in Fig. D.1 is obtained. The striking fact is that when such  $Z$  versus  $P_r$  diagrams are prepared for a number of substances, all of them nearly coincide, especially when the substances have simple, essentially spherical molecules. Correlations for substances with more complicated molecules are reasonably close, except near or at saturation or at high density. Thus, Fig. D.1 is actually a generalized diagram for simple molecules, which means that it represents the average behavior for a number of simple substances. When such a diagram is used for a particular substance, the results will generally be somewhat in error. However, if  $P$ – $v$ – $T$  information is required for a substance in a region where no experimental measurements have been made, this generalized compressibility diagram will give reasonably accurate results. We need to know only the critical pressure and critical temperature to use this basic [generalized chart](#).

In our study of thermodynamics, we will use Fig. D.1 primarily to help us decide whether, in a given circumstance, it is reasonable to assume ideal-gas behavior as a model. For example, we note from the chart that if the pressure is very low (that is,  $< P_c$ ), the ideal-gas model can be assumed with good accuracy, regardless of the temperature. Furthermore, at high temperatures (that is, greater than about twice  $T_c$ ), the ideal-gas model can be assumed with good accuracy up to pressures as high as four or five times  $P_c$ . When the temperature is less than about twice the critical temperature and the pressure is not extremely low, we are in a region, commonly termed *superheated vapor*, in which the deviation from ideal-gas behavior may be considerable. In this region it is preferable to use tables of thermodynamic properties or charts for a particular substance, as discussed in Section 3.4.

### EXAMPLE 3.11

Is it reasonable to assume ideal-gas behavior at each of the given states?

- Nitrogen at 20°C, 1.0 MPa
- Carbon dioxide at 20°C, 1.0 MPa
- Ammonia at 20°C, 1.0 MPa

#### Solution

In each case, it is first necessary to check phase boundary and critical state data.

- For nitrogen, the critical properties are, from Table A.2, 126.2 K, 3.39 MPa. Since the given temperature, 293.2 K, is more than twice  $T_c$  and the reduced pressure is less than 0.3, ideal-gas behavior is a very good assumption.

- b. For carbon dioxide, the critical properties are 304.1 K, 7.38 MPa. Therefore, the reduced properties are 0.96 and 0.136. From Fig. D.1, carbon dioxide is a gas (although  $T < T_c$ ) with a  $Z$  of about 0.95, so the ideal-gas model is accurate to within about 5% in this case.
- c. The ammonia tables, Table B.2, give the most accurate information. From Table B.2.1 at 20°C,  $P_g = 858$  kPa. Since the given pressure of 1 MPa is greater than  $P_g$ , this state is a compressed liquid, not a gas.

**EXAMPLE 3.12**

Determine the specific volume for R-134a at 100°C, 3.0 MPa for the following models:

- a. The R-134a tables, Table B.5  
 b. Ideal gas  
 c. The generalized chart, Fig. D.1

**Solution**

- a. From Table B.5.2 at 100°C, 3 MPa

$$v = 0.00665 \text{ m}^3/\text{kg} \quad (\text{most accurate value})$$

- b. Assuming ideal gas, we have

$$R = \frac{\bar{R}}{M} = \frac{8.3145}{102.03} = 0.08149 \frac{\text{kJ}}{\text{kg K}}$$

$$v = \frac{RT}{P} = \frac{0.08149 \times 373.2}{3000} = 0.01014 \text{ m}^3/\text{kg}$$

which is more than 50% too large.

- c. Using the generalized chart, Fig. D.1, we obtain

$$T_r = \frac{373.2}{374.2} = 1.0, \quad P_r = \frac{3}{4.06} = 0.74, \quad Z = 0.67$$

$$v = Z \times \frac{RT}{P} = 0.67 \times 0.01014 = 0.00679 \text{ m}^3/\text{kg}$$

which is only 2% too large.

**EXAMPLE 3.13**

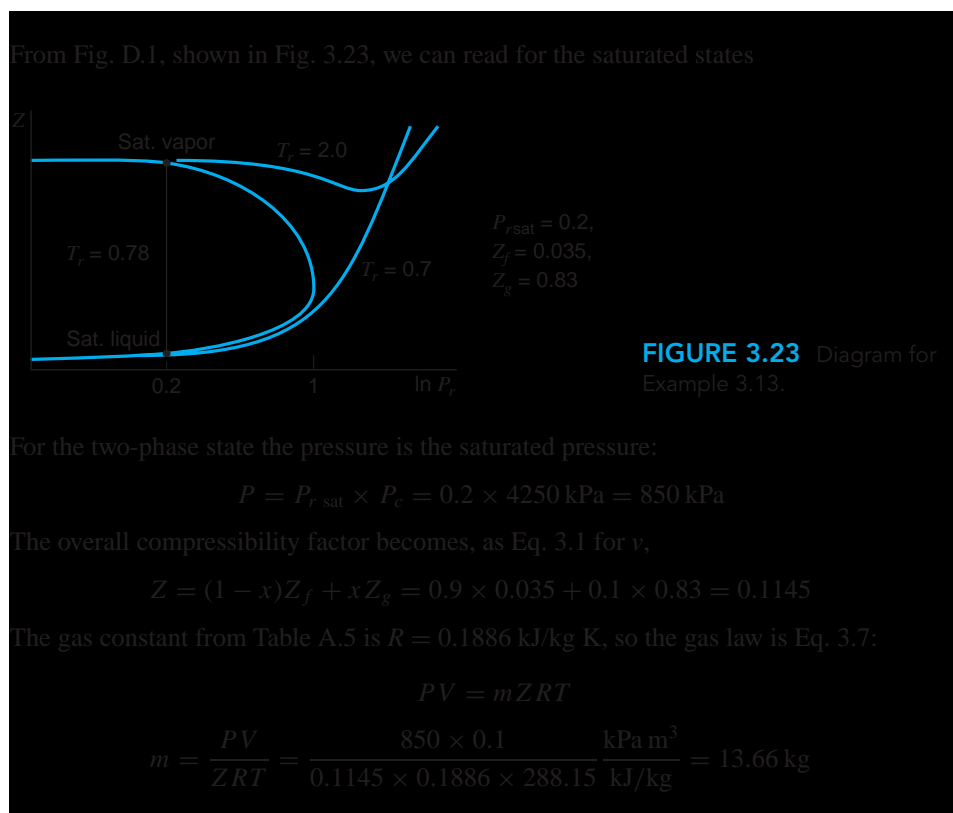
Propane in a steel bottle of volume 0.1 m<sup>3</sup> has a quality of 10% at a temperature of 15°C. Use the generalized compressibility chart to estimate the total propane mass and to find the pressure.

**Solution**

To use Fig. D.1, we need the reduced pressure and temperature. From Table A.2 for propane,  $P_c = 4250$  kPa and  $T_c = 369.8$  K. The reduced temperature is, from Eq. 3.8,

$$T_r = \frac{T}{T_c} = \frac{273.15 + 15}{369.8} = 0.7792 = 0.78$$





### In-Text Concept Questions

- How accurate is it to assume that methane is an ideal gas at room conditions?
- I want to determine a state of some substance, and I know that  $P = 200 \text{ kPa}$ ; is it helpful to write  $PV = mRT$  to find the second property?
- A bottle at  $298 \text{ K}$  should have liquid propane; how high a pressure is needed? (Use Fig. D.1.)

## 3.8 EQUATIONS OF STATE

Instead of the ideal-gas model to represent gas behavior, or even the generalized compressibility chart, which is approximate, it is desirable to have an **equation of state** that accurately represents the  $P$ - $v$ - $T$  behavior for a particular gas over the entire superheated vapor region. Such an equation is necessarily more complicated and consequently more difficult to use. Many such equations have been proposed and used to correlate the observed behavior of gases. As an example, consider the class of relatively simple equation known as *cubic equations of state*

$$P = \frac{RT}{v - b} - \frac{a}{v^2 + cbv + db^2} \quad (3.9)$$

in terms of the four parameters  $a$ ,  $b$ ,  $c$ , and  $d$ . (Note that if all four are zero, this reduces to the ideal-gas model.) Several other different models in this class are given in Appendix D. In some of these models, the parameters are functions of temperature. A more complicated equation of state, the Lee-Kesler equation, is of particular interest, since this equation, expressed in reduced properties, is the one used to correlate the generalized compressibility chart, Fig. D.1. This equation and its 12 empirical constants are also given in Appendix D. When we use a digital computer to determine and tabulate pressure, specific volume, and temperature, as well as other thermodynamic properties, as in the tables presented in Appendix B, modern equations are much more complicated, often containing 40 or more empirical constants. This subject is discussed in detail in Chapter 14.

### 3.9 COMPUTERIZED TABLES

Most of the tables in the appendix are supplied in a computer program on the disk accompanying this book. The main program operates with a visual interface in the Windows environment on a PC-type computer and is generally self-explanatory.

The main program covers the full set of tables for water, refrigerants, and cryogenic fluids, as in Tables B.1 to B.7, including the compressed liquid region, which is printed only for water. For these substances a small graph with the  $P$ - $v$  diagram shows the region around the critical point down toward the triple line covering the compressed liquid, two-phase liquid-vapor, dense fluid, and superheated vapor regions. As a state is selected and the properties are computed, a thin crosshair set of lines indicates the state in the diagram so that this can be seen with a visual impression of the state's location.

Ideal gases corresponding to Tables A.7 for air and A.8 or A.9 for other ideal gases are covered. You can select the substance and the units to work in for all the table sections, providing a wider choice than the printed tables. Metric units (SI) or standard English units for the properties can be used, as well as a mass basis (kg or lbm) or a mole basis, satisfying the need for the most common applications.

The generalized chart, Fig. D.1, with the compressibility factor, is included to allow a more accurate value of  $Z$  to be obtained than can be read from the graph. This is particularly useful for a two-phase mixture where the saturated liquid and saturated vapor values are needed. Besides the compressibility factor, this part of the program includes correction terms beyond ideal-gas approximations for changes in the other thermodynamic properties.

The only mixture application that is included with the program is moist air.

#### EXAMPLE 3.14

Find the states in Examples 3.1 and 3.2 with the computer-aided thermodynamics tables, (CATT), and list the missing property of  $P$ - $v$ - $T$  and  $x$  if applicable.

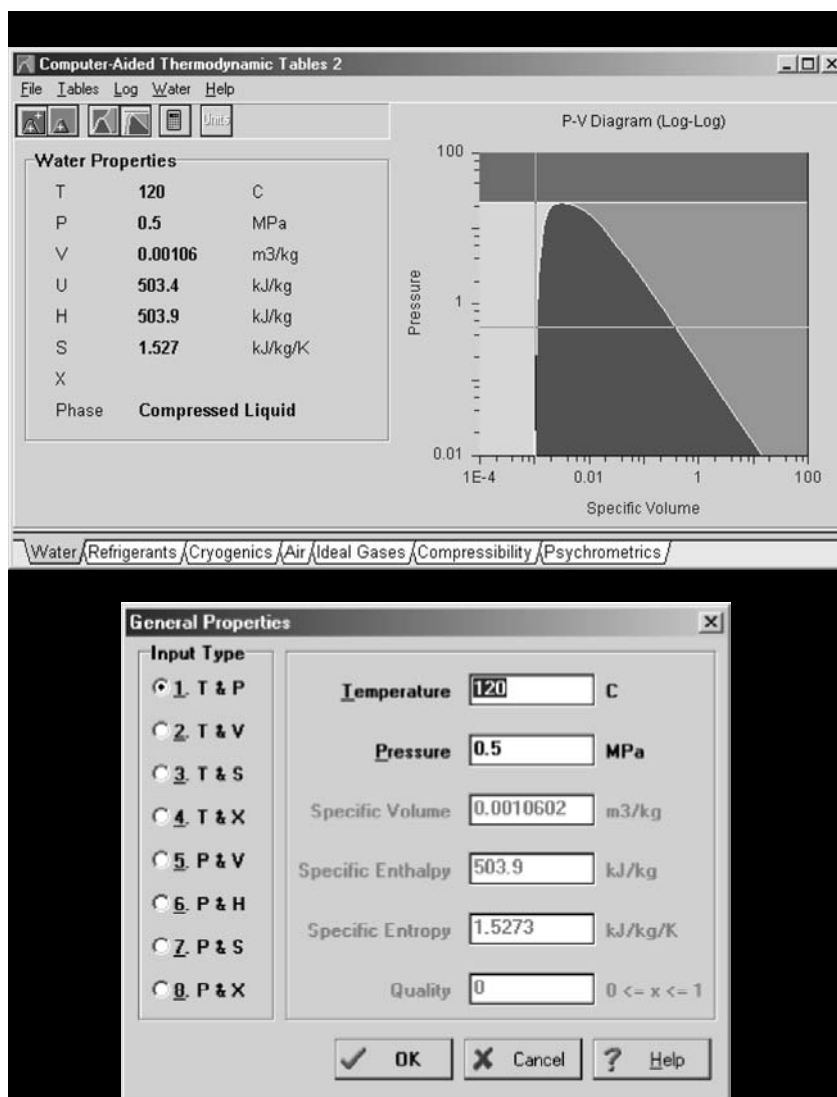
#### Solution

Water states from Example 3.1: Click Water, click Calculator, and then select Case 1 ( $T$ ,  $P$ ). Input ( $T$ ,  $P$ ) = (120, 0.5). The result is as shown in Fig. 3.24.

$$\Rightarrow \text{Compressed liquid} \quad v = 0.0106 \text{ m}^3/\text{kg} \text{ (as in Table B.1.4)}$$

Click Calculator and then select Case 2 ( $T$ ,  $v$ ). Input ( $T$ ,  $v$ ) = (120, 0.5):

$$\Rightarrow \text{Two-phase} \quad x = 0.5601, \quad P = 198.5 \text{ kPa}$$



**FIGURE 3.24** CATT result for Example 3.1.

Ammonia state from Example 3.2: Click Cryogenics; check that it is ammonia. Otherwise, select Ammonia, click Calculator, and then select Case 1 ( $T, P$ ). Input ( $T, P$ ) = (30, 1):

$$\Rightarrow \text{Superheated vapor} \quad v = 0.1321 \text{ m}^3/\text{kg} \text{ (as in Table B.2.2)}$$

R-134a state from Example 3.2: Click Refrigerants; check that it is R-134a. Otherwise, select R-134a (Alt-R), click Calculator, and then select Case 5 ( $P, v$ ). Input ( $P, v$ ) = (0.2, 0.125):

$$\Rightarrow \text{Superheated vapor} \quad T = 44.0^\circ\text{C}$$

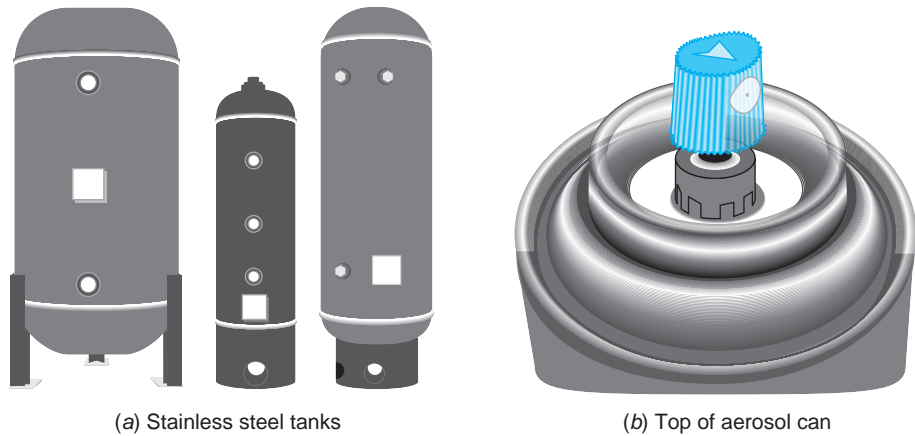
### In-Text Concept Question

1. A bottle at 298 K should have liquid propane; how high a pressure is needed? (Use the software.)

## 3.10 ENGINEERING APPLICATIONS

Information about the phase boundaries is important for storage of substances in a two-phase state like a bottle of gas. The pressure in the container is the saturation pressure for the prevailing temperature, so an estimate of the maximum temperature the system will be subject to gives the maximum pressure for which the container must be dimensioned (Figs. 3.25, 3.26).

In a refrigerator a compressor pushes the refrigerant through the system, and this determines the highest fluid pressure. The harder the compressor is driven, the higher



**FIGURE 3.25** Storage tanks.

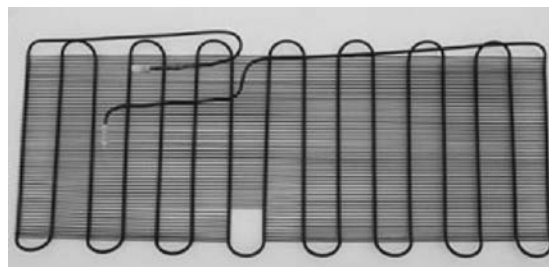


**FIGURE 3.26** A tanker to transport liquefied natural gas (LNG), which is mainly methane.

**FIGURE 3.27**

Household refrigerator components.

(a) Compressor



(b) Condenser

**FIGURE 3.28**

Thermal expansion joints.

(a) Railroad tracks



(b) Bridge expansion joint



**FIGURE 3.29** Hot air balloon.

the pressure becomes. When the refrigerant condenses, the temperature is determined by the saturation temperature for that pressure, so the system must be designed to hold the temperature and pressure within a desirable range (Fig. 3.27).

The effect of expansion-contraction of matter with temperature is important in many different situations. Two of those are shown in Fig. 3.28; the railroad tracks have small gaps to allow for expansion, which leads to the familiar clunk-clunk sound from the train wheels when they roll over the gap. A bridge may have a finger joint that provides a continuous support surface for automobile tires so that they do not bump, as the train does.

When air expands at constant pressure, it occupies a larger volume; thus, the density is smaller. This is how a hot air balloon can lift a gondola and people with a total mass equal to the difference in air mass between the hot air inside the balloon and the surrounding colder air; this effect is called buoyancy (Fig. 3.29).

## SUMMARY

Thermodynamic properties of a **pure substance** and the phase boundaries for **solid**, **liquid**, and **vapor** states are discussed. Phase equilibrium for vaporization (boiling liquid to vapor), or the opposite, condensation (vapor to liquid); sublimation (solid to vapor) or the opposite, solidification (vapor to solid); and melting (solid to liquid) or the opposite, solidifying (liquid to solid), should be recognized. The three-dimensional  **$P$ - $v$ - $T$  surface** and the two-dimensional representations in the  $(P, T)$ ,  $(T, v)$  and  $(P, v)$  diagrams, and the **vaporization**, **sublimation**, and **fusion** lines, are related to the printed tables in Appendix B. Properties from printed and computer tables covering a number of substances are introduced, including two-phase mixtures, for which we use the mass fraction of vapor (**quality**). The ideal-gas law approximates the limiting behavior for low density. An extension of the ideal-gas law is shown with the **compressibility factor**  $Z$ , and other, more complicated **equations of state** are mentioned.

You should have learned a number of skills and acquired abilities from studying this chapter that will allow you to

- Know phases and the nomenclature used for states and interphases.
- Identify a phase given a state  $(T, P)$ .
- Locate states relative to the critical point and know Tables A.2 (F.1) and 3.2.
- Recognize phase diagrams and interphase locations.
- Locate states in the Appendix B tables with any entry:  $(T, P)$ ,  $(T, v)$ , or  $(P, v)$
- Recognize how the tables show parts of the  $(T, P)$ ,  $(T, v)$ , or  $(P, v)$  diagrams.
- Find properties in the two-phase regions; use quality  $x$ .
- Locate states using any combination of  $(T, P, v, x)$  including linear interpolation.
- Know when you have a liquid or solid and the properties in Tables A.3 and A.4 (F.2 and F.3).
- Know when a vapor is an ideal gas (or how to find out).
- Know the ideal-gas law and Table A.5 (F.4).
- Know the compressibility factor  $Z$  and the compressibility chart, Fig. D.1.
- Know the existence of more general equations of state.
- Know how to get properties from the computer program.

## KEY CONCEPTS AND FORMULAS

Phases	Solid, liquid, and vapor (gas)
Phase equilibrium	$T_{\text{sat}}, P_{\text{sat}}, v_f, v_g, v_i$
Multiphase boundaries	Vaporization, sublimation, and fusion lines: Figs. 3.5 (general), 3.6 ( $\text{CO}_2$ ), and 3.7 (water) Critical point: Table 3.1, Table A.2 (F.1) Triple point: Table 3.2
Equilibrium state	Two independent properties (#1, #2)
Quality	$x = m_{\text{vap}}/m$ (vapor mass fraction) $1 - x = m_{\text{liq}}/m$ (liquid mass fraction)
Average specific volume	$v = (1 - x)v_f + xv_g$ (only two-phase mixture)
Equilibrium surface	$P$ – $v$ – $T$ Tables or equation of state
Ideal-gas law	$Pv = RT$ $PV = mRT = n\bar{R}T$
Universal gas constant	$\bar{R} = 8.3145 \text{ kJ/kmol K}$
Gas constant	$R = \bar{R}/M$ kJ/kg K, Table A.5 or $M$ from Table A.2 ft lbf/lbm R, Table F.4 or $M$ from Table F.1
Compressibility factor $Z$	$Pv = ZRT$ Chart for $Z$ in Fig. D.1
Reduced properties	$P_r = \frac{P}{P_c}$ $T_r = \frac{T}{T_c}$ Entry to compressibility chart
Equations of state	Cubic, pressure explicit: Appendix D, Table D.1 Lee Kesler: Appendix D, Table D.2, and Fig. D.1

## CONCEPT-STUDY GUIDE PROBLEMS

- 3.1 Are the pressures in the tables absolute or gauge pressures?
- 3.2 What is the minimum pressure for liquid carbon dioxide?
- 3.3 When you skate on ice, a thin liquid film forms under the skate; why?
- 3.4 At higher elevations, as in mountains, air pressure is lower; how does that affect the cooking of food?
- 3.5 Water at room temperature and room pressure has  $v \approx 1 \times 10^n \text{ m}^3/\text{kg}$ ; what is  $n$ ?
- 3.6 In Example 3.1 b, is there any mass at the indicated specific volume? Explain.
- 3.7 Sketch two constant-pressure curves (500 kPa and 30 000 kPa) in a  $T$ – $v$  diagram and indicate on the curves where in the water tables the properties are found.
- 3.8 If I have 1 L of ammonia at room pressure and temperature (100 kPa, 20°C), what is the mass?
- 3.9 Locate the state of ammonia at 200 kPa,  $-10^\circ\text{C}$ . Indicate in both the  $P$ – $v$  and  $T$ – $v$  diagrams the location of the nearest states listed in Table B.2.
- 3.10 Why are most compressed liquid or solid regions not included in the printed tables?
- 3.11 How does a constant- $v$  process for an ideal gas appear in a  $P$ – $T$  diagram?
- 3.12 If  $v = RT/P$  for an ideal gas, what is the similar equation for a liquid?
- 3.13 How accurate (find  $Z$ ) is it to assume that propane is an ideal gas at room conditions?
- 3.14 With  $T_r = 0.80$ , what is the ratio of  $v_g/v_f$  using Fig. D.1 or Table D.4?
- 3.15 To solve for  $v$  given  $(P, T)$  in Eq. 3.9, what is the mathematical problem?



## HOMEWORK PROBLEMS

### Phase Diagrams, Triple and Critical Points

- 3.16** Carbon dioxide at 280 K can be in three different phases: vapor, liquid, and solid. Indicate the pressure range for each phase.
- 3.17** Modern extraction techniques can be based on dissolving material in supercritical fluids such as carbon dioxide. How high are the pressure and density of carbon dioxide when the pressure and temperature are around the critical point? Repeat for ethyl alcohol.
- 3.18** The ice cap at the North Pole may be 1000 m thick, with a density of  $920 \text{ kg/m}^3$ . Find the pressure at the bottom and the corresponding melting temperature.
- 3.19** Find the lowest temperature at which it is possible to have water in the liquid phase. At what pressure must the liquid exist?
- 3.20** Water at  $27^\circ\text{C}$  can exist in different phases, depending on the pressure. Give the approximate pressure range in kPa for water in each of the three phases: vapor, liquid, and solid.
- 3.21** Dry ice is the name of solid carbon dioxide. How cold must it be at atmospheric (100 kPa) pressure? If it is heated at 100 kPa, what eventually happens?
- 3.22** Find the lowest temperature in Kelvin for which metal can exist as a liquid if the metal is (a) silver or (b) copper.
- 3.23** A substance is at 2 MPa and  $17^\circ\text{C}$  in a rigid tank. Using only the critical properties, can the phase of the mass be determined if the substance is nitrogen, water, or propane?
- 3.24** Give the phase for the following states:  
 a.  $\text{CO}_2$  at  $T = 40^\circ\text{C}$  and  $P = 0.5 \text{ MPa}$   
 b. Air at  $T = 20^\circ\text{C}$  and  $P = 200 \text{ kPa}$   
 c.  $\text{NH}_3$  at  $T = 170^\circ\text{C}$  and  $P = 600 \text{ kPa}$

### General Tables

- 3.25** Determine the phase of water at  
 a.  $T = 260^\circ\text{C}$ ,  $P = 5 \text{ MPa}$   
 b.  $T = -2^\circ\text{C}$ ,  $P = 100 \text{ kPa}$
- 3.26** Determine the phase of the substance at the given state using Appendix B tables.  
 a. Water:  $100^\circ\text{C}$ , 500 kPa  
 b. Ammonia:  $-10^\circ\text{C}$ , 150 kPa  
 c. R-410a:  $0^\circ\text{C}$ , 350 kPa

- 3.27** Determine whether water at each of the following states is a compressed liquid, a superheated vapor, or a mixture of saturated liquid and vapor:  
 a. 10 MPa,  $0.003 \text{ m}^3/\text{kg}$     c.  $200^\circ\text{C}$ ,  $0.1 \text{ m}^3/\text{kg}$   
 b. 1 MPa,  $190^\circ\text{C}$     d. 10 kPa,  $10^\circ\text{C}$
- 3.28** For water at 100 kPa with a quality of 10%, find the volume fraction of vapor.
- 3.29** Determine whether refrigerant R-410a in each of the following states is a compressed liquid, a superheated vapor, or a mixture of saturated liquid and vapor.  
 a.  $50^\circ\text{C}$ ,  $0.05 \text{ m}^3/\text{kg}$     c. 0.1 MPa,  $0.1 \text{ m}^3/\text{kg}$   
 b. 1.0 MPa,  $20^\circ\text{C}$     d.  $-20^\circ\text{C}$ , 200 kPa
- 3.30** Show the states in Problem 3.29 in a sketch of the  $P$ - $v$  diagram.
- 3.31** How great is the change in the liquid specific volume for water at  $20^\circ\text{C}$  as you move up from state  $i$  toward state  $j$  in Fig. 3.12, reaching 15 000 kPa?
- 3.32** Fill out the following table for substance ammonia:

	$P[\text{kPa}]$	$T[^\circ\text{C}]$	$v[\text{m}^3/\text{kg}]$	$x$
a.		50	0.1185	
b.		50		0.5

- 3.33** Place the two states  $a$ – $b$  listed in Problem 3.32 as labeled dots in a sketch of the  $P$ - $v$  and  $T$ - $v$  diagrams.
- 3.34** Give the missing property of  $P$ ,  $T$ ,  $v$ , and  $x$  for R-134a at  
 a.  $T = -20^\circ\text{C}$ ,  $P = 150 \text{ kPa}$   
 b.  $P = 300 \text{ kPa}$ ,  $v = 0.072 \text{ m}^3/\text{kg}$
- 3.35** Fill out the following table for substance water:

	$P[\text{kPa}]$	$T[^\circ\text{C}]$	$v[\text{m}^3/\text{kg}]$	$x$
a.	500	20		
b.	500		0.20	
c.	1400	200		
d.		300		0.8

- 3.36** Place the four states  $a$ – $d$  listed in Problem 3.35 as labeled dots in a sketch of the  $P$ - $v$  and  $T$ - $v$  diagrams.



- 3.37** Determine the specific volume for R-410a at these states:
- $-15^{\circ}\text{C}$ , 500 kPa
  - $20^{\circ}\text{C}$ , 1000 kPa
  - $20^{\circ}\text{C}$ , quality 25%
- 3.38** Give the missing property of  $P$ ,  $T$ ,  $v$ , and  $x$  for  $\text{CH}_4$  at
- $T = 155\text{ K}$ ,  $v = 0.04\text{ m}^3/\text{kg}$
  - $T = 350\text{ K}$ ,  $v = 0.25\text{ m}^3/\text{kg}$
- 3.39** Give the specific volume of carbon dioxide at  $-20^{\circ}\text{C}$  for 2000 kPa and for 1400 kPa.
- 3.40** Calculate the following specific volumes:
- Carbon dioxide:  $10^{\circ}\text{C}$ , 80% quality
  - Water: 4 MPa, 90% quality
  - Nitrogen: 120 K, 60% quality
- 3.41** Give the phase and  $P$ ,  $x$  for nitrogen at
- $T = 120\text{ K}$ ,  $v = 0.006\text{ m}^3/\text{kg}$
  - $T = 140\text{ K}$ ,  $v = 0.002\text{ m}^3/\text{kg}$
- 3.42** You want a pot of water to boil at  $105^{\circ}\text{C}$ . How heavy a lid should you put on the 15-cm-diameter pot when  $P_{\text{atm}} = 101\text{ kPa}$ ?
- 3.43** Water at  $120^{\circ}\text{C}$  with a quality of 25% has its temperature raised  $20^{\circ}\text{C}$  in a constant-volume process. What is the new quality and pressure?
- 3.44** A sealed rigid vessel has volume of  $1\text{ m}^3$  and contains 2 kg of water at  $100^{\circ}\text{C}$ . The vessel is now heated. If a safety pressure valve is installed, at what pressure should the valve be set to have a maximum temperature of  $200^{\circ}\text{C}$ ?
- 3.45** Saturated water vapor at 200 kPa is in a constant-pressure piston/cylinder assembly. At this state the piston is 0.1 m from the cylinder bottom. How much is this distance and what is the temperature if the water is cooled to occupy half of the original volume?
- 3.46** Saturated liquid water at  $60^{\circ}\text{C}$  is put under pressure to decrease the volume by 1% while keeping the temperature constant. To what pressure should it be compressed?
- 3.47** Water at 200 kPa with a quality of 25% has its temperature raised  $20^{\circ}\text{C}$  in a constant-pressure process. What is the new quality and volume?
- 3.48** In your refrigerator, the working substance evaporates from liquid to vapor at  $-20^{\circ}\text{C}$  inside a pipe around the cold section. Outside (on the back or below) is a black grille, inside of which the working substance condenses from vapor to liquid at

$+40^{\circ}\text{C}$ . For each location, find the pressure and the change in specific volume ( $v$ ) if the substance is ammonia.

- 3.49** Repeat the previous problem with the substances
- R-134a
  - R-410a
- 3.50** Repeat Problem 3.48 with carbon dioxide, condenser at  $+20^{\circ}\text{C}$  and evaporator at  $-30^{\circ}\text{C}$ .
- 3.51** A glass jar is filled with saturated water at 500 kPa of quality 25%, and a tight lid is put on. Now it is cooled to  $-10^{\circ}\text{C}$ . What is the mass fraction of solid at this temperature?
- 3.52** Two tanks are connected as shown in Fig. P3.52, both containing water. Tank A is at 200 kPa,  $v = 0.5\text{ m}^3/\text{kg}$ ,  $V_A = 1\text{ m}^3$ , and tank B contains 3.5 kg at 0.5 MPa and  $400^{\circ}\text{C}$ . The valve is now opened and the two tanks come to a uniform state. Find the final specific volume.

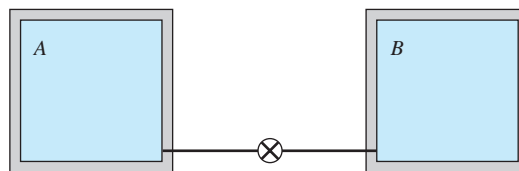


FIGURE P3.52

- 3.53** Saturated vapor R-134a at  $50^{\circ}\text{C}$  changes volume at constant temperature. Find the new pressure, and quality if saturated, if the volume doubles. Repeat the problem for the case where the volume is reduced to half of the original volume.
- 3.54** A steel tank contains 6 kg of propane (liquid + vapor) at  $20^{\circ}\text{C}$  with a volume of  $0.015\text{ m}^3$ . The tank is now slowly heated. Will the liquid level inside eventually rise to the top or drop to the bottom of the tank? What if the initial mass is 1 kg instead of 6 kg?
- 3.55** Saturated water vapor at  $60^{\circ}\text{C}$  has its pressure decreased to increase the volume by 10% while keeping the temperature constant. To what pressure should it be expanded?
- 3.56** Ammonia at  $20^{\circ}\text{C}$  with a quality of 50% and a total mass of 2 kg is in a rigid tank with an outlet valve at the bottom. How much liquid mass can be removed through the valve, assuming that the temperature stays constant?

- 3.57** A sealed, rigid vessel of  $2 \text{ m}^3$  contains a saturated mixture of liquid and vapor R-134a at  $10^\circ\text{C}$ . If it is heated to  $50^\circ\text{C}$ , the liquid phase disappears. Find the pressure at  $50^\circ\text{C}$  and the initial mass of the liquid.
- 3.58** A storage tank holds methane at  $120 \text{ K}$ , with a quality of 25%, and it warms up by  $5^\circ\text{C}$  per hour due to a failure in the refrigeration system. How much time will it take before the methane becomes single phase, and what is the pressure then?
- 3.59** Ammonia at  $10^\circ\text{C}$  with a mass of  $10 \text{ kg}$  is in a piston/cylinder assembly with an initial volume of  $1 \text{ m}^3$ . The piston initially resting on the stops has a mass such that a pressure of  $900 \text{ kPa}$  will float it. Now the ammonia is slowly heated to  $50^\circ\text{C}$ . Find the final pressure and volume.
- 3.60** A  $400\text{-m}^3$  storage tank is being constructed to hold liquified natural gas (LNG), which may be assumed to be essentially pure methane. If the tank is to contain 90% liquid and 10% vapor, by volume, at  $100 \text{ kPa}$ , what mass of LNG (kg) will the tank hold? What is the quality in the tank?
- 3.61** A boiler feed pump delivers  $0.05 \text{ m}^3/\text{s}$  of water at  $240^\circ\text{C}$ ,  $20 \text{ MPa}$ . What is the mass flow rate (kg/s)? What would be the percent error if the properties of saturated liquid at  $240^\circ\text{C}$  were used in the calculation? What if the properties of saturated liquid at  $20 \text{ MPa}$  were used?
- 3.62** A piston/cylinder arrangement is loaded with a linear spring and the outside atmosphere. It contains water at  $5 \text{ MPa}$ ,  $400^\circ\text{C}$ , with the volume being  $0.1 \text{ m}^3$ , as shown in Fig. P3.62. If the piston is at the bottom, the spring exerts a force such that  $P_{\text{lift}} = 200 \text{ kPa}$ . The system now cools until the pressure reaches  $1200 \text{ kPa}$ . Find the mass of water and the final state ( $T_2$ ,  $v_2$ ) and plot the  $P$ - $v$  diagram for the process.

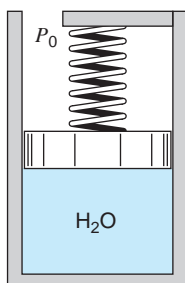


FIGURE P3.62

- 3.63** A pressure cooker (closed tank) contains water at  $100^\circ\text{C}$ , with the liquid volume being  $1/10$ th of the vapor volume. It is heated until the pressure reaches  $2.0 \text{ MPa}$ . Find the final temperature. Has the final state more or less vapor than the initial state?
- 3.64** A pressure cooker has the lid screwed on tight. A small opening with  $A = 5 \text{ mm}^2$  is covered with a petcock that can be lifted to let steam escape. How much mass should the petcock have to allow boiling at  $120^\circ\text{C}$  with an outside atmosphere at  $101.3 \text{ kPa}$ ?

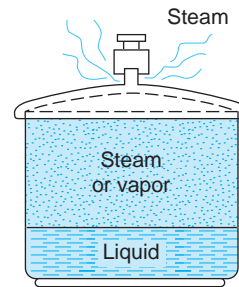


FIGURE P3.64

### Ideal Gas

- 3.65** What is the relative (%) change in  $P$  if we double the absolute temperature of an ideal gas, keeping the mass and volume constant? Repeat if we double  $V$ , keeping  $m$  and  $T$  constant.
- 3.66** A  $1\text{-m}^3$  tank is filled with a gas at room temperature ( $20^\circ\text{C}$ ) and pressure ( $100 \text{ kPa}$ ). How much mass is there if the gas is (a) air, (b) neon, or (c) propane?
- 3.67** Calculate the ideal-gas constant for argon and hydrogen based on Table A.2 and verify the value with Table A.5.
- 3.68** A pneumatic cylinder (a piston/cylinder with air) must close a door with a force of  $500 \text{ N}$ . The cylinder's cross-sectional area is  $5 \text{ cm}^2$  and its volume is  $50 \text{ cm}^3$ . What is the air pressure and its mass?
- 3.69** Is it reasonable to assume that at the given states the substance behaves as an ideal gas?
- Oxygen at  $30^\circ\text{C}$ ,  $3 \text{ MPa}$
  - Methane at  $30^\circ\text{C}$ ,  $3 \text{ MPa}$
  - Water at  $30^\circ\text{C}$ ,  $3 \text{ MPa}$
  - R-134a at  $30^\circ\text{C}$ ,  $3 \text{ MPa}$
  - R-134a at  $30^\circ\text{C}$ ,  $100 \text{ kPa}$
- 3.70** Helium in a steel tank is at  $250 \text{ kPa}$ ,  $300 \text{ K}$  with a volume of  $0.1 \text{ m}^3$ . It is used to fill a balloon. When the pressure drops to  $150 \text{ kPa}$ , the flow of helium

stops by itself. If all the helium is still at 300 K, how big a balloon is produced?

- 3.71** A hollow metal sphere with an inside diameter of 150 mm is weighed on a precision beam balance when evacuated and again after being filled to 875 kPa with an unknown gas. The difference in mass is 0.0025 kg, and the temperature is 25°C. What is the gas, assuming it is a pure substance listed in Table A.5?
- 3.72** A spherical helium balloon 10 m in diameter is at ambient  $T$  and  $P$ , 15°C and 100 kPa. How much helium does it contain? It can lift a total mass that equals the mass of displaced atmospheric air. How much mass of the balloon fabric and cage can then be lifted?
- 3.73** A glass is cleaned in hot water at 45°C and placed on the table bottom up. The room air at 20°C that was trapped in the glass is heated up to 40°C and some of it leaks out, so the net resulting pressure inside is 2 kPa above the ambient pressure of 101 kPa. Now the glass and the air inside cool down to room temperature. What is the pressure inside the glass?
- 3.74** Air in an internal-combustion engine has 227°C, 1000 kPa, with a volume of 0.1 m<sup>3</sup>. Combustion heats it to 1500 K in a constant-volume process. What is the mass of air, and how high does the pressure become?
- 3.75** Air in an automobile tire is initially at -10°C and 190 kPa. After the automobile is driven awhile, the temperature rises to 10°C. Find the new pressure. You must make one assumption on your own.

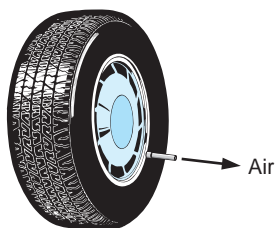


FIGURE P3.75

- 3.76** A rigid tank of 1 m<sup>3</sup> contains nitrogen gas at 600 kPa, 400 K. By mistake, someone lets 0.5 kg flow out. If the final temperature is 375 K, what is the final pressure?
- 3.77** Assume we have three states of saturated vapor R-134a at +40°C, 0°C, and -40°C. Calculate the

specific volume at the set of temperatures and corresponding saturated pressure assuming ideal-gas behavior. Find the percent relative error =  $100(v - v_g)/v_g$  with  $v_g$  from the saturated R-134a table.

- 3.78** Do Problem 3.77 for R-410a.
- 3.79** Do Problem 3.77, but for the substance ammonia.
- 3.80** A 1-m<sup>3</sup> rigid tank has propane at 100 kPa, 300 K and connected by a valve to another tank of 0.5 m<sup>3</sup> with propane at 250 kPa, 400 K. The valve is opened, and the two tanks come to a uniform state at 325 K. What is the final pressure?

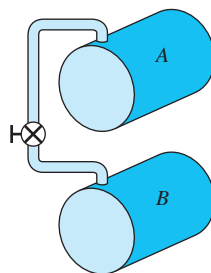


FIGURE P3.80

- 3.81** A vacuum pump is used to evacuate a chamber where some specimens are dried at 50°C. The pump rate of volume displacement is 0.5 m<sup>3</sup>/s, with an inlet pressure of 0.1 kPa and a temperature of 50°C. How much water vapor has been removed over a 30-min period?
- 3.82** A 1-m<sup>3</sup> rigid tank with air at 1 MPa and 400 K is connected to an air line as shown in Fig. P3.82. The valve is opened and air flows into the tank until the pressure reaches 5 MPa, at which point the valve is closed and the temperature inside is 450 K.
- What is the mass of air in the tank before and after the process?
  - The tank eventually cools to room temperature, 300 K. What is the pressure inside the tank then?

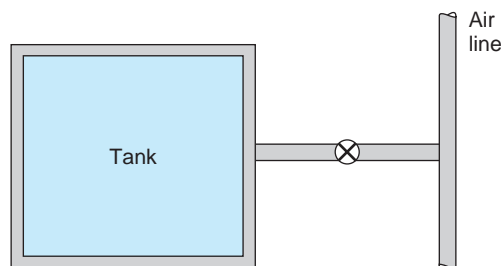


FIGURE P3.82

- 3.83** A cylindrical gas tank 1 m long, with an inside diameter of 20 cm, is evacuated and then filled with carbon dioxide gas at 20°C. To what pressure should it be charged if there is 1.2 kg of carbon dioxide?
- 3.84** Ammonia in a piston/cylinder arrangement is at 700 kPa and 80°C. It is now cooled at constant pressure to saturated vapor (state 2), at which point the piston is locked with a pin. The cooling continues to -10°C (state 3). Show the processes 1 to 2 and 2 to 3 on both a  $P$ - $v$  and a  $T$ - $v$  diagram.

### Compressibility Factor

- 3.85** Find the compressibility factor ( $Z$ ) for saturated vapor ammonia at 100 kPa and at 2000 kPa.
- 3.86** Carbon dioxide at 60°C is pumped at a very high pressure, 10 MPa, into an oil well to reduce the viscosity of oil for better flow. What is its compressibility?
- 3.87** Find the compressibility for carbon dioxide at 60°C and 10 MPa using Fig. D.1.
- 3.88** What is the percent error in specific volume if the ideal-gas model is used to represent the behavior of superheated ammonia at 40°C and 500 kPa? What if the generalized compressibility chart, Fig. D.1, is used instead?
- 3.89** A cylinder fitted with a frictionless piston contains butane at 25°C, 500 kPa. Can the butane reasonably be assumed to behave as an ideal gas at this state?
- 3.90** Estimate the saturation pressure of chlorine at 300 K.
- 3.91** A bottle with a volume of 0.1 m<sup>3</sup> contains butane with a quality of 75% and a temperature of 300 K. Estimate the total butane mass in the bottle using the generalized compressibility chart.
- 3.92** Find the volume of 2 kg of ethylene at 270 K, 2500 kPa using  $Z$  from Fig. D.1.
- 3.93** With  $T_r = 0.85$  and a quality of 0.6, find the compressibility factor using Fig. D.1.
- 3.94** Argon is kept in a rigid 5-m<sup>3</sup> tank at -30°C and 3 MPa. Determine the mass using the compressibility factor. What is the error (%) if the ideal-gas model is used?
- 3.95** Refrigerant R-32 is at -10°C with a quality of 15%. Find the pressure and specific volume.
- 3.96** To plan a commercial refrigeration system using R-123, we would like to know how much more volume saturated vapor R-123 occupies per kg at -30°C compared to the saturated liquid state.
- 3.97** A new refrigerant, R-125, is stored as a liquid at -20°C with a small amount of vapor. For 1.5 kg of R-125, find the pressure and volume.

### Equations of State

For these problems see Appendix D for the equation of state (EOS) and Chapter 14.

- 3.98** Determine the pressure of nitrogen at 160 K,  $v = 0.00291$  m<sup>3</sup>/kg using ideal gas, the van der Waals EOS, and the nitrogen table.
- 3.99** Determine the pressure of nitrogen at 160 K,  $v = 0.00291$  m<sup>3</sup>/kg using the Redlich-Kwong EOS and the nitrogen table.
- 3.100** Determine the pressure of nitrogen at 160 K,  $v = 0.00291$  m<sup>3</sup>/kg using the Soave EOS and the nitrogen table.
- 3.101** Carbon dioxide at 60°C is pumped at a very high pressure, 10 MPa, into an oil well to reduce the viscosity of oil for better flow. Find its specific volume from the carbon dioxide table, ideal gas, and van der Waals EOS by iteration.
- 3.102** Solve the previous problem using the Redlich-Kwong EOS. Notice that this becomes a trial-and-error process.
- 3.103** Solve Problem 3.101 using the Soave EOS. Notice that this becomes a trial-and-error process.
- 3.104** A tank contains 8.35 kg of methane in 0.1 m<sup>3</sup> at 250 K. Find the pressure using ideal gas, the van der Waals EOS, and the methane table.
- 3.105** Do the previous problem using the Redlich-Kwong EOS.
- 3.106** Do Problem 3.104 using the Soave EOS.

### Review Problems

- 3.107** Determine the quality (if saturated) or temperature (if superheated) of the following substances at the given two states:
- Water at
    - 120°C, 1 m<sup>3</sup>/kg; 2: 10 MPa, 0.01 m<sup>3</sup>/kg
  - Nitrogen at
    - 1 MPa, 0.03 m<sup>3</sup>/kg; 2: 100 K, 0.03 m<sup>3</sup>/kg
- 3.108** Give the phase and the missing properties of  $P$ ,  $T$ ,  $v$ , and  $x$  for
- R-410a at 10°C with  $v = 0.01$  m<sup>3</sup>/kg
  - Water at  $T = 350$ °C with  $v = 0.2$  m<sup>3</sup>/kg

- c. R-410a at  $-5^{\circ}\text{C}$  and  $P = 600\text{ kPa}$   
d. R-134a at  $294\text{ kPa}$  and  $v = 0.05\text{ m}^3/\text{kg}$
- 3.109** Find the phase, the quality  $x$  if applicable, and the missing property  $P$  or  $T$ .  
a.  $\text{H}_2\text{O}$  at  $T = 120^{\circ}\text{C}$  with  $v = 0.5\text{ m}^3/\text{kg}$   
b.  $\text{H}_2\text{O}$  at  $P = 100\text{ kPa}$  with  $v = 1.8\text{ m}^3/\text{kg}$   
c.  $\text{H}_2\text{O}$  at  $T = 263\text{ K}$  with  $v = 200\text{ m}^3/\text{kg}$
- 3.110** Find the phase, quality  $x$ , if applicable, and the missing property  $P$  or  $T$ .  
a.  $\text{NH}_3$  at  $P = 800\text{ kPa}$  with  $v = 0.2\text{ m}^3/\text{kg}$   
b.  $\text{NH}_3$  at  $T = 20^{\circ}\text{C}$  with  $v = 0.1\text{ m}^3/\text{kg}$
- 3.111** Give the phase and the missing properties of  $P$ ,  $T$ ,  $v$ , and  $x$ . These may be a little more difficult to determine if the appendix tables are used instead of the software.  
a. R-410a,  $T = 10^{\circ}\text{C}$ ,  $v = 0.02\text{ m}^3/\text{kg}$   
b.  $\text{H}_2\text{O}$ ,  $v = 0.2\text{ m}^3/\text{kg}$ ,  $x = 0.5$   
c.  $\text{H}_2\text{O}$ ,  $T = 60^{\circ}\text{C}$ ,  $v = 0.001016\text{ m}^3/\text{kg}$   
d.  $\text{NH}_3$ ,  $T = 30^{\circ}\text{C}$ ,  $P = 60\text{ kPa}$   
e. R-134a,  $v = 0.005\text{ m}^3/\text{kg}$ ,  $x = 0.5$
- 3.112** Refrigerant-410a in a piston/cylinder arrangement is initially at  $15^{\circ}\text{C}$  with  $x = 1$ . It is then expanded in a process so that  $P = Cv^{-1}$  to a pressure of  $200\text{ kPa}$ . Find the final temperature and specific volume.
- 3.113** Consider two tanks,  $A$  and  $B$ , connected by a valve, as shown in Fig. P3.113. Each has a volume of  $200\text{ L}$ , and tank  $A$  has R-410a at  $25^{\circ}\text{C}$ , 10% liquid and 90% vapor by volume, while tank  $B$  is evacuated. The valve is now opened, and saturated vapor flows from  $A$  to  $B$  until the pressure in  $B$  has reached that in  $A$ , at which point the valve is closed. This process occurs slowly such that all temperatures stay at  $25^{\circ}\text{C}$  throughout the process. How much has the quality changed in tank  $A$  during the process?

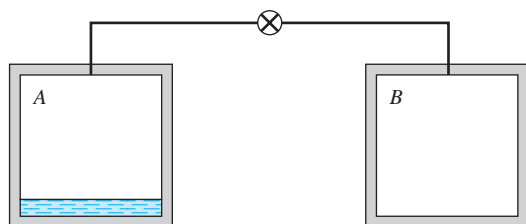


FIGURE P3.113

- 3.114** Water in a piston/cylinder is at  $90^{\circ}\text{C}$ ,  $100\text{ kPa}$ , and the piston loading is such that pressure is proportional to volume,  $P = CV$ . Heat is now added until the temperature reaches  $200^{\circ}\text{C}$ . Find the final

pressure and also the quality if the water is in the two-phase region.

- 3.115** A tank contains  $2\text{ kg}$  of nitrogen at  $100\text{ K}$  with a quality of  $50\%$ . Through a volume flowmeter and valve,  $0.5\text{ kg}$  is now removed while the temperature remains constant. Find the final state inside the tank and the volume of nitrogen removed if the valve/meter is located at  
a. the top of the tank  
b. the bottom of the tank
- 3.116** A spring-loaded piston/cylinder assembly contains water at  $500^{\circ}\text{C}$  and  $3\text{ MPa}$ . The setup is such that pressure is proportional to volume,  $P = CV$ . It is now cooled until the water becomes saturated vapor. Sketch the  $P$ - $v$  diagram and find the final pressure.
- 3.117** A container with liquid nitrogen at  $100\text{ K}$  has a cross-sectional area of  $0.5\text{ m}^2$ , as shown in Fig. P3.117. Due to heat transfer, some of the liquid evaporates, and in  $1\text{ hour}$  the liquid level drops  $30\text{ mm}$ . The vapor leaving the container passes through a valve and a heater and exits at  $500\text{ kPa}$ ,  $260\text{ K}$ . Calculate the volume rate of flow of nitrogen gas exiting the heater.

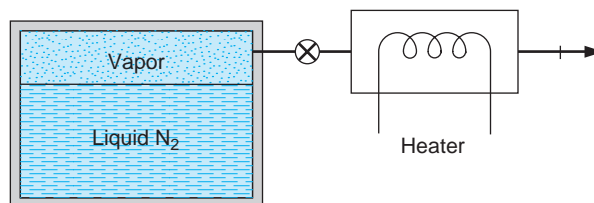


FIGURE P3.117

- 3.118** For a certain experiment, R-410a vapor is contained in a sealed glass tube at  $20^{\circ}\text{C}$ . We want to know the pressure at this condition, but there is no means of measuring it, since the tube is sealed. However, if the tube is cooled to  $-20^{\circ}\text{C}$ , small droplets of liquid are observed on the glass walls. What is the initial pressure?
- 3.119** A cylinder/piston arrangement contains water at  $105^{\circ}\text{C}$ ,  $85\%$  quality, with a volume of  $1\text{ L}$ . The system is heated, causing the piston to rise and encounter a linear spring, as shown in Fig. P3.119. At this point the volume is  $1.5\text{ L}$ , the piston diameter is  $150\text{ mm}$ , and the spring constant is  $100\text{ N/mm}$ . The heating continues, so the piston compresses the



spring. What is the cylinder temperature when the pressure reaches 200 kPa?

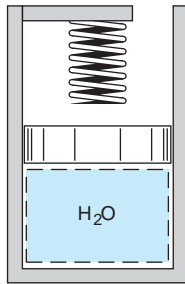


FIGURE P3.119

- 3.120** Determine the mass of methane gas stored in a 2-m<sup>3</sup> tank at  $-30^{\circ}\text{C}$ , 2 MPa. Estimate the percent error in the mass determination if the ideal-gas model is used.
- 3.121** A cylinder containing ammonia is fitted with a piston restrained by an external force that is proportional to the cylinder volume squared. Initial conditions are  $10^{\circ}\text{C}$ , 90% quality, and a volume of 5 L. A valve on the cylinder is opened and additional ammonia flows into the cylinder until the mass inside has doubled. If at this point the pressure is 1.2 MPa, what is the final temperature?
- 3.122** A cylinder has a thick piston initially held by a pin, as shown in Fig. P3.122. The cylinder contains carbon dioxide at 200 kPa and ambient temperature of 290 K. The metal piston has a density of  $8000\text{ kg/m}^3$  and the atmospheric pressure is 101 kPa. The pin is now removed, allowing the piston to move, and

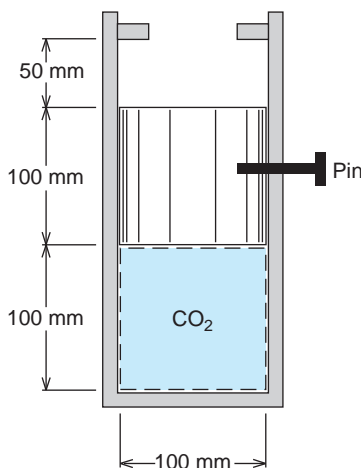


FIGURE P3.122

after a while the gas returns to ambient temperature. Is the piston against the stops?

- 3.123** What is the percent error in pressure if the ideal-gas model is used to represent the behavior of superheated vapor R-410a at  $60^{\circ}\text{C}$ ,  $0.03470\text{ m}^3/\text{kg}$ ? What if the generalized compressibility chart, Fig. D.1, is used instead? (Note that iterations are needed.)
- 3.124** An initially deflated and now flat balloon is connected by a valve to a 12-m<sup>3</sup> storage tank containing helium gas at 2 MPa and ambient temperature,  $20^{\circ}\text{C}$ . The valve is opened and the balloon is inflated at constant pressure,  $P_0 = 100\text{ kPa}$ , equal to ambient pressure, until it becomes spherical at  $D_1 = 1\text{ m}$ . If the balloon is larger than this, the balloon material is stretched, giving an inside pressure of

$$P = P_0 + C \left( 1 - \frac{D_1}{D} \right) \frac{D_1}{D}$$

The balloon is inflated to a final diameter of 4 m, at which point the pressure inside is 400 kPa. The temperature remains constant at  $20^{\circ}\text{C}$ . What is the maximum pressure inside the balloon at any time during the inflation process? What is the pressure inside the helium storage tank at this time?

- 3.125** A piston/cylinder arrangement, shown in Fig. P3.125, contains air at 250 kPa and  $300^{\circ}\text{C}$ . The 50-kg piston has a diameter of 0.1 m and initially pushes against the stops. The atmosphere is at 100 kPa and  $20^{\circ}\text{C}$ . The cylinder now cools as heat is transferred to the ambient surroundings.
- At what temperature does the piston begin to move down?
  - How far has the piston dropped when the temperature reaches ambient?
  - Show the process in a  $P$ - $v$  and a  $T$ - $v$  diagram.

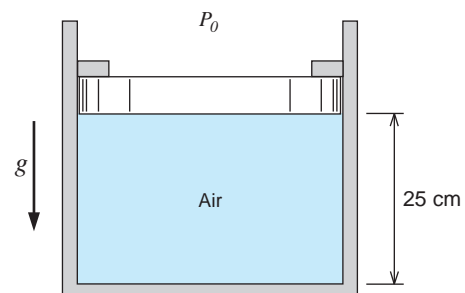


FIGURE P3.125

**Linear Interpolation**

- 3.126** Find the pressure and temperature for saturated vapor R-410a with  $v = 0.1 \text{ m}^3/\text{kg}$ .
- 3.127** Use a linear interpolation to estimate properties of ammonia to fill out the table below.

	$P[\text{kPa}]$	$T[^\circ\text{C}]$	$v[\text{m}^3/\text{kg}]$	$x$
a.	550			0.75
b.	80	20		
c.		10	0.4	

- 3.128** Use a linear interpolation to estimate  $T_{\text{sat}}$  at 900 kPa for nitrogen. Sketch by hand the curve  $P_{\text{sat}}(T)$  by using a few table entries around 900 kPa from Table B.6.1. Is your linear interpolation above or below the actual curve?
- 3.129** Use a double linear interpolation to find the pressure for superheated R-134a at  $13^\circ\text{C}$  with  $v = 0.3 \text{ m}^3/\text{kg}$ .

- 3.130** Find the specific volume for carbon dioxide at  $0^\circ\text{C}$  and 625 kPa.

**Computer Tables**

- 3.131** Use the computer software to find the properties for water at the four states in Problem 3.35.
- 3.132** Use the computer software to find the properties for ammonia at the four states listed in Problem 3.32.
- 3.133** Use the computer software to find the properties for ammonia at the three states listed in Problem 3.127.
- 3.134** Find the value of the saturated temperature for nitrogen by linear interpolation in Table B.6.1 for a pressure of 900 kPa. Compare this to the value given by the computer software.
- 3.135** Use the computer software to sketch the variation of pressure with temperature in Problem 3.44. Extend the curve slightly into the single-phase region.

**ENGLISH UNIT PROBLEMS****English Unit Concept Problems**

- 3.136E** Cabbage needs to be cooked (boiled) at 250 F. What pressure should the pressure cooker be set for?
- 3.137E** If I have  $1 \text{ ft}^3$  of ammonia at 15 psia, 60 F, what is the mass?
- 3.138E** For water at 1 atm with a quality of 10%, find the volume fraction of vapor.
- 3.139E** Locate the state of R-134a at 30 psia, 20 F. Indicate in both the  $P$ - $v$  and  $T$ - $v$  diagrams the location of the nearest states listed in Table F.10.
- 3.140E** Calculate the ideal-gas constant for argon and hydrogen based on Table F.1 and verify the value with Table F.4.

**English Unit Problems**

- 3.141E** Water at 80 F can exist in different phases, depending on the pressure. Give the approximate pressure range in  $\text{lbf}/\text{in}^2$  for water in each of the three phases: vapor, liquid, or solid.
- 3.142E** A substance is at  $300 \text{ lbf}/\text{in}^2$ ,  $65 \text{ F}$  in a rigid tank. Using only the critical properties, can the phase of the mass be determined if the substance is nitrogen, water, or propane?

- 3.143E** Determine the missing property (of  $P$ ,  $T$ ,  $v$ , and  $x$  if applicable) for water at
- 680 psia,  $0.03 \text{ ft}^3/\text{lbm}$
  - 150 psia,  $320 \text{ F}$
  - 400 F,  $3 \text{ ft}^3/\text{lbm}$
- 3.144E** Determine whether water at each of the following states is a compressed liquid, a superheated vapor, or a mixture of saturated liquid and vapor.
- $2 \text{ lbf}/\text{in}^2$ ,  $50 \text{ F}$
  - $270 \text{ F}$ ,  $30 \text{ lbf}/\text{in}^2$
  - $160 \text{ F}$ ,  $10 \text{ ft}^3/\text{lbm}$
- 3.145E** Give the phase and the missing property of  $P$ ,  $T$ ,  $v$ , and  $x$  for R-134a at
- $T = -10 \text{ F}$ ,  $P = 18 \text{ psia}$
  - $P = 40 \text{ psia}$ ,  $v = 1.3 \text{ ft}^3/\text{lbm}$
- 3.146E** Give the phase and the missing property of  $P$ ,  $T$ ,  $v$ , and  $x$  for ammonia at
- $T = 120 \text{ F}$ ,  $v = 0.9 \text{ ft}^3/\text{lbm}$
  - $T = 200 \text{ F}$ ,  $v = 11 \text{ ft}^3/\text{lbm}$
- 3.147E** Give the phase and the specific volume for the following:
- R-410a,  $T = -25 \text{ F}$ ,  $P = 30 \text{ lbf}/\text{in}^2$
  - R-410a,  $T = -25 \text{ F}$ ,  $P = 40 \text{ lbf}/\text{in}^2$
  - $\text{H}_2\text{O}$ ,  $T = 280 \text{ F}$ ,  $P = 35 \text{ lbf}/\text{in}^2$
  - $\text{NH}_3$ ,  $T = 60 \text{ F}$ ,  $P = 15 \text{ lbf}/\text{in}^2$

- 3.148E** Determine the specific volume for R-410a at these states:
- 5 F, 75 psia
  - 70 F, 200 psia
  - 70 F, quality 25%
- 3.149E** Give the specific volume of R-410a at 0 F for 70 psia and repeat for 60 psia.
- 3.150E** Saturated liquid water at 150 F is put under pressure to decrease the volume by 1% while keeping the temperature constant. To what pressure should it be compressed?
- 3.151E** A sealed rigid vessel has volume of 35 ft<sup>3</sup> and contains 2 lbm of water at 200 F. The vessel is now heated. If a safety pressure valve is installed, at what pressure should the valve be set to have a maximum temperature of 400 F?
- 3.152E** You want a pot of water to boil at 220 F. How heavy a lid should you put on the 6-in.-diameter pot when  $P_{\text{atm}} = 14.7$  psia?
- 3.153E** Saturated water vapor at 200 F has its pressure decreased to increase the volume by 10%, keeping the temperature constant. To what pressure should it be expanded?
- 3.154E** A glass jar is filled with saturated water at 300 F and quality 25%, and a tight lid is put on. Now it is cooled to 10 F. What is the mass fraction of solid at this temperature?
- 3.155E** A boiler feed pump delivers 100 ft<sup>3</sup>/min of water at 400 F, 3000 lbf/in.<sup>2</sup> What is the mass flowrate (lbm/s)? What would be the percent error if the properties of saturated liquid at 400 F were used in the calculation? What if the properties of saturated liquid at 3000 lbf/in.<sup>2</sup> were used?
- 3.156E** A pressure cooker has the lid screwed on tight. A small opening with  $A = 0.0075$  in.<sup>2</sup> is covered with a petcock that can be lifted to let steam escape. How much mass should the petcock have to allow boiling at 250 F with an outside atmosphere of 15 psia?
- 3.157E** Two tanks are connected together as shown in Fig. P3.52, both containing water. Tank A is at 30 lbf/in.<sup>2</sup>,  $v = 8$  ft<sup>3</sup>/lbm,  $V = 40$  ft<sup>3</sup>, and tank B contains 8 lbm at 80 lbf/in.<sup>2</sup>, 750 F. The valve is now opened, and the two come to a uniform state. Find the final specific volume.
- 3.158E** A steel tank contains 14 lbm of propane (liquid + vapor) at 70 F with a volume of 0.25 ft<sup>3</sup>. The tank is now slowly heated. Will the liquid level inside eventually rise to the top or drop to the bottom of the tank? What if the initial mass is 2 lbm instead of 14 lbm?
- 3.159E** Give the phase and the specific volume for the following:
- CO<sub>2</sub>,  $T = 510$  F,  $P = 75$  lbf/in.<sup>2</sup>
  - Air,  $T = 68$  F,  $P = 2$  atm
  - Ar,  $T = 300$  F,  $P = 30$  lbf/in.<sup>2</sup>
- 3.160E** A cylindrical gas tank 3 ft long, with an inside diameter of 8 in., is evacuated and then filled with carbon dioxide gas at 77 F. To what pressure should it be charged if there should be 2.6 lbm of carbon dioxide?
- 3.161E** A spherical helium balloon 30 ft in diameter is at ambient  $T$  and  $P$ , 60 F and 14.69 psia. How much helium does it contain? It can lift a total mass that equals the mass of displaced atmospheric air. How much mass of the balloon fabric and cage can then be lifted?
- 3.162E** Helium in a steel tank is at 36 psia, 540 R with a volume of 4 ft<sup>3</sup>. It is used to fill a balloon. When the pressure drops to 20 psia, the flow of helium stops by itself. If all the helium is still at 540 R, how big a balloon is produced?
- 3.163E** A 35-ft<sup>3</sup> rigid tank has propane at 15 psia, 540 R and is connected by a valve to another tank of 20 ft<sup>3</sup> with propane at 40 psia, 720 R. The valve is opened and the two tanks come to a uniform state at 600 R. What is the final pressure?
- 3.164E** What is the percent error in specific volume if the ideal-gas model is used to represent the behavior of superheated ammonia at 100 F, 80 lbf/in.<sup>2</sup>? What if the generalized compressibility chart, Fig. D.1, is used instead?
- 3.165E** Air in an internal-combustion engine has 440 F, 150 psia, with a volume of 3 ft. Combustion heats it to 2700 R in a constant-volume process. What is the mass of air, and how high does the pressure become?
- 3.166E** A 35-ft<sup>3</sup> rigid tank has air at 225 psia and ambient 600 R connected by a valve to a piston/cylinder. The piston of area 1 ft<sup>2</sup> requires 40 psia below it to float (see Fig. P3.166E). The valve is opened, the piston moves slowly 7 ft up, and the valve



is closed. During the process, air temperature remains at 600 R. What is the final pressure in the tank?

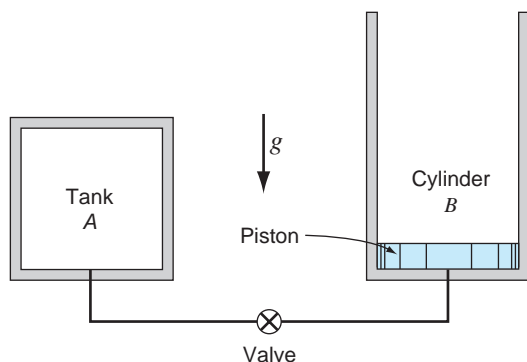


FIGURE P3.166E

**3.167E** Give the phase and the missing properties of  $P$ ,  $T$ ,  $v$ , and  $x$ . These may be a little more difficult to determine if the appendix tables are used instead of the software.

- R-410a,  $T = 50$  F,  $v = 0.4$  ft<sup>3</sup>/lbm
- H<sub>2</sub>O,  $v = 2$  ft<sup>3</sup>/lbm,  $x = 0.5$
- H<sub>2</sub>O,  $T = 150$  F,  $v = 0.01632$  ft<sup>3</sup>/lbm
- NH<sub>3</sub>,  $T = 80$  F,  $P = 13$  lbf/in.<sup>2</sup>
- R-134a,  $v = 0.08$  ft<sup>3</sup>/lbm,  $x = 0.5$

**3.168E** A pressure cooker (closed tank) contains water at 200 F, with the liquid volume being 1/10th of the vapor volume. It is heated until the pressure reaches 300 lbf/in.<sup>2</sup> Find the final temperature. Has the final state more or less vapor than the initial state?

**3.169E** Refrigerant-410a in a piston/cylinder arrangement is initially at 60 F,  $x = 1$ . It is then expanded in a process so that  $P = Cv^{-1}$  to a pressure of 30 lbf/in.<sup>2</sup> Find the final temperature and specific volume.

**3.170E** A substance is at 70 F, 300 lbf/in.<sup>2</sup> in a 10-ft<sup>3</sup> tank. Estimate the mass from the compressibility chart if the substance is (a) air, (b) butane, or (c) propane.

**3.171E** Determine the mass of an ethane gas stored in a 25-ft<sup>3</sup> tank at 250 F, 440 lbf/in.<sup>2</sup> using the compressibility chart. Estimate the error (%) if the ideal-gas model is used.

**3.172E** Determine the pressure of R-410a at 100 F,  $v = 0.2$  ft<sup>3</sup>/lbm using ideal gas and the van der Waal EOS.

**3.173E** Determine the pressure of R-410a at 100 F,  $v = 0.2$  ft<sup>3</sup>/lbm using ideal gas and the Redlich-Kwong EOS.

## COMPUTER, DESIGN AND OPEN-ENDED PROBLEMS

**3.174** Make a spreadsheet that will tabulate and plot saturated pressure versus temperature for ammonia starting at  $T = -40^{\circ}\text{C}$  and ending at the critical point in steps of 10 $^{\circ}\text{C}$ .

**3.175** Make a spreadsheet that will tabulate and plot values of  $P$  and  $T$  along a constant specific volume line for water. The starting state is 100 kPa, the quality is 50%, and the ending state is 800 kPa.

**3.176** Use the computer software to sketch the variation of pressure with temperature in Problem 3.58. Extend the curve a little into the single-phase region.

**3.177** Using the computer software, find a few of the states between the beginning and end states and show the variation of pressure and temperature as a function of volume for Problem 3.114.

**3.178** In Problem 3.112 follow the path of the process for the R-410a for any state between the initial and final states inside the cylinder.

**3.179** For any specified substance in Tables B.1–B.7, fit a polynomial equation of degree  $n$  to tabular data for pressure as a function of density along any given isotherm in the superheated vapor region.

**3.180** The refrigerant fluid in a household refrigerator changes phase from liquid to vapor at the low temperature in the refrigerator. It changes phase from vapor to liquid at the higher temperature in the heat exchanger that gives the energy to the room air. Measure or otherwise estimate these temperatures. Based on these temperatures, make a table with the refrigerant pressures for the refrigerants for which tables are available in Appendix B. Discuss the results and the requirements for a substance to be a potential refrigerant.

**3.181** Repeat the previous problem for refrigerants listed in Table A.2 and use the compressibility chart, Fig. D.1, to estimate the pressures.

- 3.182** Saturated pressure as a function of temperature follows the correlation developed by Wagner as

$$\ln P_r = [w_1\tau + w_2\tau^{1.5} + w_3\tau^3 + w_4\tau^6]/T_r$$

where the reduced pressure and temperature are  $P_r = P/P_c$  and  $T_r = T/T_c$ . The temperature variable is  $\tau = 1 - T_r$ . The parameters are found for R-134a as

	$w_1$	$w_2$	$w_3$	$w_4$
R-134a	-7.59884	1.48886	-3.79873	1.81379

Compare this correlation to the table in Appendix B.

- 3.183** Find the constants in the curve fit for the saturation pressure using Wagner's correlation, as shown in the previous problem for water and methane. Find other correlations in the literature, compare them to the tables, and give the maximum deviation.

- 3.184** The specific volume of saturated liquid can be approximated by the Rackett equation as

$$v_f = \frac{\bar{R}T_c}{MP_c} Z_c^n, n = 1 + (1 - T_r)^{2/7}$$

with the reduced temperature,  $T_r = T/T_c$ , and the compressibility factor,  $Z_c = P_c v_c / RT_c$ . Using values from Table A.2 with the critical constants, compare the formula to the tables for substances where the saturated specific volume is available.

# 4

## Work and Heat

In this chapter we consider work and heat. It is essential for the student of thermodynamics to understand clearly the definitions of both work and heat, because the correct analysis of many thermodynamic problems depends on distinguishing between them.

Work and heat are energy in transfer from one system to another and thus play a crucial role in most thermodynamic systems or devices. To analyze such systems, we need to model heat and work as functions of properties and parameters characteristic of the system or the way it functions. An understanding of the physics involved allows us to construct a model for heat and work and use the result in our analysis of energy transfers and changes, which we will do with the first law of thermodynamics in Chapter 5.

To facilitate understanding of the basic concepts, we present a number of physical arrangements that will enable us to express the work done from changes in the system during a process. We also examine work that is the result of a given process without describing in detail how the process physically can be made to occur. This is done because such a description is too complex and involves concepts that have not been covered so far, but at least we can examine the result of the process.

Heat transfer in different situations is a subject that usually is studied separately. However, a very simple introduction is beneficial so that the concept of heat transfer does not become too abstract and so that it can be related to the processes we examine. Heat transfer by conduction, convection (flow), and radiation is presented in terms of very simple models, emphasizing that it is driven by a temperature difference.

### 4.1 DEFINITION OF WORK

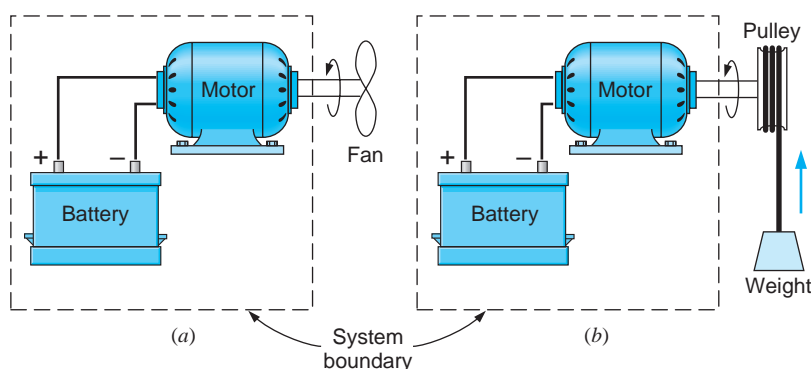
**Work** is usually defined as a force  $F$  acting through a displacement  $x$ , where the displacement is in the direction of the force. That is,

$$W = \int_1^2 F dx \quad (4.1)$$

This is a very useful relationship because it enables us to find the work required to raise a weight, to stretch a wire, or to move a charged particle through a magnetic field.

However, when treating thermodynamics from a macroscopic point of view, it is advantageous to link the definition of work with the concepts of systems, properties, and processes. We therefore define work as follows: Work is done by a system if the sole effect on the surroundings (everything external to the system) could be the raising of a weight. Notice that the raising of a weight is in effect a force acting through a distance. Notice also that our definition does not state that a weight was actually raised or that a force actually acted through a given distance, but only that the sole effect external to the system could be

**FIGURE 4.1** Example of work crossing the boundary of a system.



the raising of a weight. Work done *by* a system is considered positive and work done *on* a system is considered negative. The symbol  $W$  designates the work done by a system.

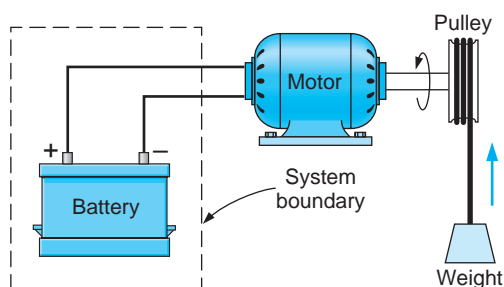
In general, work is a form of energy in transit, that is, energy being transferred across a system boundary. The concept of energy and energy storage or possession was discussed in detail in Section 2.6. Work is the form of energy that fulfills the definition given in the preceding paragraph.

Let us illustrate this definition of work with a few examples. Consider as a system the battery and motor of Fig. 4.1a, and let the motor drive a fan. Does work cross the boundary of the system? To answer this question using the definition of work given earlier, replace the fan with the pulley and weight arrangement shown in Fig. 4.1b. As the motor turns, the weight is raised, and the sole effect external to the system is the raising of a weight. Thus, for our original system of Fig. 4.1a, we conclude that work is crossing the boundary of the system, since the sole effect external to the system could be the raising of a weight.

Let the boundaries of the system be changed now to include only the battery shown in Fig. 4.2. Again we ask, does work cross the boundary of the system? To answer this question, we need to ask a more general question: Does the flow of electrical energy across the boundary of a system constitute work?

The only limiting factor when the sole external effect is the raising of a weight is the inefficiency of the motor. However, as we design a more efficient motor, with lower bearing and electrical losses, we recognize that we can approach a certain limit that meets the requirement of having the only external effect be the raising of a weight. Therefore, we can conclude that when there is a flow of electricity across the boundary of a system, as in Fig. 4.2, it is work.

**FIGURE 4.2** Example of work crossing the boundary of a system because of an electric current flow across the system boundary.



## 4.2 UNITS FOR WORK

As already noted, work done *by* a system, such as that done by a gas expanding against a piston, is positive, and work done *on* a system, such as that done by a piston compressing a gas, is negative. Thus, positive work means that energy leaves the system, and negative work means that energy is added to the system.

Our definition of work involves raising of a weight, that is, the product of a unit force (one newton) acting through a unit distance (one meter). This unit for work in SI units is called the **joule (J)**.

$$1 \text{ J} = 1 \text{ N m}$$

**Power** is the time rate of doing work and is designated by the symbol  $\dot{W}$ :

$$\dot{W} \equiv \frac{\delta W}{dt}$$

The unit for power is a rate of work of one joule per second, which is a **watt (W)**:

$$1 \text{ W} = 1 \text{ J/s}$$

A familiar unit for power in English units is the **horsepower (hp)**, where

$$1 \text{ hp} = 550 \text{ ft lbf/s}$$

Note that the work crossing the boundary of the system in Fig. 4.1 is that associated with a rotating shaft. To derive the expression for power, we use the differential work from Eq. 4.1:

$$\delta W = F dx = Fr d\theta = T d\theta$$

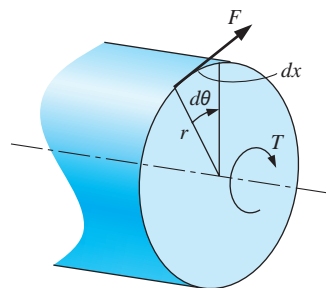
that is, force acting through a distance  $dx$  or a torque ( $T = Fr$ ) acting through an angle of rotation, as shown in Fig. 4.3. Now the power becomes

$$\dot{W} = \frac{\delta W}{dt} = F \frac{dx}{dt} = F \mathbf{V} = Fr \frac{d\theta}{dt} = T \omega \quad (4.2)$$

that is, force times rate of displacement (velocity) or torque times angular velocity.

It is often convenient to speak of the work per unit mass of the system, often termed *specific work*. This quantity is designated  $w$  and is defined as

$$w \equiv \frac{W}{m}$$



**FIGURE 4.3** Force acting at radius  $r$  gives a torque  $T = Fr$ .

### In-Text Concept Questions

- The electric company charges the customers per kW-hour. What is that in SI units?
- Torque, energy, and work have the same units (Nm). Explain the difference.

## 4.3 WORK DONE AT THE MOVING BOUNDARY OF A SIMPLE COMPRESSIBLE SYSTEM

We have already noted that there are a variety of ways in which work can be done on or by a system. These include work done by a rotating shaft, electrical work, and work done by the movement of the system boundary, such as the work done in moving the piston in a cylinder. In this section we will consider in some detail the work done at the moving boundary of a simple compressible system during a quasi-equilibrium process.

Consider as a system the gas contained in a cylinder and piston, as in Fig. 4.4. Remove one of the small weights from the piston, which will cause the piston to move upward a distance  $dL$ . We can consider this quasi-equilibrium process and calculate the amount of work  $W$  done by the system during this process. The total force on the piston is  $PA$ , where  $P$  is the pressure of the gas and  $A$  is the area of the piston. Therefore, the work  $\delta W$  is

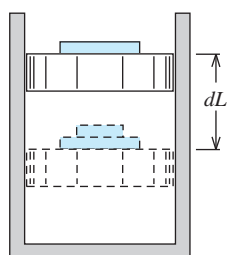
$$\delta W = PA \, dL$$

But  $A \, dL = dV$ , the change in volume of the gas. Therefore,

$$\delta W = P \, dV \quad (4.3)$$

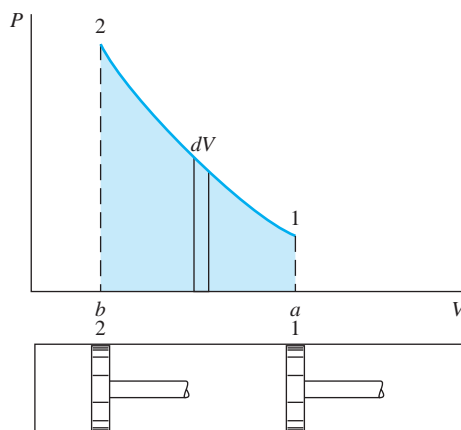
The work done at the moving boundary during a given quasi-equilibrium process can be found by integrating Eq. 4.3. However, this integration can be performed only if we know the relationship between  $P$  and  $V$  during this process. This relationship may be expressed as an equation, or it may be shown as a graph.

Let us consider a graphical solution first. We use as an example a compression process such as occurs during the compression of air in a cylinder, Fig. 4.5. At the beginning of the process the piston is at position 1, and the pressure is relatively low. This state is represented



**FIGURE 4.4**

Example of work done at the moving boundary of a system in a quasi-equilibrium process.



**FIGURE 4.5** Use of a  $P$ - $V$  diagram to show work done at the moving boundary of a system in a quasi-equilibrium process.

on a pressure–volume diagram (usually referred to as a  $P$ – $V$  diagram). At the conclusion of the process the piston is in position 2, and the corresponding state of the gas is shown at point 2 on the  $P$ – $V$  diagram. Let us assume that this compression was a quasi-equilibrium process and that during the process the system passed through the states shown by the line connecting states 1 and 2 on the  $P$ – $V$  diagram. The assumption of a quasi-equilibrium process is essential here because each point on line 1–2 represents a definite state, and these states correspond to the actual state of the system only if the deviation from equilibrium is infinitesimal. The work done on the air during this compression process can be found by integrating Eq. 4.3:

$${}_1W_2 = \int_1^2 \delta W = \int_1^2 P dV \quad (4.4)$$

The symbol  ${}_1W_2$  is to be interpreted as the work done during the process from state 1 to state 2. It is clear from the  $P$ – $V$  diagram that the work done during this process,

$$\int_1^2 P dV$$

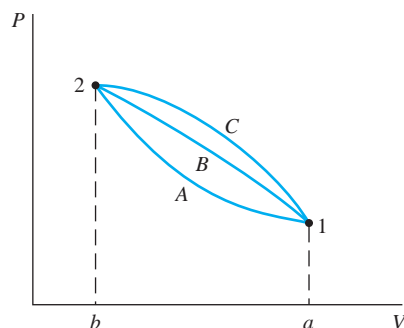
is represented by the area under curve 1–2, area  $a$ –1–2– $b$ – $a$ . In this example the volume decreased, and area  $a$ –1–2– $b$ – $a$  represents work done on the system. If the process had proceeded from state 2 to state 1 along the same path, the same area would represent work done by the system.

Further consideration of a  $P$ – $V$  diagram, such as Fig. 4.6, leads to another important conclusion. It is possible to go from state 1 to state 2 along many different quasi-equilibrium paths, such as  $A$ ,  $B$ , or  $C$ . Since the area under each curve represents the work for each process, the amount of work done during each process not only is a function of the end states of the process but also depends on the path followed in going from one state to another. For this reason, work is called a *path function* or, in mathematical parlance,  $\delta W$  is an inexact differential.

This concept leads to a brief consideration of point and path functions or, to use other terms, *exact* and *inexact differentials*. Thermodynamic properties are *point functions*, a name that comes from the fact that for a given point on a diagram (such as Fig. 4.6) or surface (such as Fig. 3.18) the state is fixed, and thus there is a definite value for each property corresponding to this point. The differentials of point functions are exact differentials, and the integration is simply

$$\int_1^2 dV = V_2 - V_1$$

**FIGURE 4.6** Various quasi-equilibrium processes between two given states, indicating that work is a path function.



Thus, we can speak of the volume in state 2 and the volume in state 1, and the change in volume depends only on the initial and final states.

Work, however, is a path function, for, as has been indicated, the work done in a quasi-equilibrium process between two given states depends on the path followed. The differentials of path functions are inexact differentials, and the symbol  $\delta$  will be used in this book to designate inexact differentials (in contrast to  $d$  for exact differentials). Thus, for work, we write

$$\int_1^2 \delta W = {}_1W_2$$

It would be more precise to use the notation  ${}_1W_{2A}$ , which would indicate the work done during the change from state 1 to state 2 along path  $A$ . However, the notation  ${}_1W_2$  indicates that the process between states 1 and 2 has been specified. Note that we never speak about the work in the system in state 1 or state 2, and thus we never write  $W_2 - W_1$ .

In evaluating the integral of Eq. 4.4, we should always keep in mind that we wish to determine the area under the curve in Fig. 4.6. In connection with this point, we identify the following two classes of problems:

1. The relationship between  $P$  and  $V$  is given in terms of experimental data or in graphical form (as, for example, the trace on an oscilloscope). Therefore, we may evaluate the integral, Eq. 4.4, by graphical or numerical integration.
2. The relationship between  $P$  and  $V$  makes it possible to fit an analytical relationship between them. We may then integrate directly.

One common example of this second type of functional relationship is a process called a **polytropic process**, one in which

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

throughout the process. The exponent  $n$  may be any value from  $-\infty$  to  $+\infty$ , depending on the process. For this type of process, we can integrate Eq. 4.4 as follows:

$$\begin{aligned} PV^n &= \text{constant} = P_1 V_1^n = P_2 V_2^n \\ P &= \frac{\text{constant}}{V^n} = \frac{P_1 V_1^n}{V^n} = \frac{P_2 V_2^n}{V^n} \\ \int_1^2 P dV &= \text{constant} \int_1^2 \frac{dV}{V^n} = \text{constant} \left( \frac{V^{-n+1}}{-n+1} \right) \Big|_1^2 \\ \int_1^2 P dV &= \frac{\text{constant}}{1-n} (V_2^{1-n} - V_1^{1-n}) = \frac{P_2 V_2^n V_2^{1-n} - P_1 V_1^n V_1^{1-n}}{1-n} \\ &= \frac{P_2 V_2 - P_1 V_1}{1-n} \end{aligned} \quad (4.5)$$

Note that the resulting equation, Eq. 4.5, is valid for any exponent  $n$  except  $n = 1$ . Where  $n = 1$ ,

$$PV = \text{constant} = P_1 V_1 = P_2 V_2$$



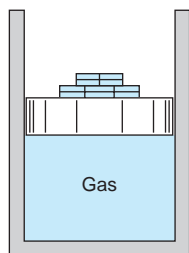
and

$$\int_1^2 P dV = P_1 V_1 \int_1^2 \frac{dV}{V} = P_1 V_1 \ln \frac{V_2}{V_1} \quad (4.6)$$

Note that in Eqs. 4.5 and 4.6 we did not say that the work is equal to the expressions given in these equations. These expressions give us the value of a certain integral, that is, a mathematical result. Whether or not that integral equals the work in a particular process depends on the result of a thermodynamic analysis of that process. It is important to keep the mathematical result separate from the thermodynamic analysis, for there are many situations in which work is not given by Eq. 4.4.

The polytropic process as described demonstrates one special functional relationship between  $P$  and  $V$  during a process. There are many other possible relations, some of which will be examined in the problems at the end of this chapter.

### EXAMPLE 4.1



**FIGURE 4.7**  
Sketch for  
Example 4.1.

Consider as a system the gas in the cylinder shown in Fig. 4.7; the cylinder is fitted with a piston on which a number of small weights are placed. The initial pressure is 200 kPa, and the initial volume of the gas is  $0.04 \text{ m}^3$ .

- a. Let a Bunsen burner be placed under the cylinder, and let the volume of the gas increase to  $0.1 \text{ m}^3$  while the pressure remains constant. Calculate the work done by the system during this process.

$${}_1W_2 = \int_1^2 P dV$$

Since the pressure is constant, we conclude from Eq. 4.4 that

$${}_1W_2 = P \int_1^2 dV = P(V_2 - V_1)$$

$${}_1W_2 = 200 \text{ kPa} \times (0.1 - 0.04) \text{ m}^3 = 12.0 \text{ kJ}$$

- b. Consider the same system and initial conditions, but at the same time that the Bunsen burner is under the cylinder and the piston is rising, remove weights from the piston at such a rate that, during the process, the temperature of the gas remains constant.

If we assume that the ideal-gas model is valid, then, from Eq. 3.5,

$$PV = mRT$$

We note that this is a polytropic process with exponent  $n = 1$ . From our analysis, we conclude that the work is given by Eq. 4.4 and that the integral in this equation is given by Eq. 4.6. Therefore,

$$\begin{aligned} {}_1W_2 &= \int_1^2 P dV = P_1 V_1 \ln \frac{V_2}{V_1} \\ &= 200 \text{ kPa} \times 0.04 \text{ m}^3 \times \ln \frac{0.10}{0.04} = 7.33 \text{ kJ} \end{aligned}$$

c. Consider the same system, but during the heat transfer remove the weights at such a rate that the expression  $PV^{1.3} = \text{constant}$  describes the relation between pressure and volume during the process. Again, the final volume is  $0.1 \text{ m}^3$ . Calculate the work.

This is a polytropic process in which  $n = 1.3$ . Analyzing the process, we conclude again that the work is given by Eq. 4.4 and that the integral is given by Eq. 4.5. Therefore,

$$P_2 = 200 \left( \frac{0.04}{0.10} \right)^{1.3} = 60.77 \text{ kPa}$$

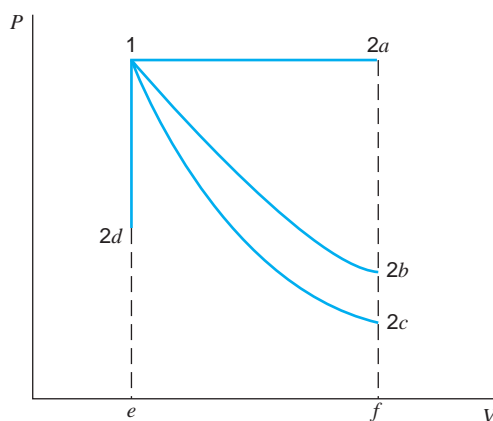
$${}_1W_2 = \int_1^2 P dV = \frac{P_2 V_2 - P_1 V_1}{1 - 1.3} = \frac{60.77 \times 0.1 - 200 \times 0.04}{1 - 1.3} \text{ kPa m}^3$$

$$= 6.41 \text{ kJ}$$

d. Consider the system and the initial state given in the first three examples, but let the piston be held by a pin so that the volume remains constant. In addition, let heat be transferred from the system until the pressure drops to 100 kPa. Calculate the work.

Since  $\delta W = P dV$  for a quasi-equilibrium process, the work is zero, because there is no change in volume.

The process for each of the four examples is shown on the  $P$ - $V$  diagram of Fig. 4.8. Process 1-2a is a constant-pressure process, and area 1-2a-f-e-1 represents the work. Similarly, line 1-2b represents the process in which  $PV = \text{constant}$ , line 1-2c the process in which  $PV^{1.3} = \text{constant}$ , and line 1-2d the constant-volume process. The student should compare the relative areas under each curve with the numerical results obtained for the amounts of work done.



**FIGURE 4.8**  $P$ - $V$  diagram showing work done in the various processes of Example 4.1.

## EXAMPLE 4.2

Consider a slightly different piston/cylinder arrangement, as shown in Fig. 4.9. In this example the piston is loaded with a mass  $m_p$ , the outside atmosphere  $P_0$ , a linear spring, and a single point force  $F_1$ . The piston traps the gas inside with a pressure  $P$ . A force balance on the piston in the direction of motion yields

$$m_p a \cong 0 = \sum F_{\uparrow} - \sum F_{\downarrow}$$

with a zero acceleration in a quasi-equilibrium process. The forces, when the spring is in contact with the piston, are

$$\sum F_{\uparrow} = PA, \quad \sum F_{\downarrow} = m_p g + P_0 A + k_s(x - x_0) + F_1$$

with the linear spring constant,  $k_s$ . The piston position for a relaxed spring is  $x_0$ , which depends on how the spring is installed. The force balance then gives the gas pressure by division with area  $A$  as

$$P = P_0 + [m_p g + F_1 + k_s(x - x_0)]/A$$

To illustrate the process in a  $P$ - $V$  diagram, the distance  $x$  is converted to volume by division and multiplication with  $A$ :

$$P = P_0 + \frac{m_p g}{A} + \frac{F_1}{A} + \frac{k_s}{A^2}(V - V_0) = C_1 + C_2 V$$

This relation gives the pressure as a linear function of the volume, with the line having a slope of  $C_2 = k_s/A^2$ . Possible values of  $P$  and  $V$  are as shown in Fig. 4.10 for an expansion. Regardless of what substance is inside, any process must proceed along the line in the  $P$ - $V$  diagram. The work term in a quasi-equilibrium process then follows as

$${}_1W_2 = \int_1^2 P dV = \text{area under the process curve}$$

$${}_1W_2 = \frac{1}{2}(P_1 + P_2)(V_2 - V_1)$$

For a contraction instead of an expansion, the process would proceed in the opposite direction from the initial point 1 along a line of the same slope shown in Fig. 4.10.

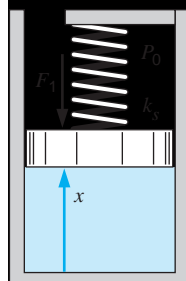
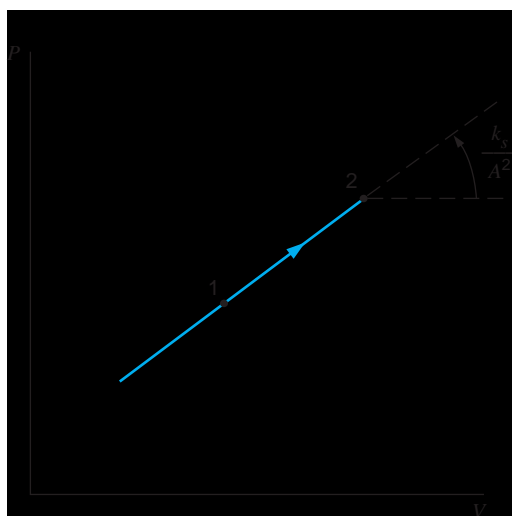


FIGURE 4.9 Sketch of the physical system for Example 4.2.



**FIGURE 4.10** The process curve showing possible  $P$ - $v$  combinations for Example 4.2.

### EXAMPLE 4.3

The cylinder/piston setup of Example 4.2 contains 0.5 kg of ammonia at  $-20^\circ\text{C}$  with a quality of 25%. The ammonia is now heated to  $+20^\circ\text{C}$ , at which state the volume is observed to be 1.41 times larger. Find the final pressure and the work the ammonia produced.

#### Solution

The forces acting on the piston, the gravitation constant, the external atmosphere at constant pressure, and the linear spring give a linear relation between  $P$  and  $v(V)$ .

*State 1:*  $(T_1, x_1)$  from Table B.2.1

$$P_1 = P_{\text{sat}} = 190.2 \text{ kPa}$$

$$v_1 = v_f + x_1 v_{fg} = 0.001504 + 0.25 \times 0.62184 = 0.15696 \text{ m}^3/\text{kg}$$

*State 2:*  $(T_2, v_2 = 1.41 v_1 = 1.41 \times 0.15696 = 0.2213 \text{ m}^3/\text{kg})$

Table B.2.2 state very close to  $P_2 = 600 \text{ kPa}$

*Process:*  $P = C_1 + C_2 v$

The work term can now be integrated, knowing  $P$  versus  $v$ , and can be seen as the area in the  $P$ - $v$  diagram, shown in Fig. 4.11.

$$\begin{aligned} {}_1W_2 &= \int_1^2 P dV = \int_1^2 P m dv = \text{area} = m \frac{1}{2} (P_1 + P_2)(v_2 - v_1) \\ &= 0.5 \text{ kg} \frac{1}{2} (190.2 + 600) \text{ kPa} (0.2213 - 0.15696) \text{ m}^3/\text{kg} \\ &= 12.71 \text{ kJ} \end{aligned}$$

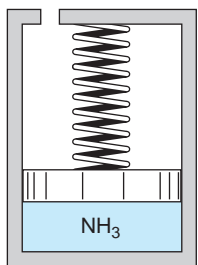
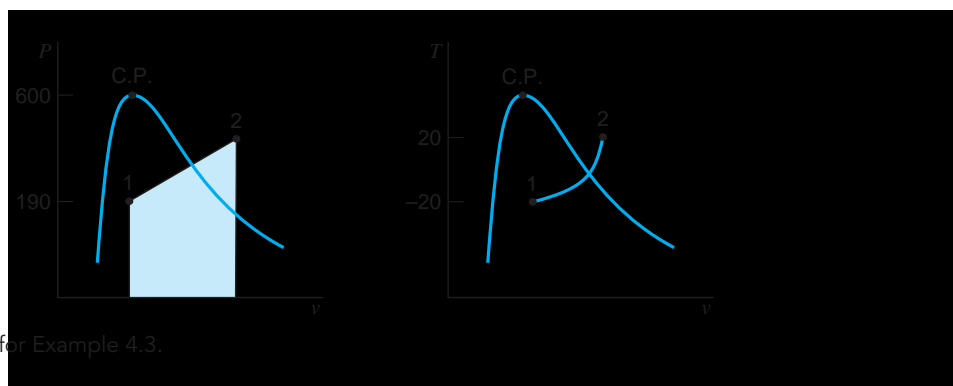


FIGURE 4.11 Diagrams for Example 4.3.



## EXAMPLE 4.4

The piston/cylinder setup shown in Fig. 4.12 contains 0.1 kg of water at 1000 kPa, 500°C. The water is now cooled with a constant force on the piston until it reaches half the initial volume. After this it cools to 25°C while the piston is against the stops. Find the final water pressure and the work in the overall process, and show the process in a  $P$ - $v$  diagram.

## Solution

We recognize that this is a two-step process, one of constant  $P$  and one of constant  $V$ . This behavior is dictated by the construction of the device.

*State 1:* ( $P, T$ ) From Table B.1.3;  $v_1 = 0.35411 \text{ m}^3/\text{kg}$

*Process 1–1a:*  $P = \text{constant} = F/A$

*1a–2:*  $v = \text{constant} = v_{1a} = v_2 = v_1/2$

*State 2:* ( $T, v_2 = v_1/2 = 0.17706 \text{ m}^3/\text{kg}$ )

From Table B.1.1,  $v_2 < v_g$ , so the state is two phase and  $P_2 = P_{\text{sat}} = 3.169 \text{ kPa}$ .

$$\begin{aligned} {}_1W_2 &= \int_1^2 P dV = m \int_1^2 P dv = m P_1 (v_{1a} - v_1) + 0 \\ &= 0.1 \text{ kg} \times 1000 \text{ kPa} (0.17706 - 0.35411) \text{ m}^3/\text{kg} = -17.7 \text{ kJ} \end{aligned}$$

Note that the work done from 1a to 2 is zero (no change in volume), as shown in Fig. 4.13.

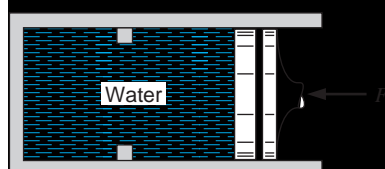
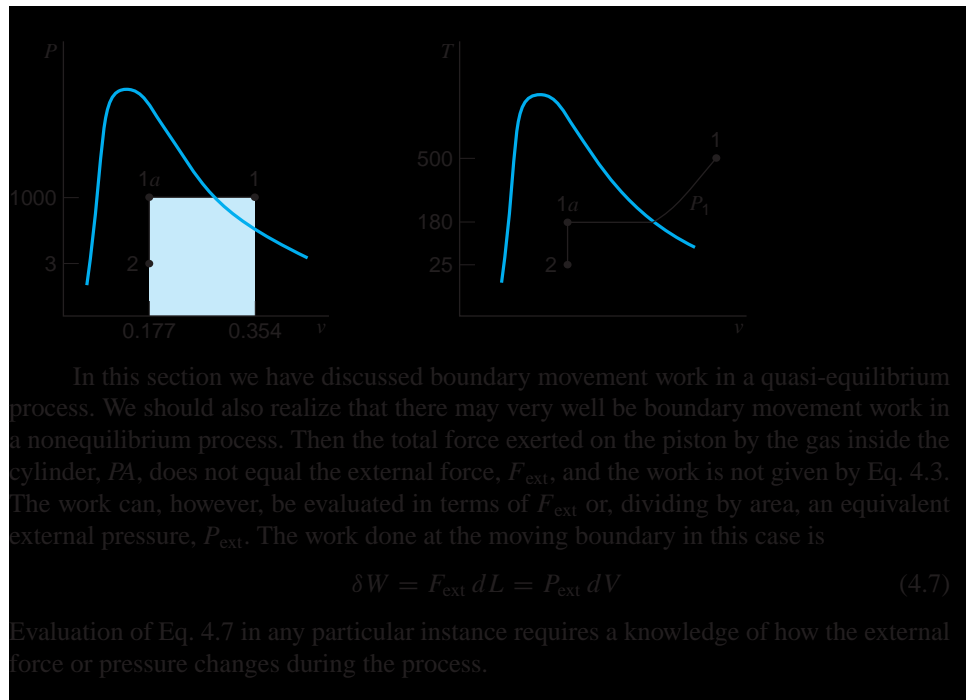


FIGURE 4.12 Sketch for Example 4.4.

**FIGURE 4.13**  
Diagrams for Example 4.4.



### EXAMPLE 4.5

Consider the system shown in Fig. 4.14, in which the piston of mass  $m_p$  is initially held in place by a pin. The gas inside the cylinder is initially at pressure  $P_1$  and volume  $V_1$ . When the pin is released, the external force per unit area acting on the system (gas) boundary is comprised of two parts:

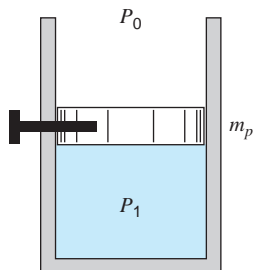
$$P_{\text{ext}} = F_{\text{ext}}/A = P_0 + m_p g/A$$

Calculate the work done by the system when the piston has come to rest.

After the piston is released, the system is exposed to the boundary pressure equal to  $P_{\text{ext}}$ , which dictates the pressure inside the system, as discussed in Section 2.8 in connection with Fig. 2.9. We further note that neither of the two components of this external force will change with a boundary movement, since the cylinder is vertical (gravitational force) and the top is open to the ambient surroundings (movement upward merely pushes the air out of the way). If the initial pressure  $P_1$  is greater than that resisting the boundary, the piston will move upward at a finite rate, that is, in a nonequilibrium process, with the cylinder pressure eventually coming to equilibrium at the value  $P_{\text{ext}}$ . If we were able to trace the average cylinder pressure as a function of time, it would typically behave as shown in Fig. 4.15. However, the work done by the system during this process is done against the force resisting the boundary movement and is therefore given by Eq. 4.7. Also, since the external force is constant during this process, the result is

$${}_1W_2 = \int_1^2 P_{\text{ext}} dV = P_{\text{ext}}(V_2 - V_1)$$

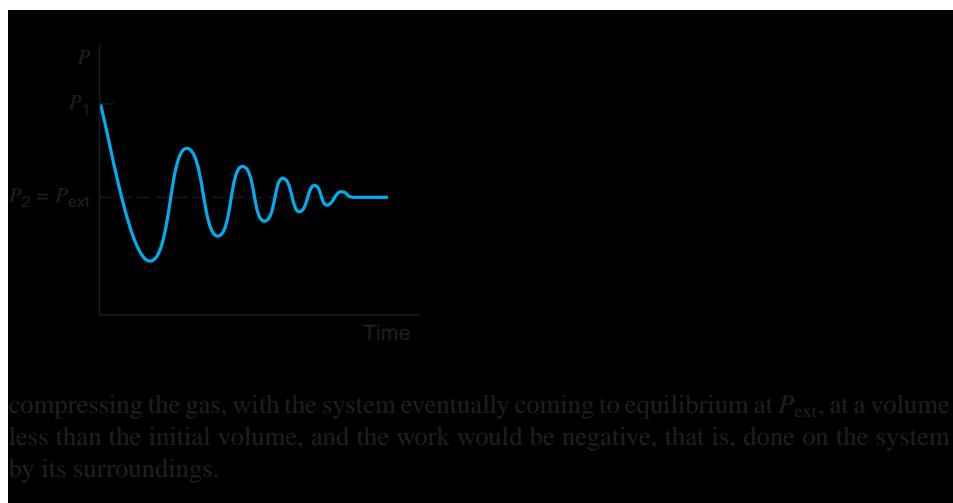
where  $V_2$  is greater than  $V_1$ , and the work done by the system is positive. If the initial pressure had been less than the boundary pressure, the piston would have moved downward,



**FIGURE 4.14**  
Example of a nonequilibrium process.

**FIGURE 4.15**

Cylinder pressure as a function of time.



compressing the gas, with the system eventually coming to equilibrium at  $P_{\text{ext}}$ , at a volume less than the initial volume, and the work would be negative, that is, done on the system by its surroundings.

### In-Text Concept Questions

- What is roughly the relative magnitude of the work in process 1–2c versus process 1–2a shown in Fig. 4.8?
- Helium gas expands from 125 kPa, 350 K, and  $0.25 \text{ m}^3$  to 100 kPa in a polytropic process with  $n = 1.667$ . Is the work positive, negative, or zero?
- An ideal gas goes through an expansion process in which the volume doubles. Which process will lead to the larger work output: an isothermal process or a polytropic process with  $n = 1.25$ ?

## 4.4 OTHER SYSTEMS THAT INVOLVE WORK

In the preceding section we considered the work done at the moving boundary of a simple compressible system during a quasi-equilibrium process and during a nonequilibrium process. There are other types of systems in which work is done at a moving boundary. In this section we briefly consider three such systems: a stretched wire, a surface film, and electrical work.

Consider as a system a stretched wire that is under a given tension  $\mathcal{T}$ . When the length of the wire changes by the amount  $dL$ , the work done by the system is

$$\delta W = -\mathcal{T} dL \quad (4.8)$$

The minus sign is necessary because work is done by the system when  $dL$  is negative. This equation can be integrated to have

$${}_1W_2 = -\int_1^2 \mathcal{T} dL \quad (4.9)$$

The integration can be performed either graphically or analytically if the relation between  $\mathcal{T}$  and  $L$  is known. The stretched wire is a simple example of the type of problem in solid-body mechanics that involves the calculation of work.

**EXAMPLE 4.6**

A metallic wire of initial length  $L_0$  is stretched. Assuming elastic behavior, determine the work done in terms of the modulus of elasticity and the strain.

Let  $\sigma$  = stress,  $e$  = strain, and  $E$  = the modulus of elasticity.

$$\sigma = \frac{\mathcal{T}}{A} = Ee$$

Therefore,

$$\mathcal{T} = AEe$$

From the definition of strain,

$$de = \frac{dL}{L_0}$$

Therefore,

$$\begin{aligned}\delta W &= -\mathcal{T}dL = -AEeL_0 de \\ W &= -AEL_0 \int_{e=0}^e e de = -\frac{AEL_0}{2}(e)^2\end{aligned}$$

Now consider a system that consists of a liquid film with a surface tension  $\mathcal{S}$ . A schematic arrangement of such a film, maintained on a wire frame, one side of which can be moved, is shown in Fig. 4.16. When the area of the film is changed, for example, by sliding the movable wire along the frame, work is done on or by the film. When the area changes by an amount  $dA$ , the work done by the system is

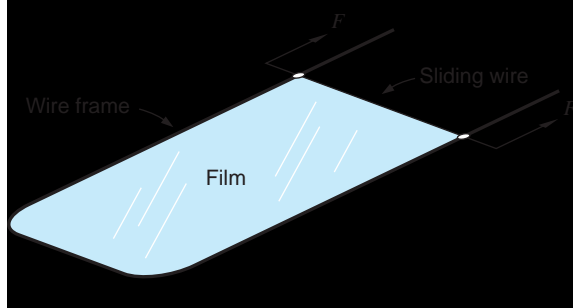
$$\delta W = -\mathcal{S} dA \quad (4.10)$$

For finite changes,

$${}_1W_2 = -\int_1^2 \mathcal{S} dA \quad (4.11)$$

We have already noted that electrical energy flowing across the boundary of a system is work. We can gain further insight into such a process by considering a system in which the only work mode is electrical. Examples of such a system include a charged condenser, an electrolytic cell, and the type of fuel cell described in Chapter 1. Consider a quasi-equilibrium process for such a system, and during this process let the potential difference be  $\mathcal{E}$  and the amount of electrical charge that flows into the system be  $dZ$ . For this quasi-equilibrium process the work is given by the relation

$$\delta W = -\mathcal{E} dZ \quad (4.12)$$



**FIGURE 4.16**

Schematic arrangement showing work done on a surface film.



Since the current,  $i$ , equals  $dZ/dt$  (where  $t$  = time), we can also write

$$\delta W = -\mathcal{E} i dt$$

$${}_1W_2 = - \int_1^2 \mathcal{E} i dt \quad (4.13)$$

Equation 4.13 may also be written as a rate equation for work (power):

$$\dot{W} = \frac{\delta W}{dt} = -\mathcal{E} i \quad (4.14)$$

Since the **ampere** (electric current) is one of the fundamental units in the International System and the watt was defined previously, this relation serves as the definition of the unit for electric potential, the **volt (V)**, which is one watt divided by one ampere.

## 4.5 CONCLUDING REMARKS REGARDING WORK

The similarity of the expressions for work in the three processes discussed in Section 4.4 and in the processes in which work is done at a moving boundary should be noted. In each of these quasi-equilibrium processes, work is expressed by the integral of the product of an intensive property and the change of an extensive property. The following is a summary list of these processes and their work expressions:

Simple compressible system	${}_1W_2 = \int_1^2 P dV$
Stretched wire	${}_1W_2 = - \int_1^2 \mathcal{T} dL$
Surface film	${}_1W_2 = - \int_1^2 \mathcal{S} dA$
System in which the work is completely electrical	${}_1W_2 = - \int_1^2 \mathcal{E} dZ \quad (4.15)$

Although we will deal primarily with systems in which there is only one mode of work, it is quite possible to have more than one work mode in a given process. Thus, we could write

$$\delta W = P dV - \mathcal{T} dL - \mathcal{S} dA - \mathcal{E} dZ + \dots \quad (4.16)$$

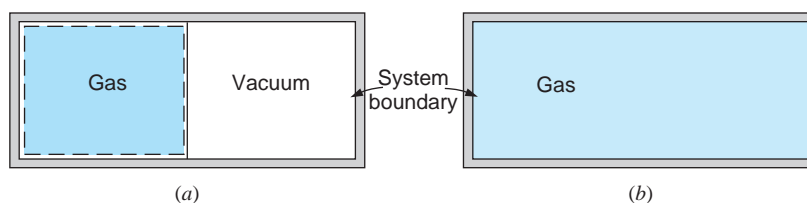
where the dots represent other products of an intensive property and the derivative of a related extensive property. In each term the intensive property can be viewed as the driving force that causes a change to occur in the related extensive property, which is often termed the *displacement*. Just as we can derive the expression for power for the single point force in Eq. 4.2, the rate form of Eq. 4.16 expresses the power as

$$\dot{W} = \frac{dW}{dt} = P \dot{V} - \mathcal{T} \dot{L} - \mathcal{S} \dot{A} - \mathcal{E} \dot{Z} + \dots \quad (4.17)$$

It should also be noted that many other forms of work can be identified in processes that are not quasi-equilibrium processes. For example, there is the work done by shearing

**FIGURE 4.17**

Example of a process involving a change of volume for which the work is zero.



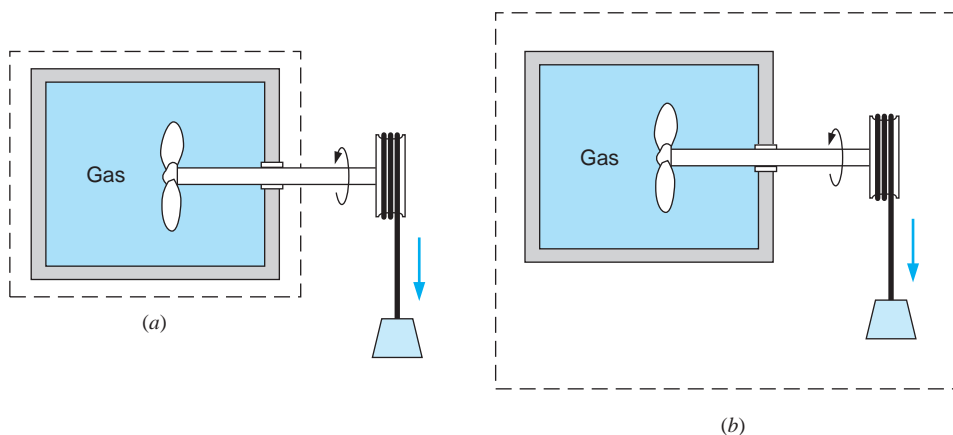
forces in the friction in a viscous fluid or the work done by a rotating shaft that crosses the system boundary.

The identification of work is an important aspect of many thermodynamic problems. We have already noted that work can be identified only at the boundaries of the system. For example, consider Fig. 4.17, which shows a gas separated from the vacuum by a membrane. Let the membrane rupture and the gas fill the entire volume. Neglecting any work associated with the rupturing of the membrane, we can ask whether work is done in the process. If we take as our system the gas and the vacuum space, we readily conclude that no work is done because no work can be identified at the system boundary. If we take the gas as a system, we do have a change of volume, and we might be tempted to calculate the work from the integral

$$\int_1^2 P dV$$

However, this is not a quasi-equilibrium process, and therefore the work cannot be calculated from this relation. Because there is no resistance at the system boundary as the volume increases, we conclude that for this system no work is done in this process of filling the vacuum.

Another example can be cited with the aid of Fig. 4.18. In Fig. 4.18a the system consists of the container plus the gas. Work crosses the boundary of the system at the point where the system boundary intersects the shaft, and this work can be associated with the shearing forces in the rotating shaft. In Fig. 4.18b the system includes the shaft and the weight as well as the gas and the container. Therefore, no work crosses the system boundary as the weight moves downward. As we will see in the next chapter, we can identify a change of potential energy within the system, but this should not be confused with work crossing the system boundary.

**FIGURE 4.18**

Example showing how selection of the system determines whether work is involved in a process.

## 4.6 DEFINITION OF HEAT

The thermodynamic definition of heat is somewhat different from the everyday understanding of the word. It is essential to understand clearly the definition of heat given here, because it plays a part in many thermodynamic problems.

If a block of hot copper is placed in a beaker of cold water, we know from experience that the block of copper cools down and the water warms up until the copper and water reach the same temperature. What causes this decrease in the temperature of the copper and the increase in the temperature of the water? We say that it is the result of the transfer of energy from the copper block to the water. It is from such a transfer of energy that we arrive at a definition of heat.

**Heat** is defined as the form of energy that is transferred across the boundary of a system at a given temperature to another system (or the surroundings) at a lower temperature by virtue of the temperature difference between the two systems. That is, heat is transferred from the system at the higher temperature to the system at the lower temperature, and the heat transfer occurs solely because of the temperature difference between the two systems. Another aspect of this definition of heat is that a body never contains heat. Rather, heat can be identified only as it crosses the boundary. Thus, heat is a transient phenomenon. If we consider the hot block of copper as one system and the cold water in the beaker as another system, we recognize that originally neither system contains any heat (they do contain energy, of course). When the copper block is placed in the water and the two are in thermal communication, heat is transferred from the copper to the water until equilibrium of temperature is established. At this point we no longer have heat transfer, because there is no temperature difference. Neither system contains heat at the conclusion of the process. It also follows that heat is identified at the boundary of the system, for heat is defined as energy transferred across the system boundary.

Heat, like work, is a form of energy transfer to or from a system. Therefore, the units for heat, and for any other form of energy as well, are the same as the units for work, or at least are directly proportional to them. In the International System the unit for heat (energy) is the joule. In the English System, the foot pound force is an appropriate unit for heat. However, another unit came to be used naturally over the years, the result of an association with the process of heating water, such as that used in connection with defining heat in the previous section. Consider as a system 1 lbm of water at 59.5 F. Let a block of hot copper of appropriate mass and temperature be placed in the water so that when thermal equilibrium is established, the temperature of the water is 60.5 F. This unit amount of heat transferred from the copper to the water in this process is called the **British thermal unit (Btu)**. More specifically, it is called the *60-degree Btu*, defined as the amount of heat required to raise 1 lbm of water from 59.5 F to 60.5 F. (The Btu as used today is actually defined in terms of the standard SI units.) It is worth noting here that a unit of heat in metric units, the **calorie**, originated naturally in a manner similar to the origin of the Btu in the English System. The **calorie** is defined as the amount of heat required to raise 1 g of water from 14.5°C to 15.5°C.

Heat transferred *to* a system is considered positive, and heat transferred *from* a system is considered negative. Thus, positive heat represents energy transferred to a system, and negative heat represents energy transferred from a system. The symbol  $Q$  represents heat. A process in which there is no heat transfer ( $Q = 0$ ) is called an **adiabatic process**.

From a mathematical perspective, heat, like work, is a path function and is recognized as an inexact differential. That is, the amount of heat transferred when a system undergoes a change from state 1 to state 2 depends on the path that the system follows during the

change of state. Since heat is an inexact differential, the differential is written as  $\delta Q$ . On integrating, we write

$$\int_1^2 \delta Q = {}_1Q_2$$

In words,  ${}_1Q_2$  is the heat transferred during the given process between states 1 and 2.

The rate at which heat is transferred to a system is designated by the symbol  $\dot{Q}$ :

$$\dot{Q} \equiv \frac{\delta Q}{dt}$$

It is also convenient to speak of the heat transfer per unit mass of the system,  $q$ , often termed *specific heat transfer*, which is defined as

$$q \equiv \frac{Q}{m}$$

## 4.7 HEAT TRANSFER MODES

Heat transfer is the transport of energy due to a temperature difference between different amounts of matter. We know that an ice cube taken out of the freezer will melt when it is placed in a warmer environment such as a glass of liquid water or on a plate with room air around it. From the discussion about energy in Section 2.6, we realize that molecules of matter have translational (kinetic), rotational, and vibrational energy. Energy in these modes can be transmitted to the nearby molecules by interactions (collisions) or by exchange of molecules such that energy is emitted by molecules that have more on average (higher temperature) to those that have less on average (lower temperature). This energy exchange between molecules is heat transfer by **conduction**, and it increases with the temperature difference and the ability of the substance to make the transfer. This is expressed in Fourier's law of conduction,

$$\dot{Q} = -kA \frac{dT}{dx} \quad (4.18)$$

giving the rate of heat transfer as proportional to the conductivity,  $k$ , the total area,  $A$ , and the temperature gradient. The minus sign indicates the direction of the heat transfer from a higher-temperature to a lower-temperature region. Often the gradient is evaluated as a temperature difference divided by a distance when an estimate has to be made if a mathematical or numerical solution is not available.

Values of conductivity,  $k$ , are on the order of 100 W/m K for metals, 1 to 10 for nonmetallic solids as glass, ice, and rock, 0.1 to 10 for liquids, around 0.1 for insulation materials, and 0.1 down to less than 0.01 for gases.

A different mode of heat transfer takes place when a medium is flowing, called **convective** heat transfer. In this mode the bulk motion of a substance moves matter with a certain energy level over or near a surface with a different temperature. Now the heat transfer by conduction is dominated by the manner in which the bulk motion brings the two substances in contact or close proximity. Examples are the wind blowing over a building or flow through heat exchangers, which can be air flowing over/through a radiator with water flowing inside the radiator piping. The overall heat transfer is typically correlated with Newton's law of cooling as

$$\dot{Q} = Ah \Delta T \quad (4.19)$$

where the transfer properties are lumped into the heat transfer coefficient,  $h$ , which then becomes a function of the media properties, the flow and geometry. A more detailed study of fluid mechanics and heat transfer aspects of the overall process is necessary to evaluate the heat transfer coefficient for a given situation.

Typical values for the convection coefficient (all in  $\text{W/m}^2 \text{K}$ ) are:

Natural convection	$h = 5\text{--}25$ , gas	$h = 50\text{--}1000$ , liquid
Forced convection	$h = 25\text{--}250$ , gas	$h = 50\text{--}20\,000$ , liquid
Boiling phase change	$h = 2500\text{--}100\,000$	

The final mode of heat transfer is **radiation**, which transmits energy as electromagnetic waves in space. The transfer can happen in empty space and does not require any matter, but the emission (generation) of the radiation and the absorption do require a substance to be present. Surface emission is usually written as a fraction, emissivity  $\varepsilon$ , of a perfect black body emission as

$$\dot{Q} = \varepsilon \sigma A T_s^4 \quad (4.20)$$

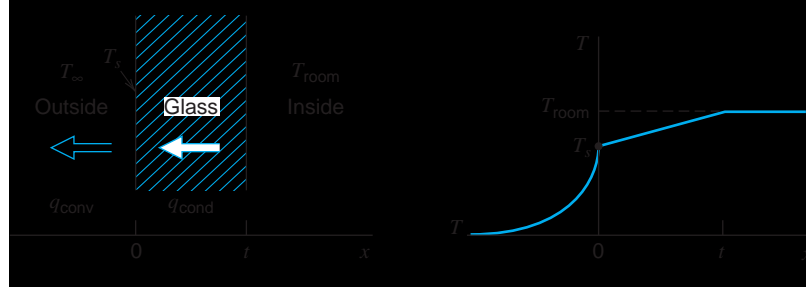
with the surface temperature,  $T_s$ , and the Stefan-Boltzmann constant,  $\sigma$ . Typical values of emissivity range from 0.92 for nonmetallic surfaces to 0.6 to 0.9 for nonpolished metallic surfaces to less than 0.1 for highly polished metallic surfaces. Radiation is distributed over a range of wavelengths and it is emitted and absorbed differently for different surfaces, but such a description is beyond the scope of this book.

### EXAMPLE 4.7

Consider the constant transfer of energy from a warm room at  $20^\circ\text{C}$  inside a house to the colder ambient temperature of  $-10^\circ\text{C}$  through a single-pane window, as shown in Fig. 4.19. The temperature variation with distance from the outside glass surface is shown by an outside convection heat transfer layer, but no such layer is inside the room (as a simplification). The glass pane has a thickness of 5 mm (0.005 m) with a conductivity of  $1.4 \text{ W/m K}$  and a total surface area of  $0.5 \text{ m}^2$ . The outside wind is blowing, so the convective heat transfer coefficient is  $100 \text{ W/m}^2 \text{K}$ . With an outer glass surface temperature of  $12.1^\circ\text{C}$ , we would like to know the rate of heat transfer in the glass and the convective layer.

For the conduction through the glass we have

$$\dot{Q} = -kA \frac{dT}{dx} = -kA \frac{\Delta T}{\Delta x} = -1.4 \frac{\text{W}}{\text{m K}} \times 0.5 \text{ m}^2 \frac{20 - 12.1 \text{ K}}{0.005 \text{ m}} = -1106 \text{ W}$$



**FIGURE 4.19**

Conduction and convection heat transfer through a window pane.

and the negative sign shows that energy is leaving the room. For the outside convection layer we have

$$\dot{Q} = hA \Delta T = 100 \frac{\text{W}}{\text{m}^2 \text{K}} \times 0.5 \text{ m}^2 [12.1 - (-10)] \text{ K} = 1105 \text{ W}$$

with a direction from the higher to the lower temperature, that is, toward the outside.

## 4.8 COMPARISON OF HEAT AND WORK

At this point it is evident that there are many similarities between heat and work.

1. Heat and work are both transient phenomena. Systems never possess heat or work, but either or both cross the system boundary when a system undergoes a change of state.
2. Both heat and work are boundary phenomena. Both are observed only at the boundary of the system, and both represent energy crossing the boundary.
3. Both heat and work are path functions and inexact differentials.

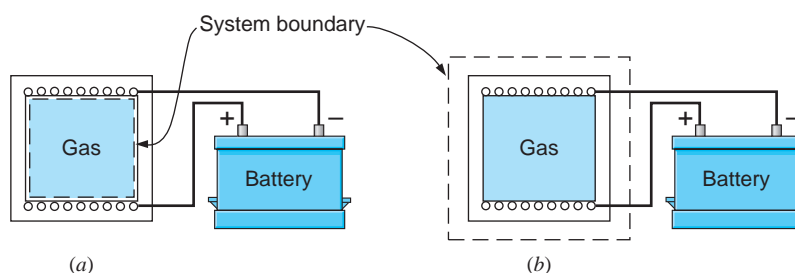
It should also be noted that in our sign convention,  $+Q$  represents heat transferred *to* the system and thus is energy added to the system, and  $+W$  represents work done *by* the system and thus is energy leaving the system.

Another illustration may help explain the difference between heat and work. Figure 4.20 shows a gas contained in a rigid vessel. Resistance coils are wound around the outside of the vessel. When current flows through the resistance coils, the temperature of the gas increases. Which crosses the boundary of the system, heat or work?

In Fig. 4.20*a* we consider only the gas as the system. The energy crosses the boundary of the system because the temperature of the walls is higher than the temperature of the gas. Therefore, we recognize that heat crosses the boundary of the system.

In Fig. 4.20*b* the system includes the vessel and the resistance heater. Electricity crosses the boundary of the system and, as indicated earlier, this is work.

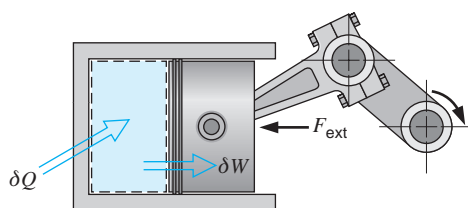
Consider a gas in a cylinder fitted with a movable piston, as shown in Fig. 4.21. There is a positive heat transfer to the gas, which tends to increase the temperature. It also tends to increase the gas pressure. However, the pressure is dictated by the external force acting on its movable boundary, as discussed in Section 2.8. If this remains constant, then the volume increases instead. There is also the opposite tendency for a negative heat transfer, that is,



**FIGURE 4.20**

An example of the difference between heat and work.

**FIGURE 4.21** The effects of heat addition to a control volume that also can give out work.



one out of the gas. Consider again the positive heat transfer, except that in this case the external force simultaneously decreases. This causes the gas pressure to decrease so that the temperature tends to go down. In this case, there is a simultaneous tendency toward temperature change in the opposite direction, which effectively decouples the directions of heat transfer and temperature change.

Often when we want to evaluate a finite amount of energy transferred as either work or heat, we must integrate the instantaneous rate over time:

$${}_1W_2 = \int_1^2 \dot{W} dt, \quad {}_1Q_2 = \int_1^2 \dot{Q} dt$$

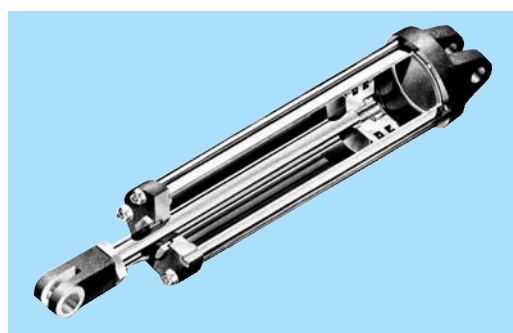
In order to perform the integration, we must know how the rate varies with time. For time periods when the rate does not change significantly, a simple average may be sufficiently accurate to allow us to write

$${}_1W_2 = \int_1^2 \dot{W} dt = \dot{W}_{\text{avg}} \Delta t \quad (4.21)$$

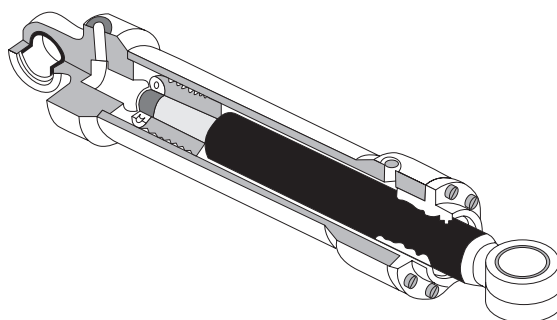
which is similar to the information given on your electric utility bill in kW-hours.

## 4.9 ENGINEERING APPLICATIONS

When work needs to be transferred from one body to another, a moving part is required, which can be a piston/cylinder combination. Examples are shown in Fig. 4.22. If the



(a) Hydraulic cylinder

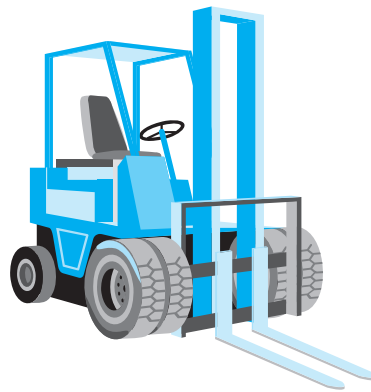


(b) Hydraulic or pneumatic cylinder

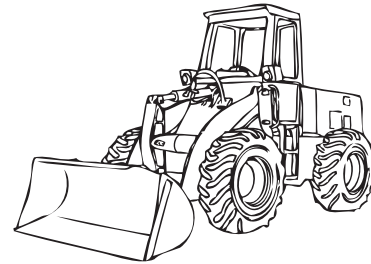
**FIGURE 4.22** Basic hydraulic or pneumatic cylinders.

**FIGURE 4.23**

Heavy-duty equipment using hydraulic cylinders.



(a) Forklift

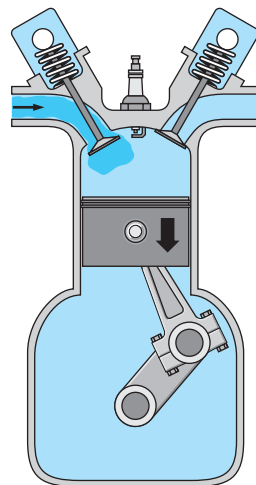


(b) Construction frontloader

substance that generates the motion is a gas, it is a pneumatic system, and if the substance is a liquid, it is a hydraulic system. The gas or vapor is typically used when the motion has to be fast or the volume change large and the pressures moderate. For high-pressure (large-force) displacements a hydraulic cylinder is used (examples include a bulldozer, forklift, frontloader, and backhoe. Also, see Example 2.7). Two of these large pieces of equipment are shown in Fig. 4.23.

We also consider cases where the substance inside the piston/cylinder undergoes a combustion process, as in gasoline and diesel engines. A schematic of an engine cylinder and a photo of a modern V6 automotive engine are shown in Fig. 4.24. This subject is discussed in detail in Chapter 12.

Many other transfers of work involve rotating shafts, such as the transmission and drive shaft in a car or a chain and rotating gears in a bicycle or motorcycle (Fig. 4.25).



(a) Schematic of engine cylinder



(b) V6 automotive engine

**FIGURE 4.24**

Schematic and photo of an automotive engine.

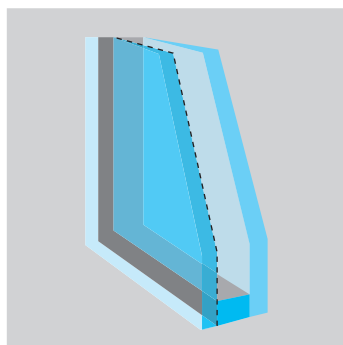




**FIGURE 4.25** Bicycle chain drive.

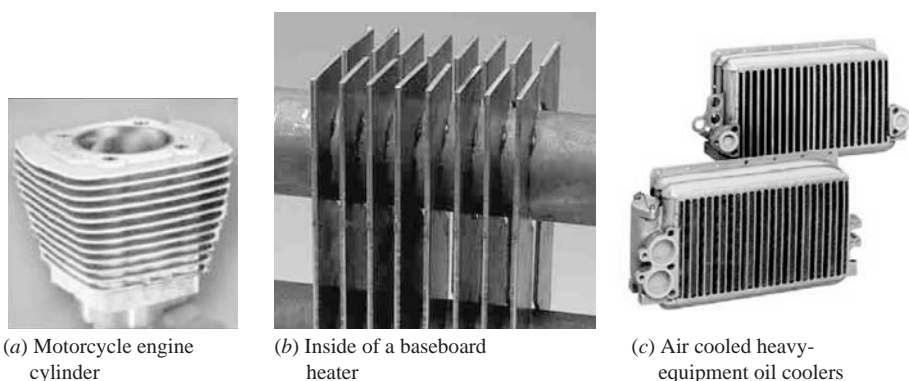


**FIGURE 4.26** Electrical power transmission tower and line.



**FIGURE 4.27** Thermopane window.

**FIGURE 4.28**  
Examples of  
fin-enhanced heat  
transfer.



For transmission of power over long distances, the most convenient and efficient form is electricity. A transmission tower and line are shown in Fig. 4.26.

Heat transfer occurs between domains at different temperatures, as in a building with different inside and outside temperatures. The double set of window panes shown in Fig. 4.27 is used to reduce the rate of heat transfer through the window. In situations where an increased rate of heat transfer is desirable, fins are often used to increase the surface area for heat transfer to occur. Examples are shown in Fig. 4.28.

## SUMMARY

**Work** and **heat** are energy transfers between a control volume and its surroundings. Work is energy that can be transferred mechanically (or electrically or chemically) from one system to another and must cross the control surface either as a transient phenomenon or as a steady rate of work, which is **power**. Work is a function of the process path as well as the beginning state and end state. The displacement work is equal to the area below the process curve drawn in a  $P$ – $V$  diagram in an equilibrium process. A number of ordinary processes can be expressed as **polytropic** processes having a particular simple mathematical form for the  $P$ – $V$  relation. Work involving the action of surface tension, single-point forces, or electrical systems should be recognized and treated separately. Any nonequilibrium processes (say, dynamic forces, which are important due to accelerations) should be identified so that only equilibrium force or pressure is used to evaluate the work term.

Heat transfer is energy transferred due to a temperature difference, and the **conduction**, **convection**, and **radiation** modes are discussed.

You should have learned a number of skills and acquired abilities from studying this chapter that will allow you to

- Recognize force and displacement in a system.
- Understand power as the rate of work (force  $\times$  velocity, torque  $\times$  angular velocity).
- Know that work is a function of the end states and the path followed in a process.
- Calculate the work term knowing the  $P$ – $V$  or  $F$ – $x$  relationship.
- Evaluate the work involved in a polytropic process between two states.
- Know that work is the area under the process curve in a  $P$ – $V$  diagram.

- Apply a force balance on a mass and determine work in a process from it.
- Distinguish between an equilibrium process and a nonequilibrium process.
- Recognize the three modes of heat transfer: conduction, convection, and radiation.
- Be familiar with Fourier's law of conduction and its use in simple applications.
- Know the simple models for convection and radiation heat transfer.
- Understand the difference between the rates ( $\dot{W}$ ,  $\dot{Q}$ ) and the amounts ( ${}_1W_2$ ,  ${}_1Q_2$ ) of work.

## KEY CONCEPTS AND FORMULAS

Work	Energy in transfer: mechanical, electrical, and chemical
Heat	Energy in transfer caused by $\Delta T$
Displacement work	$W = \int_1^2 F dx = \int_1^2 P dV = \int_1^2 \mathcal{P} dA = \int_1^2 T d\theta$
Specific work	$w = W/m$ (work per unit mass)
Power, rate of work	$\dot{W} = F \mathbf{V} = P \dot{V} = T\omega$ ( $\dot{V}$ displacement rate) Velocity $\mathbf{V} = r\omega$ , torque $T = Fr$ , angular velocity $= \omega$
Polytropic process	$PV^n = \text{constant}$ or $Pv^n = \text{constant}$
Polytropic process work	${}_1W_2 = \frac{1}{1-n}(P_2V_2 - P_1V_1)$ (if $n \neq 1$ ) ${}_1W_2 = P_1V_1 \ln \frac{V_2}{V_1}$ (if $n = 1$ )
Conduction heat transfer	$\dot{Q} = -kA \frac{dT}{dx}$
Conductivity	$k$ (W/m K)
Convection heat transfer	$\dot{Q} = -hA \Delta T$
Convection coefficient	$h$ (W/m <sup>2</sup> K)
Radiation heat transfer (net to ambient)	$\dot{Q} = \varepsilon \sigma A(T_s^4 - T_{\text{amb}}^4)$ ( $\sigma = 5.67 \times 10^{-8}$ W/m <sup>2</sup> K <sup>4</sup> )
Rate integration	${}_1Q_2 = \int \dot{Q} dt \approx \dot{Q}_{\text{avg}} \Delta t$

## CONCEPT-STUDY GUIDE PROBLEMS

- 4.1** A car engine is rated at 160 hp. What is the power in SI units?
- 4.2** Two engines provide the same amount of work to lift a hoist. One engine can provide 3  $F$  in a cable and the other 1  $F$ . What can you say about the motion of the point where the force  $F$  acts in the two engines?
- 4.3** Two hydraulic piston/cylinders are connected through a hydraulic line so that they have roughly the same pressure. If they have diameters  $D_1$  and  $D_2 = 2D_1$ , respectively, what can you say about the piston forces  $F_1$  and  $F_2$ ?
- 4.4** Normally pistons have a flat head, but in diesel engines pistons can contain bowls and protruding ridges. Does this geometry influence the work term?
- 4.5** CV  $A$  is the mass inside a piston/cylinder. CV  $B$  is that mass plus the mass of the piston, outside which is the standard atmosphere. Write the process equation and the work term for the two CVs.

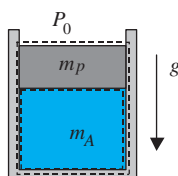


FIGURE P4.5

- 4.6** Assume a physical setup as in Fig. P4.5. We now heat the cylinder. What happens to  $P$ ,  $T$ , and  $v$  (up, down, or constant)? What transfers do we have for  $Q$  and  $W$  (positive, negative, or zero)?
- 4.7** For a buffer storage of natural gas ( $\text{CH}_4$ ), a large bell in a container can move up and down, keeping a pressure of 105 kPa inside. The sun then heats the container and the gas from 280 K to 300 K for 4 h. What happens to the volume of the gas, and what is the sign of the work term?
- 4.8** A drag force on an object moving through a medium (like a car through air or a submarine through water) is  $F_d = 0.225 A \rho \mathbf{V}^2$ . Verify that the unit becomes newton.
- 4.9** Figure P4.9 shows a physical situation. Illustrate the possible process in a  $P$ - $v$  diagram.

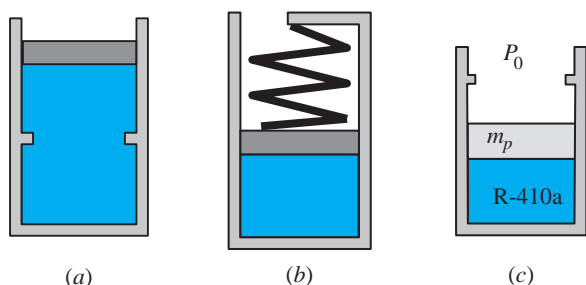


FIGURE P4.9

- 4.10** For the indicated physical setup in Fig. P4.9a–c, write a process equation and the expression for work.

- 4.11** Assume the physical situation in Fig. P4.9b; what is the work term  $a$ ,  $b$ ,  $c$ , or  $d$ ?

$a: {}_1w_2 = P_1(v_2 - v_1)$

$b: {}_1w_2 = v_1(P_2 - P_1)$

$c: {}_1w_2 = \frac{1}{2}(P_1 + P_2)(v_2 - v_1)$

$d: {}_1w_2 = \frac{1}{2}(P_1 - P_2)(v_2 + v_1)$

- 4.12** Figure P4.12 shows a physical situation; illustrate the possible process in a  $P$ - $v$  diagram.

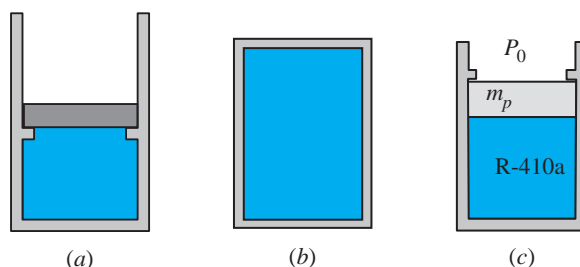


FIGURE P4.12

- 4.13** What can you say about the beginning state of the R-410a in Fig. P4.9 versus that in Fig. P4.12 for the same piston/cylinder?
- 4.14** Show how the polytropic exponent  $n$  can be evaluated if you know the end state properties ( $P_1$ ,  $V_1$ ) and ( $P_2$ ,  $V_2$ ).
- 4.15** A piece of steel has a conductivity of  $k = 15 \text{ W/mK}$ , and a brick has  $k = 1 \text{ W/mK}$ . How thick a steel wall will provide the same insulation as a 10-cm-thick brick?
- 4.16** A thermopane window (see Fig. 4.27) traps some gas between the two glass panes. Why is this beneficial?
- 4.17** On a chilly fall day with an ambient temperature of  $10^\circ\text{C}$ , a house with an inside temperature of  $20^\circ\text{C}$  loses 6 kW by heat transfer. What transfer occurs on a warm summer day at  $30^\circ\text{C}$ , assuming all other conditions are the same?

## HOMEWORK PROBLEMS

### Force Displacement Work

- 4.18** A piston of mass 2 kg is lowered 0.5 m in the standard gravitational field. Find the required force and the work involved in the process.

- 4.19** A hydraulic cylinder of area  $0.01 \text{ m}^2$  must push a 1000-kg arm and shovel 0.5 m straight up. What pressure is needed and how much work is done?

- 4.20** An escalator raises a 100-kg bucket of sand 10 m in 1 min. Determine the total amount of work done during the process.
- 4.21** A bulldozer pushes 500 kg of dirt 100 m with a force of 1500 N. It then lifts the dirt 3 m up to put it in a dump truck. How much work did it do in each situation?
- 4.22** A hydraulic cylinder has a piston cross-sectional area of  $15 \text{ cm}^2$  and a fluid pressure of 2 MPa. If the piston is moved 0.25 m, how much work is done?
- 4.23** A linear spring,  $F = k_s(x - x_0)$  with spring constant  $k_s = 500 \text{ N/m}$  is stretched until it is 100 mm longer. Find the required force and the work input.
- 4.24** Two hydraulic cylinders maintain a pressure of 1200 kPa. One has a cross-sectional area of  $0.01 \text{ m}^2$ , the other  $0.03 \text{ m}^2$ . To deliver work of 1 kJ to the piston, how large a displacement  $V$  and piston motion  $H$  are needed for each cylinder? Neglect  $P_{\text{atm}}$ .
- 4.25** Two hydraulic piston/cylinders are connected with a line. The master cylinder has an area of  $5 \text{ cm}^2$ , creating a pressure of 1000 kPa. The slave cylinder has an area of  $3 \text{ cm}^2$ . If 25 J is the work input to the master cylinder, what is the force and displacement of each piston and the work output of the slave cylinder piston?
- 4.26** The rolling resistance of a car depends on its weight as  $F = 0.006 m_{\text{car}} g$ . How long will a car of 1400 kg drive for a work input of 25 kJ?
- 4.27** The air drag force on a car is  $0.225 A \rho \mathbf{V}^2$ . Assume air at 290 K, 100 kPa and a car frontal area of  $4 \text{ m}^2$  driving at 90 km/h. How much energy is used to overcome the air drag driving for 30 min?

### Boundary Work: Simple One-Step Process

- 4.28** The R-410a in Problem 4.12c is at 1000 kPa,  $50^\circ\text{C}$  with a mass of 0.1 kg. It is cooled so that the volume is reduced to half the initial volume. The piston mass and gravitation are such that a pressure of 400 kPa will float the piston. Find the work in the process.
- 4.29** A steam radiator in a room at  $25^\circ\text{C}$  has saturated water vapor at 110 kPa flowing through it when the inlet and exit valves are closed. What are the pressure and the quality of the water when it has cooled to  $25^\circ\text{C}$ ? How much work is done?
- 4.30** A constant-pressure piston/cylinder assembly contains 0.2 kg of water as saturated vapor at 400 kPa. It is now cooled so that the water occupies half of the original volume. Find the work done in the process.
- 4.31** Find the specific work in Problem 3.47.
- 4.32** A 400-L tank, *A* (see Fig. P4.32), contains argon gas at 250 kPa and  $30^\circ\text{C}$ . Cylinder *B*, having a frictionless piston of such mass that a pressure of 150 kPa will float it, is initially empty. The valve is opened, and argon flows into *B* and eventually reaches a uniform state of 150 kPa and  $30^\circ\text{C}$  throughout. What is the work done by the argon?

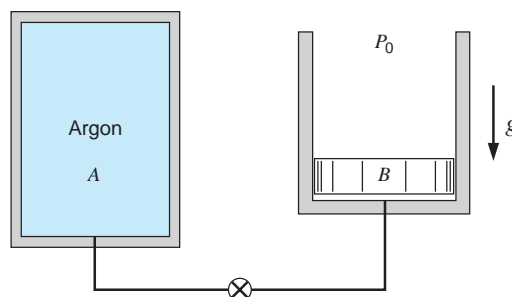


FIGURE P4.32

- 4.33** A piston/cylinder contains 1.5 kg of water at 200 kPa,  $150^\circ\text{C}$ . It is now heated by a process in which pressure is linearly related to volume to a state of 600 kPa,  $350^\circ\text{C}$ . Find the final volume and the work in the process.
- 4.34** A cylinder fitted with a frictionless piston contains 5 kg of superheated R-134a vapor at 1000 kPa and  $140^\circ\text{C}$ . The setup is cooled at constant pressure until the R-134a reaches a quality of 25%. Calculate the work done in the process.
- 4.35** A piston/cylinder contains air at 600 kPa, 290 K and a volume of  $0.01 \text{ m}^3$ . A constant-pressure process gives 54 kJ of work out. Find the final volume and temperature of the air.
- 4.36** A piston/cylinder has 5 m of liquid  $20^\circ\text{C}$  water on top of the piston ( $m = 0$ ) with a cross-sectional area of  $0.1 \text{ m}^2$ ; see Fig. P2.56. Air let in under the piston rises and pushes the water out over the top edge. Find the work needed to push all the water out and plot the process in a  $P$ - $V$  diagram.
- 4.37** Saturated water vapor at 200 kPa is in a constant-pressure piston/cylinder. In this state, the piston is 0.1 m from the cylinder bottom and the cylinder

area is  $0.25 \text{ m}^2$ . The temperature is then changed to  $200^\circ\text{C}$ . Find the work in the process.

- 4.38** A piston/cylinder assembly contains 1 kg of liquid water at  $20^\circ\text{C}$  and 300 kPa, as shown in Fig. P4.38. There is a linear spring mounted on the piston such that when the water is heated, the pressure reaches 3 MPa with a volume of  $0.1 \text{ m}^3$ .
- Find the final temperature.
  - Plot the process in a  $P$ - $v$  diagram.
  - Find the work in the process.

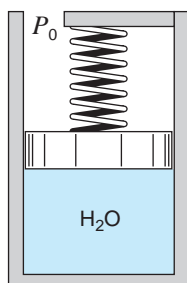


FIGURE P4.38

- 4.39** Find the specific work in Problem 3.53 for the case where the volume is reduced.
- 4.40** A piston/cylinder contains 1 kg of water at  $20^\circ\text{C}$  with a volume of  $0.1 \text{ m}^3$ . By mistake someone locks the piston, preventing it from moving while we heat the water to saturated vapor. Find the final temperature and volume and the process work.
- 4.41** Ammonia (0.5 kg) in a piston/cylinder at 200 kPa,  $-10^\circ\text{C}$  is heated by a process in which pressure varies linearly with volume to a state of  $120^\circ\text{C}$ , 300 kPa. Find the work the ammonia gives out in the process.
- 4.42** Air in a spring-loaded piston/cylinder setup has a pressure that is linear with volume,  $P = A + BV$ . With an initial state of  $P = 150 \text{ kPa}$ ,  $V = 1 \text{ L}$  and a final state of  $800 \text{ kPa}$ ,  $V = 1.5 \text{ L}$ , it is similar to the setup in Problem 4.38. Find the work done by the air.
- 4.43** Air (3 kg) is in a piston/cylinder similar to Fig. P4.5 at  $27^\circ\text{C}$ , 300 kPa. It is now heated to 500 K. Plot the process path in a  $P$ - $v$  diagram and find the work in the process.
- 4.44** Find the work in the process described in Problem 3.62.
- 4.45** Heat transfer to a 1.5-kg block of ice at  $-10^\circ\text{C}$  melts it to liquid at  $10^\circ\text{C}$  in a kitchen. How much work does the water give out?

- 4.46** A piston/cylinder assembly contains 0.5 kg of air at 500 kPa and 500 K. The air expands in a process such that  $P$  is linearly decreasing with volume to a final state of 100 kPa, 300 K. Find the work in the process.

### Polytropic process

- 4.47** A nitrogen gas goes through a polytropic process with  $n = 1.3$  in a piston/cylinder. It starts out at 600 K, 600 kPa and ends at 800 K. Is the work positive, negative, or zero?
- 4.48** Consider a mass going through a polytropic process where pressure is directly proportional to volume ( $n = -1$ ). The process starts with  $P = 0$ ,  $V = 0$  and ends with  $P = 600 \text{ kPa}$ ,  $V = 0.01 \text{ m}^3$ . Find the boundary work done by the mass.
- 4.49** Helium gas expands from 125 kPa, 350 K, and  $0.25 \text{ m}^3$  to 100 kPa in a polytropic process with  $n = 1.667$ . How much work does it give out?
- 4.50** Air at 1500 K, 1000 kPa expands in a polytropic process with  $n = 1.5$  to a pressure of 200 kPa. How cold does the air become, and what is the specific work put out?
- 4.51** The piston/cylinder arrangement shown in Fig. P4.51 contains carbon dioxide at 300 kPa and  $100^\circ\text{C}$  with a volume of  $0.2 \text{ m}^3$ . Weights are added to the piston such that the gas compresses according to the relation  $PV^{1.2} = \text{constant}$  to a final temperature of  $200^\circ\text{C}$ . Determine the work done during the process.

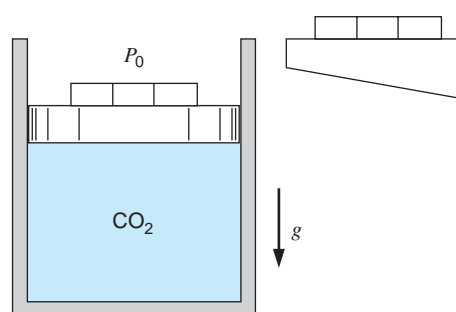


FIGURE P4.51

- 4.52** Air goes through a polytropic process from 125 kPa and 325 K to 300 kPa and 500 K. Find the polytropic exponent  $n$  and the specific work in the process.
- 4.53** A gas initially at 1 MPa and  $500^\circ\text{C}$  is contained in a piston/cylinder arrangement with an initial volume



of  $0.1 \text{ m}^3$ . The gas then slowly expands according to the relation  $PV = \text{constant}$  until a final pressure of  $100 \text{ kPa}$  is reached. Determine the work for this process.

- 4.54** A balloon behaves so that the pressure is  $P = C_2 V^{1/3}$  and  $C_2 = 100 \text{ kPa/m}$ . The balloon is blown up with air from a starting volume of  $1 \text{ m}^3$  to a volume of  $3 \text{ m}^3$ . Find the final mass of air, assuming it is at  $25^\circ\text{C}$ , and the work done by the air.
- 4.55** A piston/cylinder contains  $0.1 \text{ kg}$  of nitrogen at  $100 \text{ kPa}$ ,  $27^\circ\text{C}$ , and it is now compressed in a polytropic process with  $n = 1.25$  to a pressure of  $250 \text{ kPa}$ . What is the work involved?
- 4.56** A piston/cylinder device contains  $0.1 \text{ kg}$  of air at  $100 \text{ kPa}$  and  $400 \text{ K}$  that goes through a polytropic compression process with  $n = 1.3$  to a pressure of  $300 \text{ kPa}$ . How much work has the air done in the process?
- 4.57** A balloon behaves such that the pressure inside is proportional to the diameter squared. It contains  $2 \text{ kg}$  of ammonia at  $0^\circ\text{C}$ , with  $60\%$  quality. The balloon and ammonia are now heated so that a final pressure of  $600 \text{ kPa}$  is reached. Considering the ammonia as a control mass, find the amount of work done in the process.
- 4.58** Consider a piston/cylinder setup with  $0.5 \text{ kg}$  of R-134a as saturated vapor at  $-10^\circ\text{C}$ . It is now compressed to a pressure of  $500 \text{ kPa}$  in a polytropic process with  $n = 1.5$ . Find the final volume and temperature and determine the work done during the process.
- 4.59** A piston/cylinder contains water at  $500^\circ\text{C}$ ,  $3 \text{ MPa}$ . It is cooled in a polytropic process to  $200^\circ\text{C}$ ,  $1 \text{ MPa}$ . Find the polytropic exponent and the specific work in the process.
- 4.60** A spring-loaded piston/cylinder assembly contains  $1 \text{ kg}$  of water at  $500^\circ\text{C}$ ,  $3 \text{ MPa}$ . The setup is such that the pressure is proportional to the volume:  $P = CV$ . It is now cooled until the water becomes saturated vapor. Sketch the  $P$ - $v$  diagram, and find the final state and the work in the process.

### Boundary Work: Multistep Process

- 4.61** Consider a two-part process with an expansion from  $0.1$  to  $0.2 \text{ m}^3$  at a constant pressure of  $150 \text{ kPa}$  followed by an expansion from  $0.2$  to  $0.4 \text{ m}^3$  with a linearly rising pressure from  $150 \text{ kPa}$  end-

ing at  $300 \text{ kPa}$ . Show the process in a  $P$ - $V$  diagram and find the boundary work.

- 4.62** A helium gas is heated at constant volume from  $100 \text{ kPa}$ ,  $300 \text{ K}$  to  $500 \text{ K}$ . A following process expands the gas at constant pressure to three times the initial volume. What is the specific work in the combined process?
- 4.63** Find the work in Problem 3.59.
- 4.64** A piston/cylinder arrangement shown in Fig. P4.64 initially contains air at  $150 \text{ kPa}$  and  $400^\circ\text{C}$ . The setup is allowed to cool to the ambient temperature of  $20^\circ\text{C}$ .
- Is the piston resting on the stops in the final state? What is the final pressure in the cylinder?
  - What is the specific work done by the air during the process?

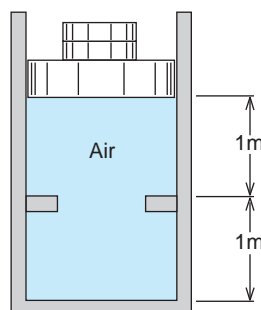


FIGURE P4.64

- 4.65** A cylinder containing  $1 \text{ kg}$  of ammonia has an externally loaded piston. Initially the ammonia is at  $2 \text{ MPa}$  and  $180^\circ\text{C}$ . It is now cooled to saturated vapor at  $40^\circ\text{C}$  and then further cooled to  $20^\circ\text{C}$ , at which point the quality is  $50\%$ . Find the total work for the process, assuming a piecewise linear variation of  $P$  versus  $V$ .
- 4.66** A piston/cylinder has  $1.5 \text{ kg}$  of air at  $300 \text{ K}$  and  $150 \text{ kPa}$ . It is now heated in a two-step process: first, a constant-volume process to  $1000 \text{ K}$  (state 2), followed by a constant-pressure process to  $1500 \text{ K}$  (state 3). Find the final volume and the work in the process.
- 4.67** The refrigerant R-410a is contained in a piston/cylinder, as shown in Fig. P4.67, where the volume is  $11 \text{ L}$  when the piston hits the stops. The initial state is  $-30^\circ\text{C}$ ,  $150 \text{ kPa}$ , with a volume of  $10 \text{ L}$ . This system is brought indoors and warms up to  $15^\circ\text{C}$ .

- a. Is the piston at the stops in the final state?
- b. Find the work done by the R-410a during this process.

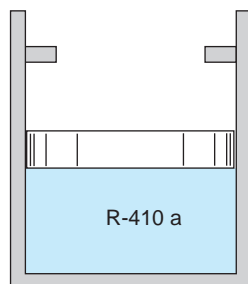


FIGURE P4.67

- 4.68** A piston/cylinder assembly contains 1 kg of liquid water at 20°C and 300 kPa. Initially the piston floats, similar to the setup in Problem 4.67, with a maximum enclosed volume of 0.002 m<sup>3</sup> if the piston touches the stops. Now heat is added so that a final pressure of 600 kPa is reached. Find the final volume and the work in the process.
- 4.69** A piston/cylinder assembly contains 50 kg of water at 200 kPa with a volume of 0.1 m<sup>3</sup>. Stops in the cylinder restrict the enclosed volume to 0.5 m<sup>3</sup>, similar to the setup in Problem 4.67. The water is now heated to 200°C. Find the final pressure, volume, and work done by the water.
- 4.70** A piston/cylinder assembly (Fig. P4.70) has 1 kg of R-134a at state 1 with 110°C, 600 kPa. It is then brought to saturated vapor, state 2, by cooling while the piston is locked with a pin. Now the piston is balanced with an additional constant force and the pin is removed. The cooling continues to state 3, where the R-134a is saturated liquid. Show the processes in a  $P$ - $V$  diagram and find the work in each of the two steps, 1 to 2 and 2 to 3.

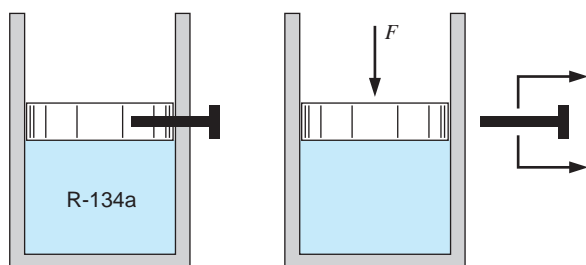


FIGURE P4.70

- 4.71** Find the work in Problem 3.84.

- 4.72** Ten kilograms of water in a piston/cylinder arrangement exists as saturated liquid/vapor at 100 kPa, with a quality of 50%. It is now heated so that the volume triples. The mass of the piston is such that a cylinder pressure of 200 kPa will float it (see Fig. P4.72).
- a. Find the final temperature and volume of the water.
  - b. Find the work given out by the water.

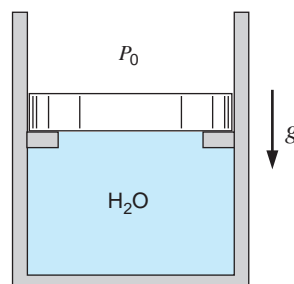


FIGURE P4.72

- 4.73** A piston/cylinder setup similar to Problem 4.72 contains 0.1 kg of saturated liquid and vapor water at 100 kPa with quality 25%. The mass of the piston is such that a pressure of 500 kPa will float it. The water is heated to 300°C. Find the final pressure, volume, and work,  ${}_1W_2$ .
- 4.74** A piston cylinder contains air at 1000 kPa, 800 K with a volume of 0.05 m<sup>3</sup>. The piston is pressed against the upper stops (see Fig. P4.12c) and it will float at a pressure of 750 kPa. Now the air is cooled to 400 K. What is the process work?

### Other Types of Work and General Concepts

- 4.75** Electric power is volts times amperes ( $P = Vi$ ). When a car battery at 12 V is charged with 6 amps for 3 h, how much energy is delivered?
- 4.76** A copper wire of diameter 2 mm is 10 m long and stretched out between two posts. The normal stress (pressure),  $\sigma = E(L - L_0)/L_0$ , depends on the length,  $L$ , versus the unstretched length,  $L_0$ , and Young's modulus,  $E = 1.1 \times 10^6$  kPa. The force is  $F = A\sigma$  and is measured to be 110 N. How much longer is the wire, and how much work was put in?
- 4.77** A 0.5-m-long steel rod with a 1-cm diameter is stretched in a tensile test. What is the work required to obtain a relative strain of 0.1%? The modulus of elasticity of steel is  $2 \times 10^8$  kPa.



- 4.78** A soap bubble has a surface tension of  $\mathcal{S} = 3 \times 10^{-4}$  N/cm as it sits flat on a rigid ring of diameter 5 cm. You now blow on the film to create a half-sphere surface of diameter 5 cm. How much work was done?
- 4.79** A film of ethanol at  $20^\circ\text{C}$  has a surface tension of 22.3 mN/m and is maintained on a wire frame, as shown in Fig. P4.79. Consider the film with two surfaces as a control mass and find the work done when the wire is moved 10 mm to make the film  $20 \times 40$  mm.

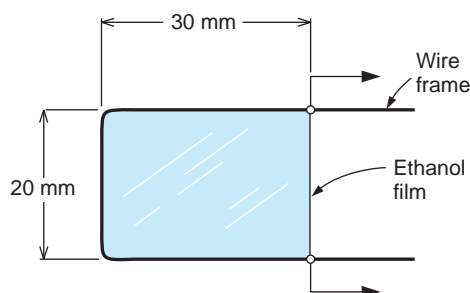


FIGURE P4.79

- 4.80** Assume that we fill a spherical balloon from a bottle of helium gas. The helium gas provides work  $\int P dV$  that stretches the balloon material  $\int \mathcal{S} dA$  and pushes back the atmosphere  $\int P_0 dV$ . Write the incremental balance for  $dW_{\text{helium}} = dW_{\text{stretch}} + dW_{\text{atm}}$  to establish the connection between the helium pressure, the surface tension  $\mathcal{S}$ , and  $P_0$  as a function of the radius.
- 4.81** Assume a balloon material with a constant surface tension of  $\mathcal{S} = 2$  N/m. What is the work required to stretch a spherical balloon up to a radius of  $r = 0.5$  m? Neglect any effect from atmospheric pressure.
- 4.82** A sheet of rubber is stretched out over a ring of radius 0.25 m. I pour liquid water at  $20^\circ\text{C}$  on it, as in Fig. P4.82, so that the rubber forms a half-sphere (cup). Neglect the rubber mass and find the surface tension near the ring.

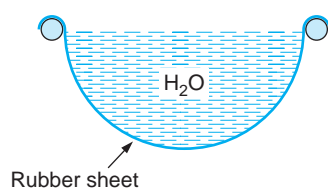


FIGURE P4.82

- 4.83** Consider a window-mounted air-conditioning unit used in the summer to cool incoming air. Examine the system boundaries for rates of work and heat transfer, including signs.
- 4.84** Consider a light bulb that is on. Explain where there are rates of work and heat transfer (include modes) that moves energy.
- 4.85** Consider a household refrigerator that has just been filled up with room-temperature food. Define a control volume (mass) and examine its boundaries for rates of work and heat transfer, including the sign:
- Immediately after the food is placed in the refrigerator
  - After a long period of time has elapsed and the food is cold
- 4.86** A room is heated with an electric space heater on a winter day. Examine the following control volumes, regarding heat transfer and work, including the sign:
- The space heater
  - The room
  - The space heater and the room together

### Rates of Work

- 4.87** A 100-hp car engine has a drive shaft rotating at 2000 RPM. How much torque is on the shaft for 25% of full power?
- 4.88** A car uses 25 hp to drive at a horizontal level at a constant speed of 100 km/h. What is the traction force between the tires and the road?
- 4.89** An escalator raises a 100-kg bucket 10 m in 1 min. Determine the rate of work in the process.
- 4.90** A crane lifts a bucket of cement with a total mass of 450 kg vertically upward with a constant velocity of 2 m/s. Find the rate of work needed to do this.
- 4.91** A force of 1.2 kN moves a truck at a speed of 60 km/h up a hill. What is the power?
- 4.92** A piston/cylinder of cross-sectional area  $0.01$  m<sup>2</sup> maintains constant pressure. It contains 1 kg of water with a quality of 5% at  $150^\circ\text{C}$ . If we heat the water so that 1 g/s of liquid turns into vapor, what is the rate of work out?
- 4.93** Consider the car with the rolling resistance in Problem 4.26. How fast can it drive using 30 hp?
- 4.94** Consider the car with the air drag force in Problem 4.27. How fast can it drive using 30 hp?

- 4.95** Consider a 1400-kg car having the rolling resistance in Problem 4.26 and the air resistance in Problem 4.27. How fast can it drive using 30 hp?
- 4.96** A current of 10 A runs through a resistor with a resistance of  $15\ \Omega$ . Find the rate of work that heats the resistor.
- 4.97** A battery is well insulated while being charged by 12.3 V at a current of 6 A. Take the battery as a control mass and find the instantaneous rate of work and the total work done over 4 h.
- 4.98** A torque of 650 Nm rotates a shaft of diameter 0.25 m with  $\omega = 50$  rad/s. What are the shaft surface speed and the transmitted power?
- 4.99** Air at a constant pressure in a piston/cylinder is at 300 kPa, 300 K and has a volume of  $0.1\ \text{m}^3$ . It is heated to 600 K over 30 s in a process with constant piston velocity. Find the power delivered to the piston.
- 4.100** A pressure of 650 kPa pushes a piston of diameter 0.25 m with  $\mathbf{V} = 5$  m/s. What are the volume displacement rate, the force, and the transmitted power?
- 4.101** Assume that the process in Problem 4.61 takes place with a constant rate of change in volume over 2 min. Show the power (rate of work) as a function of time.

### Heat Transfer Rates

- 4.102** Find the rate of conduction heat transfer through a 1.5-cm-thick hardwood board,  $k = 0.16$  W/m K, with a temperature difference between the two sides of  $20^\circ\text{C}$ .
- 4.103** A steel pot, with conductivity of 50 W/m K and a 5-mm-thick bottom, is filled with  $15^\circ\text{C}$  liquid water. The pot has a diameter of 20 cm and is now placed on an electric stove that delivers 250 W as heat transfer. Find the temperature on the outer pot bottom surface, assuming the inner surface is at  $15^\circ\text{C}$ .
- 4.104** The sun shines on a  $150\text{-m}^2$  road surface so that it is at  $45^\circ\text{C}$ . Below the 5-cm-thick asphalt, with average conductivity of 0.06 W/m K, is a layer of compacted rubble at a temperature of  $15^\circ\text{C}$ . Find the rate of heat transfer to the rubble.
- 4.105** A water heater is covered with insulation boards over a total surface area of  $3\ \text{m}^2$ . The inside board surface is at  $75^\circ\text{C}$ , the outside surface is at  $18^\circ\text{C}$ , and the board material has a conductivity of 0.08 W/m K. How thick should the board be to limit the heat transfer loss to 200 W?
- 4.106** A large condenser (heat exchanger) in a power plant must transfer a total of 100 MW from steam running in a pipe to seawater being pumped through the heat exchanger. Assume that the wall separating the steam and seawater is 4 mm of steel, with conductivity of 15 W/m K, and that a maximum  $5^\circ\text{C}$  difference between the two fluids is allowed in the design. Find the required minimum area for the heat transfer, neglecting any convective heat transfer in the flows.
- 4.107** A  $2\text{-m}^2$  window has a surface temperature of  $15^\circ\text{C}$ , and the outside wind is blowing air at  $2^\circ\text{C}$  across it with a convection heat transfer coefficient of  $h = 125\ \text{W/m}^2\ \text{K}$ . What is the total heat transfer loss?
- 4.108** You drive a car on a winter day with the atmospheric air at  $-15^\circ\text{C}$ , and you keep the outside front windshield surface temperature at  $+2^\circ\text{C}$  by blowing hot air on the inside surface. If the windshield is  $0.5\ \text{m}^2$  and the outside convection coefficient is  $250\ \text{W/m}^2\ \text{K}$ , find the rate of energy loss through the front windshield. For that heat transfer rate and a 5-mm-thick glass with  $k = 1.25$  W/m K, what is the inside windshield surface temperature?
- 4.109** The brake shoe and steel drum of a car continuously absorb 25 W as the car slows down. Assume a total outside surface area of  $0.1\ \text{m}^2$  with a convective heat transfer coefficient of  $10\ \text{W/m}^2\ \text{K}$  to the air at  $20^\circ\text{C}$ . How hot does the outside brake and drum surface become when steady conditions are reached?
- 4.110** Owing to a faulty door contact, the small light bulb (25 W) inside a refrigerator is kept on and limited insulation lets 50 W of energy from the outside seep into the refrigerated space. How much of a temperature difference from the ambient surroundings at  $20^\circ\text{C}$  must the refrigerator have in its heat exchanger with an area of  $1\ \text{m}^2$  and an average heat transfer coefficient of  $15\ \text{W/m}^2\ \text{K}$  to reject the leaks of energy?
- 4.111** The black grille on the back of a refrigerator has a surface temperature of  $35^\circ\text{C}$  with a total surface area of  $1\ \text{m}^2$ . Heat transfer to the room air at  $20^\circ\text{C}$  takes place with an average convective heat transfer coefficient of  $15\ \text{W/m}^2\ \text{K}$ . How

much energy can be removed during 15 minutes of operation?

- 4.112** A wall surface on a house is  $30^{\circ}\text{C}$  with an emissivity of  $\varepsilon = 0.7$ . The surrounding ambient air is at  $15^{\circ}\text{C}$  with an average emissivity of 0.9. Find the rate of radiation energy from each of those surfaces per unit area.
- 4.113** A radiant heating lamp has a surface temperature of 1000 K with  $\varepsilon = 0.8$ . How large a surface area is needed to provide 250 W of radiation heat transfer?
- 4.114** A log of burning wood in the fireplace has a surface temperature of  $450^{\circ}\text{C}$ . Assume that the emissivity is 1 (a perfect black body) and find the radiant emission of energy per unit surface area.
- 4.115** A radiant heat lamp is a rod, 0.5 m long and 0.5 cm in diameter, through which 400 W of electric energy is deposited. Assume that the surface has an emissivity of 0.9 and neglect incoming radiation. What will the rod surface temperature be?

### Review Problems

- 4.116** A nonlinear spring has a force versus displacement relation of  $F = k_s(x - x_0)^n$ . If the spring end is moved to  $x_1$  from the relaxed state, determine the formula for the required work.
- 4.117** A vertical cylinder (Fig. P4.117) has a 61.18-kg piston locked with a pin, trapping 10 L of R-410a at  $10^{\circ}\text{C}$  with 90% quality inside. Atmospheric pressure is 100 kPa, and the cylinder cross-sectional area is  $0.006\text{ m}^2$ . The pin is removed, allowing the piston to move and come to rest with a final temperature of  $10^{\circ}\text{C}$  for the R-410a. Find the final pressure, final volume, and work done by the R-410a.

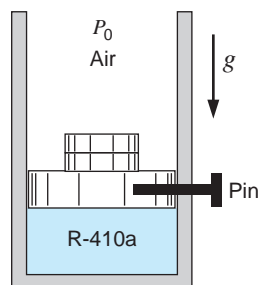


FIGURE P4.117

- 4.118** Two kilograms of water is contained in a piston/cylinder (Fig. P4.118) with a massless piston

loaded with a linear spring and the outside atmosphere. Initially the spring force is zero and  $P_1 = P_0 = 100\text{ kPa}$  with a volume of  $0.2\text{ m}^3$ . If the piston just hits the upper stops, the volume is  $0.8\text{ m}^3$  and  $T = 600^{\circ}\text{C}$ . Heat is now added until the pressure reaches 1.2 MPa. Find the final temperature, show the  $P$ - $V$  diagram, and find the work done during the process.

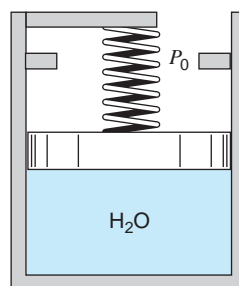


FIGURE P4.118

- 4.119** A piston/cylinder assembly contains butane,  $\text{C}_4\text{H}_{10}$ , at  $300^{\circ}\text{C}$  and 100 kPa with a volume of  $0.02\text{ m}^3$ . The gas is now compressed slowly in an isothermal process to 300 kPa.
- Show that it is reasonable to assume that butane behaves as an ideal gas during this process.
  - Determine the work done by the butane during the process.
- 4.120** Consider the process described in Problem 3.116. With 1 kg of water as a control mass, determine the boundary work during the process.
- 4.121** A cylinder having an initial volume of  $3\text{ m}^3$  contains 0.1 kg of water at  $40^{\circ}\text{C}$ . The water is then compressed in an isothermal quasi-equilibrium process until it has a quality of 50%. Calculate the work done by splitting the process into two steps. Assume that the water vapor is an ideal gas during the first step of the process.
- 4.122** A piston/cylinder setup (Fig. P4.72) contains 1 kg of water at  $20^{\circ}\text{C}$  with a volume of  $0.1\text{ m}^3$ . Initially, the piston rests on some stops with the top surface open to the atmosphere,  $P_0$ , and a mass such that a water pressure of 400 kPa will lift it. To what temperature should the water be heated to lift the piston? If it is heated to saturated vapor, find the final temperature, volume, and work,  ${}_1W_2$ .
- 4.123** Find the work done in Problem 3.112.

- 4.124** A cylinder fitted with a piston contains propane gas at 100 kPa and 300 K with a volume of  $0.2 \text{ m}^3$ . The gas is now slowly compressed according to the relation  $PV^{1.1} = \text{constant}$  to a final temperature of 340 K. Justify the use of the ideal-gas model. Find the final pressure and the work done during the process.
- 4.125** Consider the nonequilibrium process described in Problem 3.122. Determine the work done by the carbon dioxide in the cylinder during the process.
- 4.126** The gas space above the water in a closed storage tank contains nitrogen at  $25^\circ\text{C}$  and 100 kPa. Total tank volume is  $4 \text{ m}^3$ , and there is 500 kg of water at  $25^\circ\text{C}$ . An additional 500 kg of water is now forced into the tank. Assuming constant temperature throughout, find the final pressure of the nitrogen and the work done on the nitrogen in this process.
- 4.127** Consider the problem of inflating the helium balloon described in Problem 3.124. For a control volume that consists of the helium inside the balloon, determine the work done during the filling process when the diameter changes from 1 m to 4 m.
- 4.128** Air at 200 kPa,  $30^\circ\text{C}$  is contained in a cylinder/piston arrangement with an initial volume of  $0.1 \text{ m}^3$ . The inside pressure balances ambient pressure of 100 kPa plus an externally imposed force that is proportional to  $V^{0.5}$ . Now heat is transferred to the system to a final pressure of 225 kPa. Find the final temperature and the work done in the process.

- 4.129** Two springs with the same spring constant are installed in a massless piston/cylinder arrangement with the outside air at 100 kPa. If the piston is at the bottom, both springs are relaxed, and the second spring comes in contact with the piston at  $V = 2 \text{ m}^3$ . The cylinder (Fig. P4.129) contains ammonia initially at  $-2^\circ\text{C}$ ,  $x = 0.13$ ,  $V = 1 \text{ m}^3$ , which is then heated until the pressure reaches 1200 kPa. At what pressure will the piston touch the second spring? Find the final temperature and the total work done by the ammonia.

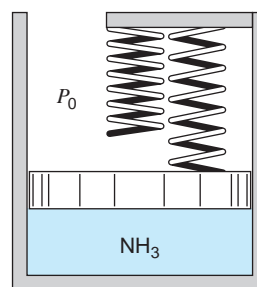


FIGURE P4.129

- 4.130** A spring-loaded piston/cylinder arrangement contains R-134a at  $20^\circ\text{C}$ , 24% quality with a volume of 50 L. The setup is heated and thus expands, moving the piston. It is noted that when the last drop of liquid disappears, the temperature is  $40^\circ\text{C}$ . The heating is stopped when  $T = 130^\circ\text{C}$ . Verify that the final pressure is about 1200 kPa by iteration and find the work done in the process.

## ENGLISH UNIT PROBLEMS

### English Unit Concept Problems

- 4.131E** The electric company charges customers per kW-hour. What is that amount in English System units?
- 4.132E** Work as  $F \Delta x$  has units of lbf-ft; what is the equivalent in Btu?
- 4.133E** Work in the expression in Eq. 4.5 or Eq. 4.6 involves  $PV$ . For  $P$  in psia and  $V$  in  $\text{ft}^3$ , how does  $PV$  become Btu?
- 4.134E** The air drag force on a car is  $0.225 A \rho \mathbf{V}^2$ . Verify that the unit becomes lbf.

### English Unit Problems

- 4.135E** An escalator raises a 200-lbm bucket of sand 30 ft in 1 min. Determine the amount of work done during the process.
- 4.136E** A bulldozer pushes 1000 lbm of dirt 300 ft with a force of 400 lbf. It then lifts the dirt 10 ft up to put it in a dump truck. How much work did it do in each situation?
- 4.137E** A linear spring,  $F = k_s(x - x_0)$ , with spring constant  $k_s = 35 \text{ lbf/ft}$ , is stretched until it is 2.5 in. longer. Find the required force and work input.

- 4.138E** Two hydraulic cylinders maintain a pressure of 175 psia. One has a cross-sectional area of  $0.1 \text{ ft}^2$ , the other  $0.3 \text{ ft}^2$ . To deliver a work of 1 Btu to the piston, how large a displacement ( $V$ ) and piston motion ( $H$ ) are needed for each cylinder? Neglect  $P_{\text{atm}}$ .
- 4.139E** The rolling resistance of a car depends on its weight as  $F = 0.006 m_{\text{car}} g$ . How long will a car of 3000 lbm drive for a work input of 25 Btu?
- 4.140E** A steam radiator in a room at 75 F has saturated water vapor at  $16 \text{ lbf/in.}^2$  flowing through it when the inlet and exit valves are closed. What is the pressure and the quality of the water when it has cooled to 75 F? How much work is done?
- 4.141E** A cylinder fitted with a frictionless piston contains 10 lbm of superheated refrigerant R-134a vapor at  $100 \text{ lbf/in.}^2$ , 300 F. The setup is cooled at constant pressure until the R-134a reaches a quality of 25%. Calculate the work done in the process.
- 4.142E** A piston/cylinder has 15 ft of liquid 70 F water on top of the piston ( $m = 0$ ) with a cross-sectional area of  $1 \text{ ft}^2$  (see Fig. P2.56). Air let in under the piston rises and pushes the water out over the top edge. Find the work needed to push all the water out and plot the process in a  $P$ - $V$  diagram.
- 4.143E** Ammonia (1 lbm) in a piston/cylinder at 30 psia, 20 F is heated in a process in which the pressure varies linearly with the volume to a state of 240 F, 40 psia. Find the work the ammonia gives out in the process.
- 4.144E** Consider a mass going through a polytropic process where pressure is directly proportional to volume ( $n = -1$ ). The process starts with  $P = 0$ ,  $V = 0$  and ends with  $P = 90 \text{ lbf/in.}^2$ ,  $V = 0.4 \text{ ft}^3$ . The physical setup could be as in Problem 2.89. Find the boundary work done by the mass.
- 4.145E** Helium gas expands from 20 psia, 600 R, and  $9 \text{ ft}^3$  to 15 psia in a polytropic process with  $n = 1.667$ . How much work does it give out?
- 4.146E** The piston/cylinder shown in Fig. P4.51 contains carbon dioxide at  $50 \text{ lbf/in.}^2$ , 200 F with a volume of  $5 \text{ ft}^3$ . Mass is added at such a rate that the gas compresses according to the relation  $PV^{1.2} = \text{constant}$  to a final temperature of 350 F. Determine the work done during the process.
- 4.147E** A piston/cylinder contains water at 900 F, 400 psia. It is cooled in a polytropic process to 400 F, 150 psia. Find the polytropic exponent and the specific work in the process.
- 4.148E** Consider a two-part process with an expansion from 3 to  $6 \text{ ft}^3$  at a constant pressure of  $20 \text{ lbf/in.}^2$  followed by an expansion from 6 to  $12 \text{ ft}^3$  with a linearly rising pressure from  $20 \text{ lbf/in.}^2$  ending at  $40 \text{ lbf/in.}^2$ . Show the process in a  $P$ - $V$  diagram and find the boundary work.
- 4.149E** A cylinder containing 2 lbm of ammonia has an externally loaded piston. Initially the ammonia is at  $280 \text{ lbf/in.}^2$ , 360 F. It is now cooled to saturated vapor at 105 F and then further cooled to 65 F, at which point the quality is 50%. Find the total work for the process, assuming piecewise linear variation of  $P$  versus  $V$ .
- 4.150E** A piston/cylinder has 2 lbm of R-134a at state 1 with 200 F,  $90 \text{ lbf/in.}^2$ , and is then brought to saturated vapor, state 2, by cooling while the piston is locked with a pin. Now the piston is balanced with an additional constant force and the pin is removed. The cooling continues to state 3, where the R-134a is saturated liquid. Show the processes in a  $P$ - $V$  diagram and find the work in each of the two steps, 1 to 2 and 2 to 3.
- 4.151E** A piston/cylinder contains air at 150 psia, 1400 R with a volume of  $1.75 \text{ ft}^3$ . The piston is pressed against the upper stops (see Fig. P4.12c), and it will float at a pressure of 110 psia. Now the air is cooled to 700 R. What is the process work?
- 4.152E** A 1-ft-long steel rod with a 0.5-in. diameter is stretched in a tensile test. What is the work required to obtain a relative strain of 0.1%? The modulus of elasticity of steel is  $30 \times 10^6 \text{ lbf/in.}^2$ .
- 4.153E** A force of 300 lbf moves a truck at a speed of 40 mi/h up a hill. What is the power?
- 4.154E** A 1200-hp dragster engine drives the car at a speed of 65 mi/h. How much force is between the tires and the road?
- 4.155E** A 100-hp car engine has a drive shaft rotating at 2000 RPM. How much torque is on the shaft for 25% of full power?
- 4.156E** An escalator raises a 200-lbm bucket of sand 30 ft in 1 min. Determine the rate of work in the process.



- 4.157E** A piston/cylinder of diameter 10 in. moves a piston with a velocity of 18 ft/s. The instantaneous pressure is 100 psia. What is the volume displacement rate, the force, and the transmitted power?
- 4.158E** Find the rate of conduction heat transfer through a 1.5-cm-thick hardwood board,  $k = 0.09$  Btu/h-ft-R, with a temperature difference between the two sides of 40 F.
- 4.159E** The sun shines on a 1500-ft<sup>2</sup> road surface so that it is at 115 F. Below the 2-in.-thick asphalt, average conductivity of 0.035 Btu/h ft F, is a layer of compacted rubble at a temperature of 60 F. Find the rate of heat transfer to the rubble.
- 4.160E** A water heater is covered up with insulation boards over a total surface area of 30 ft<sup>2</sup>. The inside board surface is at 175 F, the outside surface is at 70 F, and the board material has a conductivity of 0.05 Btu/h ft F. How thick should the board be to limit the heat transfer loss to 720 Btu/h?
- 4.161E** The black grille on the back of a refrigerator has a surface temperature of 95 F with a total surface area of 10 ft<sup>2</sup>. Heat transfer to the room air at 70 F takes place with an average convective heat transfer coefficient of 3 Btu/h ft<sup>2</sup> R. How much energy can be removed during 15 min of operation?
- 4.162E** A cylinder having an initial volume of 100 ft<sup>3</sup> contains 0.2 lbm of water at 100 F. The water is then compressed in an isothermal quasi-equilibrium process until it has a quality of 50%. Calculate the work done in the process, assuming that water vapor is an ideal gas.
- 4.163E** Find the specific work for Problem 3.169E.
- 4.164E** The gas space above the water in a closed storage tank contains nitrogen at 80 F, 15 lbf/in.<sup>2</sup>. The total tank volume is 150 ft<sup>3</sup>, and there is 1000 lbm of water at 80 F. An additional 1000 lbm of water is now forced into the tank. Assuming constant temperature throughout, find the final pressure of the nitrogen and the work done on the nitrogen in this process.

## COMPUTER, DESIGN, AND OPEN-ENDED PROBLEMS

- 4.165** In Problem 4.51, determine the work done by the carbon dioxide at any point during the process.
- 4.166** In Problem 4.128, determine the work done by the air at any point during the process.
- 4.167** A piston/cylinder arrangement of initial volume 0.025 m<sup>3</sup> contains saturated water vapor at 200°C. The steam now expands in a quasi-equilibrium isothermal process to a final pressure of 200 kPa while it does work against the piston. Determine the work done in this process by a numerical integration (summation) of the area below the  $P$ - $V$  process curve. Compute about 10 points along the curve by using the computerized software to find the volume at 200°C and the various pressures. How different is the work calculated if ideal gas is assumed?
- 4.168** Reconsider the process in Problem 4.65, in which three states were specified. Solve the problem by fitting a single smooth curve ( $P$  versus  $v$ ) through the three points. Map out the path followed (including temperature and quality) during the process.
- 4.169** Write a computer program to determine the boundary movement work for a specified substance undergoing a process for a given set of data (values of pressure and corresponding volume during the process).
- 4.170** Ammonia vapor is compressed inside a cylinder by an external force acting on the piston. The ammonia is initially at 30°C, 500 kPa, and the final pressure is 1400 kPa. The following data have been measured for the process:

Pressure, kPa	500	653	802	945	1100	1248	1400
Volume, L	1.25	1.08	0.96	0.84	0.72	0.60	0.50

Determine the work done by the ammonia by summing the area below the  $P$ - $V$  process curve. As you plot it,  $P$  is the height and the change in volume is the base of a number of rectangles.

- 4.171** A substance is brought from a state of  $P_1, v_1$  to a state of  $P_2, v_2$  in a piston/cylinder arrangement. Assume that the process can be approximated as a polytropic process. Write a program that will find the polytropic exponent,  $n$ , and the boundary work per unit mass. The four state properties are input

variables. Check the program with cases that you can easily hand calculate.

- 4.172** Assume that you have a plate of  $A = 1 \text{ m}^2$  with thickness  $L = 0.02 \text{ m}$  over which there is a temperature difference of  $20^\circ\text{C}$ . Find the conductivity,  $k$ , from the literature and compare the heat transfer rates if the plate substance is a metal like aluminum or steel, or wood, foam insulation, air, argon, or liq-

uid water. Assume that the average substance temperature is  $25^\circ\text{C}$ .

- 4.173** Make a list of household appliances such as refrigerators, electric heaters, vacuum cleaners, hair dryers, TVs, stereo sets, and any others you may think of. For each, list its energy consumption and explain where energy transfer occurs as work and where heat transfer occurs.

# The First Law of Thermodynamics

Having completed our review of basic definitions and concepts, we are ready to discuss the first law of thermodynamics. This law is often called the *conservation of energy law* and, as we will see later, this is essentially true. Our procedure will be to state this law for a system (control mass) undergoing a cycle and then for a change of state of a system.

After the energy equation is formulated, we will use it to relate the change of state inside a control volume to the amount of energy that is transferred in a process as work or heat transfer. When a car engine has transferred some work to the car, the car's speed is increased, so we can relate the kinetic energy increase to the work; or, if a stove provides a certain amount of heat transfer to a pot with water, we can relate the water temperature increase to the heat transfer. More complicated processes can also occur, such as the expansion of very hot gases in a piston cylinder, as in a car engine, in which work is given out and at the same time heat is transferred to the colder walls. In other applications we can also see a change in state without any work or heat transfer, such as a falling object that changes kinetic energy at the same time it is changing elevation. The energy equation then relates the two forms of energy of the object.

## 5.1 THE FIRST LAW OF THERMODYNAMICS FOR A CONTROL MASS UNDERGOING A CYCLE

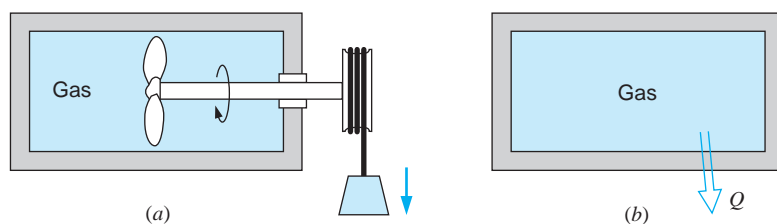
The first law of thermodynamics states that during any cycle a system (control mass) undergoes, the cyclic integral of the heat is proportional to the cyclic integral of the work.

To illustrate this law, consider as a control mass the gas in the container shown in Fig. 5.1. Let this system go through a cycle that is made up of two processes. In the first process, work is done on the system by the paddle that turns as the weight is lowered. Let the system then return to its initial state by transferring heat from the system until the cycle has been completed.

Historically, work was measured in mechanical units of force times distance, such as foot pounds force or joules, and heat was measured in thermal units, such as the British thermal unit or the calorie. Measurements of work and heat were made during a cycle for a wide variety of systems and for various amounts of work and heat. When the amounts of work and heat were compared, it was found that they were always proportional. Such



**FIGURE 5.1** Example of a control mass undergoing a cycle.



observations led to the formulation of the first law of thermodynamics, which in equation form is written

$$J \oint \delta Q = \oint \delta W \quad (5.1)$$

The symbol  $\oint \delta Q$ , which is called the *cyclic integral of the heat transfer*, represents the net heat transfer during the cycle, and  $\oint \delta W$ , the *cyclic integral of the work*, represents the net work during the cycle. Here,  $J$  is a proportionality factor that depends on the units used for work and heat.

The basis of every law of nature is experimental evidence, and this is true also of the first law of thermodynamics. Many different experiments have been conducted on the first law, and every one thus far has verified it either directly or indirectly. The first law has never been disproved.

As was discussed in Chapter 4, the units for work and heat or for any other form of energy either are the same or are directly proportional. In SI units, the joule is used as the unit for both work and heat and for any other energy unit. In English units, the basic unit for work is the foot pound force, and the basic unit for heat is the British thermal unit (Btu). James P. Joule (1818–1889) did the first accurate work in the 1840s on measurement of the proportionality factor  $J$ , which relates these units. Today, the Btu is defined in terms of the basic SI metric units,

$$1 \text{ Btu} = 778.17 \text{ ft lbf}$$

This unit is termed the *International British thermal unit*. For much engineering work, the accuracy of other data does not warrant more accuracy than the relation  $1 \text{ Btu} = 778 \text{ ft lbf}$ , which is the value used with English units in the problems in this book. Because these units are equivalent, it is not necessary to include the factor  $J$  explicitly in Eq. 5.1, but simply to recognize that for any system of units, each equation must have consistent units throughout. Therefore, we may write Eq. 5.1 as

$$\oint \delta Q = \oint \delta W \quad (5.2)$$

which can be considered the basic statement of the [first law of thermodynamics](#).

## 5.2 THE FIRST LAW OF THERMODYNAMICS FOR A CHANGE IN STATE OF A CONTROL MASS

Equation 5.2 states the first law of thermodynamics for a control mass during a cycle. Many times, however, we are concerned with a process rather than a cycle. We now consider the first law of thermodynamics for a control mass that undergoes a change of state. We begin by introducing a new property, energy, which is given the symbol  $E$ . Consider a system





















































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































