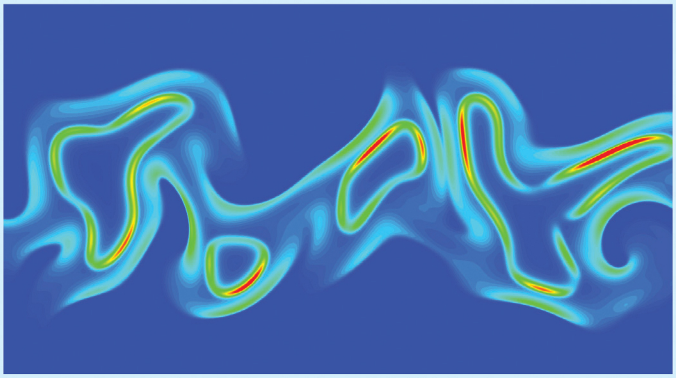
Tenth Edition

Fundamentals of Thermodynamics

Borgnakke · Sonntag



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Fundamentals of Thermodynamics

10/e

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Preface

In this tenth edition the basic objective of the earlier editions have been retained:

- 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.

The presentation is deliberately directed to students. New concepts and definitions are presented in the context where they are first relevant in a natural progression. The introduction has been reorganized with a very short introduction followed by the first thermodynamic properties to be defined (Chapter 1) which are those that can be readily measured: pressure, specific volume, and temperature. In Chapter 2, tables of thermodynamic properties are introduced, but only in regard to these measurable properties. Internal energy and enthalpy are introduced in connection with the energy equation and 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 and contemporary topics 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 large number of examples, illustrations and problems, 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 AND OVERALL BOOK ORGANIZATION

The tenth edition completes the transition to the e-book format that was started with the ninth edition. This includes a fully searchable text, select interactivity, and convenient direct access to supplemental material. The primary interactive element is the set of new student practice problems for which students can reveal the solutions with a simple click or tap. These problems expand the examples beyond those in the main chapter text and allows students to immediately test their knowledge. The digital format also enables students to access supplemental notes and files directly from the text. (Supplemental materials also are available from the companion web site: www.wiley.com/go/borgnakke/FundofThermo10e.)

The e-book organization includes:

- Problems, including both student practice problems with the solution as a drop down selection together with regular homework problems
- Chapter summary and skill sets includes a new student study guide table
- The main expository text ends with a concept list and equations for each chapter
- Additional study resources, such as extra student problems and how-to notes
- Links to appendices and other reference tables

The e-book also is available bundled with an abridged print companion that includes the main expository text for Chapters 1-10 and the appendices. Problems are not included in the print companion.

Chapter Reorganization and Revisions

The majority of the changes for the tenth edition have been to shorten some of the presentations and to reduce the amount of mathematical derivations of the theory. Material including derivations that contribute to the understanding of the subject have been left in the text. Many of the examples have been shortened and they include the units and their conversions without being too repetitive in the presentation keeping the dublication of some examples to show the use of english units. The application sections in the end of the chapters have been expanded somewhat to emphasize the real world examples of devices and processes for which this subject is important in their analysis and design.

Chapters 1 still contains the most important concepts from physics and the concepts of the thermodynamic properties that describes the condition of the substance that is included in the analysis. To have the tools for the analysis the order of the presentation has been kept from the previous editions so the behavior of pure substances is presented in chapter 2 with a slight expansion and separation of the different domains for solid, liquid and gas phase behavior. Though the introduction of the property program CATT3 has been left out the program is still available from Wiley's web-site that is related to this book.

Chapter 3 contains the first major change namely to include a description of the energy resources we consume and the typical energy conversions that are used in modern societies. Together with the mentioning of renewable energy resources and the end use of energy it provides a better background for all the subsequent processes and details that we study. A short description of energy storage systems and some of the energy transfer processes devices are also presented accompanied by small tables with typical numbers for such devices. Students typically have only vague ideas about the size of many of the devices and processes we study. This material is covered under applications in chapter 3 after the introduction of the energy equation. The following chapters deals with analysis of processes and devices which relates to this and also include a special section of the homework problems where approbriate. By highlighting this material early it can serve as a motivating factor to study the subsequent material where the use and need for the theory becomes evident. Suggested homework that can be included in assignments for this category are also available on Wiley's website for the book for those that desire to emphasize the energy conversion and conservation subjects.

The balance equations for mass, momentum, energy and entropy follow the same format to show the uniformity in the basic principles and make the concept something to be understood and not merely memorized. This is also the reason to use the name energy equation and entropy equation for the first and second law of thermodynamics to stress they are universally valid not just used in the field of thermodynamics but apply to all situations and fields of study with no exceptions. Clearly, special cases requires extensions not covered in this text, but a few of these have been added in Chapter 12 together with the thermodynamic property relations.

The energy equation applied to a general control volme is retained from the previous edition that included a section with multi-flow devices. Again this is done to reinforce to students that the analysis is done by applying the basic principles to systems under investigation. This means the actual mathematical form of the general laws follows the sketches and figures of the system and the analysis is not a question about finding a suitable formula in the text. A small table is added in the end to give students some sense of the relative magnitude of flow devices in terms of the energy transfer per unit mass.

The historical development of the second law of thermodynamics in chapter 5 has been expanded to include the in-equality of Clausius. This chapter then includes all the historical statements of the second law so chapter 6 exclusively deals with the entropy equation. To show the generality of the entropy equation a small example is written up applying the energy and entropy equations to heat engines and heat pumps so it can be demonstrated that the historical presentation of the second law in Chapter 5 can be completely substituted with the postulation of the entropy equation and the existence of the absolute temperature scale. Carnot cycle efficiencies and the fact that real devices have lower efficiency follows from the basic general laws. Also the direction of heat transfer from a higher temperature domain towards a lower temperature domain is predicted by the entropy equation due to the requirement of a positive entropy generation. These are examples that practice the application of the general laws for specific cases and improves the students understanding of the material.

The application section in chapter 7 has been expanded a little to include some description of intercoolers and reheaters as a mean of energy conservation and efficiency improvements. The device efficiencies is also placed here as an application of the entropy equation and this whole section has about 30 homwork problems associated with it. The general summary of the control volume analysis has been removed and will be available on-line from Wiley website.

Exergy in chapter 8 has been shortened a little to reduce the mathematical manipulation of the equations and a small application section with the second law efficiency for cycles have been added to illustrate an important aspect of its use. A more detailed discussion of this is now included as a separate section in Chapter 9.

The chapters with cycles are expanded with a few details for specific cycles and some extensions shown to tie the theory to industrial applications with real systems. The expression for cycle efficiency is now included for the Stirling, Atkinson and Miller cycles to show that they all are related to compression and expansion ratios.

The property relations in chapter 12 has been updated to include effects of dilution and fugacity for mixtures and as a special application the effect of a surface tension is included under engineering applications. This revision has also removed the older method for development of thermodynamic tables and now only inlcudes the Helmholtz function based development.

Web-Based Material

Although most of the supplemental material for this edition of the book is accessible directly or by links from the e-book, several documents also are available from Wiley's web site for the book. The following material will be accessible for students through links to the book companion site and additional material reserved for instructors of the course will also by at Wiley's book companion site.

Notes for classical thermodynamics. A very short set of notes covers the basic thermodynamic analysis with the general laws (continuity, energy and entropy equations) and some of the specific laws like device equations, process equations, etc. This is useful for students doing review of the course or for exam preparation as it gives a comprehensive presentation in a condensed form.

General Control Volume Analysis. This is the short step by step procedure that was at the end of chapter 7 in the eighth edition.

Extended set of study examples. This document includes a updated collection of additional examples for students to study. These examples are written slightly longer and more detailed in the solution than the examples printed in the book and thus are excellent for self-study. There are about 8 SI unit problems with 3-4 english unit problems for each chapter covering most of the material in the chapters.

How-to-notes. Frequently asked questions are listed for each of the set of subject areas in the book with detailed answers. These are questions that are difficult to have room for in the book. Examples:

How do I find a certain state for R-410A in the B-section tables?

How do I make a linear interpolation?

Should I use internal energy (u) or enthalpy (h) in the energy equation?

When can I use ideal gas law?

Instructor material. A set of powerpoint lecture slides are available. These also include repeat copies of some book examples with specific heat done with the ideal gas tables and visa versa. Additional english unit examples are also listed as copies of the SI unit problems and modified if needed due to the tables. Other material for instructors covers typical syllabus and homework assignments for a first and a second course in thermodynamics. Additionally examples of 2 standard 1 hour midterm exams, and a 2 hour final exam are given for typical Thermodynamics I and Thermodynamics II classes.

FEATURES CONTINUED FROM 9TH EDITION

In-Text-Concept Question

The in-text concept questions appear in the text after major sections of material to allow student to reflect over 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 and most of these are emphasizing the understanding of the material without being memory facts.

End-of-Chapter Engineering Applications

The last section in each chapter, called engineering applications, have been revised with updated illustrations and a few more examples. These sections are intended to be motivating material mostly informative examples of how this particular chapter material is being used in actual engineering.

End-of-Chapter Summaries with Main Concepts and Formulas

The end-of-chapter summaries provide a review of the main concepts covered in the chapter, with highlighted key words are now located as suplemental material directly accessible from the e-book. The only part still with the chapter material is an expanded listing of the key concepts and the formulas including equation numbers. The list of skills that the student should have mastered after studying the chapter is presented together with a table of detailed references to examples, equations and homework problems for each specific skill. These main concepts and formulas are included after the summary for reference and a collection of these will be accessible through the links to the book companion site. The main summary of the general control volume analysis has been removed from chapter 7 and placed together with the online material.

Concept-Study Guide Problems

Additional concept questions are placed as problems in the first section of the end of chapter homework problems. These problems are similar to the in-text concept questions and serve as study guide problems for each chapter they are a little more like homework problems with numbers to provide 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 significantly reduced but still contains introductory problems over all aspects of the chapter material and listed according to the subject sections for easy selection according to the particular coverage given and they are generally ordered to be progressive more complex and involved. Later problems in many sections are related to real industrial processes and devices and lebeled under **applications** or **energy conservation** with more comprehensive problems retained and grouped as **review problems**. The more comprehensive and lengthy problems have been removed to conserve space.

New and modified problems are reserved for instructors and available from Wileys website for the book.

Tables

The tables of the substances have been carried over from the 8th edition with **alternative refrigerant R-410A** which is the replacement for R-22 and **carbon dioxide** which is a natural refrigerant. Several more substances are included in the software.

FLEXIBILITY IN COVERAGE AND SCOPE

The book attempts to cover fairly comprehensively the basic subject matter of classical thermodynamics, and I 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. I also recognize that a number of colleges offer a single introductory course in thermodynamics for all departments, and 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, the material is arranged in sections, particularly in the later chapters, so considerable flexibility exist in the amount of material that may be covered.

The book covers more material than required for a two-semester course sequence, which provides flexibility for specific choices of topic coverage. Instructors may want to visit the publisher's Website at www.wiley.com/go/borgnakke/FundofThermo10e for information and suggestions on possible course structure and schedules, and the additional material mentioned as Web-material which will be updated to include current errata for the book.

Flexibility with HW simple and extended problems to satisfy depth and time requirements Examples of this are constant specific heat question extended to be with variable specific heats (gas tables), a piston cylinder includes the metal mass besides the contained mass, some problems are also in english units. Many problems from earlier chapters are repeated when entropy is added to the analysis.

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I hope 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 communicate those to me at claus@umich.edu.

Claus Borgnakke
Ann Arbor, Michigan
October 2018

Contents

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, electrical potential, volt
ER	expansion ratio
f	fugacity, pseudo pressure
F	Faradays constant
F	force, also tension
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
HR, HP	enthalpy of reactants and enthalpy of products
HV	heating value
i	electrical current
i, I	specifc and total irreversibility
k	conductivity
k	specific heat ratio: C_p/C_v
K	equilibrium constant
ke, KE	specific and total 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, PE	specific and total 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
$\overline{R}$	universal gas constant
s, S	specific entropy and total entropy
S_{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, power
w^{rev}	specific reversible work between two states
x	quality
y	gas-phase mole fraction
y	extraction fraction
Z	elevation
Z	compressibility factor
Z	electrical charge

Greek Letters

α	residual volume
α	dimensionless Helmholtz function a/RT
α_p	volume expansivity
β	coefficient of performance for a refrigerator
β'	coefficient of performance for a heat pump
β_S	adiabatic compressibility
β_T	isothermal compressibility
δ	dimensionless density ρ/ρ_c
η	efficiency
μ	chemical potential
ν	stoichiometric coefficient
ρ	density
σ	surface tension (F/L), surface energy (E/A)
σ	Stefan-Boltzman constant
τ	dimensionless temperature variable T_c/T
τ_0	dimensionless temperature variable $1 - T_r$

Φ	equivalence ratio
ϕ	relative humidity
ϕ, Φ	exergy or availability for a control mass
ψ	specific exergy, flow availability
ω	humidity ratio or specific humidity
ω	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

CHAPTER 1 PROBLEMS

SS Student solution available in interactive e-text.

CONCEPT-STUDY GUIDE PROBLEMS

1.1 Separate the list P, F, V, v, ρ, T, a, m, L, t, and **V** into intensive properties, extensive properties, and nonproperties.

1.2 A tray of liquid water is placed in a freezer where it cools from 20 to −5°C. Show the energy flow(s) and storage and explain what changes.

1.3 The overall density of fibers, rock wool insulation, foams, and cotton is fairly low. Why?

1.4 Is density a unique measure of mass distribution in a volume? Does it vary? If so, on what kind of scale (distance)?

SS **1.5** 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.

1.6 What is the approximate mass of 1 L of gasoline? Of helium in a balloon at T_0, P_0?

1.7 Can you carry 1 m^3 of liquid water?

1.8 A heavy refrigerator has four height-adjustable feet. What feature of the feet will ensure that they do not make dents in the floor?

1.9 A swimming pool has an evenly distributed pressure at the bottom. Consider a stiff steel plate lying on the ground. Is the pressure below it just as evenly distributed?

1.10 If something floats in water, what does it say about its density?

1.11 Two divers swim at a depth of 20 m. One of them swims directly under a supertanker; the other avoids the tanker. Who feels a greater pressure?

1.12 An operating room has a positive gage pressure, whereas an engine test cell has a vacuum; why is that?

1.13 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? SS

1.14 What is the lowest temperature in degrees Celsius? In degrees Kelvin?

1.15 How cold can it be on Earth and in empty space?

1.16 A thermometer that indicates the temperature with a liquid column has a bulb with a larger volume of liquid. Why?

1.17 How can you illustrate the binding energy between the three atoms in water as they sit in a triatomic water molecule. *Hint:* imagine what must happen to create three separate atoms.

HOMEWORK PROBLEMS

Properties, Units, and Force

SS **1.18** 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)?

1.19 A stainless steel storage tank contains 5 kg of carbon dioxide gas and 7 kg of argon gas. How many kmoles are in the tank?

1.20 A steel cylinder of mass 4 kg contains 4 L of water at 25°C at 100 kPa. Find the total mass and volume of the system. List two extensive and three intensive properties of the water.

1.21 The Rover Explorer has a mass of 185 kg, how much does this weigh on the Moon ($g = g_{std}/6$) and on Mars where $g = 3.75$ m/s^2.

1.22 A 1700 kg car moving at 80 km/h is decelerated at a constant rate of 4 m/s^2 to a speed of 20 km/h. What are the force and total time required?

1.23 The elevator in a hotel has a mass of 750 kg, and it carries six people with a total mass of 450 kg. How much force should the cable pull up with to have an acceleration of 1 m/s^2 in the upward direction?

1.24 One of the people in the previous problem weighs 80 kg standing still. How much weight does this person feel when the elevator starts moving?

Specific Volume

1.25 A 1-m^3 container is filled with 400 kg of granite stone, 200 kg of dry sand, and 0.2 m^3 of liquid 25°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.

1.26 A power plant that separates carbon dioxide from the exhaust gases compresses it to a density of 110 kg/m^3 and stores it in an unminable coal seam with a porous volume of 100 000 m^3. Find the mass that can be stored.

1.27 A 5-m^3 container is filled with 900 kg of granite (density of 2400 kg/m^3). The rest of the volume is air, with density equal to 1.15 kg/m^3. Find the mass of air and the overall (average) specific volume.

Pressure

1.28 A 5000-kg elephant has a cross-sectional area of 0.02 m^2 on each foot. Assuming an even distribution, what is the pressure under its feet?

1.29 A valve in the cylinder shown in Fig. P1.29 has a cross-sectional area of 11 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?

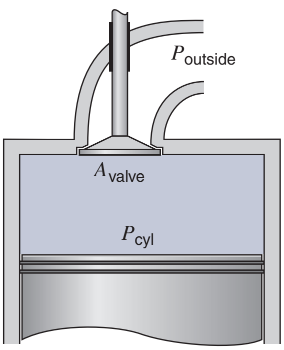

Figure P1.29

1.30 The piston cylinder in Fig. P1.29 has a diameter of 10 cm, inside pressure 735 kPa. What is the force holding the massless piston up as the piston lower side has P_0 besides the force.

1.31 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? SS

1.32 Ahydraulic cylinder has a 125-mm diameter piston with an ambient pressure of 1 bar. Assuming standard gravity, find the total mass this piston can lift if the inside hydraulic fluid pressure is 2500 kPa.

1.33 A 75-kg human total footprint is 0.05 m^2 when the human is wearing boots. Suppose that you want to walk on snow that can at most support an extra 3 kPa; what should the total snowshoe area be?

1.34 A piston/cylinder with a cross-sectional area of 0.01 m^2 has a piston mass of 65 kg plus a force of 800 N resting on the stops, as shown in Fig. P1.34. With an outside atmospheric pressure of 101 kPa, what should the water pressure be to lift the piston?

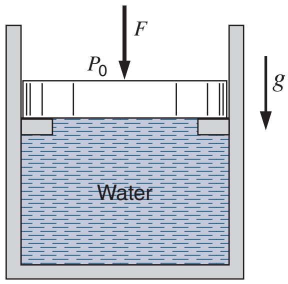

Figure P1.34

1.35 A 2.5-m-tall steel cylinder has a cross-sectional area of 1.5 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 engine oil. This is shown in Fig. P1.35. The oil surface is exposed to atmospheric air at 101 kPa. What is the highest pressure in the water?

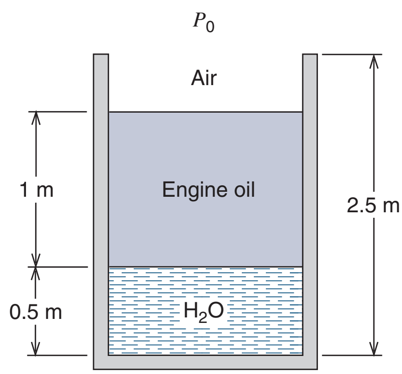

Figure P1.35

1.36 An underwater buoy is anchored at the seabed with a cable, and it contains a total mass of 250 kg. What should the volume be so that the cable holds it down with a force of 1000 N?

1.37 A floating oil rig is anchored in the seabed with cables giving a net pull of 10 000 kN down. How large a water displacement volume does that lead to?

SS **1.38** At the beach, atmospheric pressure is 1025 mbar. You dive 15 m down in the ocean, and you later climb a hill up to 450 m in elevation. Assume that the density of water is about 1000 kg/m^3, and the density of air is 1.18 kg/m^3. What pressure do you feel at each place?

1.39 A steel tank of cross-sectional area 3 m^2 and height 16 m weighs 10 000 kg and is open at the top, as shown in Fig. P1.39. 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?

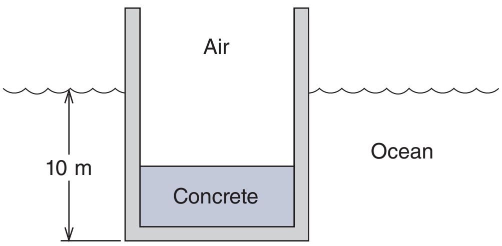

Figure P1.39

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

1.41 A container ship is 240 m long and 22 m wide. Assume that the shape is like a rectangular box. How much mass does the ship carry as load if it is 10 m down in the water and the mass of the ship itself is 30 000 tonnes?

Manometers and Barometers

1.42 A probe is lowered 16 m into a lake. Find the absolute pressure there.

1.43 A person, 75 kg, wants to fly (hoover) on a 2 kg skateboard of size 0.6 m by 0.25 m. How large a gauge pressure under the board is needed?

1.44 The density of atmospheric air is about 1.15 kg/m^3, 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? SS

1.45 A barometer to measure absolute pressure shows a mercury column height of 735 mm. The temperature is such that the density of the mercury is 13 550 kg/m^3. Find the ambient pressure.

1.46 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.

1.47 What pressure difference does a 100-m column of atmospheric air show?

1.48 A barometer measures 760 mm Hg at street level and 745 mm Hg on top of a building. How tall is the building if we assume air density of 1.15 kg/m^3?

1.49 An exploration submarine should be able to descend 1200 m down in the ocean. If the ocean density is 1020 kg/m^3, what is the maximum pressure on the submarine hull? SS

1.50 The absolute pressure in a tank is 115 kPa and the local ambient absolute pressure is 102 kPa. If a U-tube with mercury (density = 13 550 kg/m^3) is attached to the tank to measure the gauge pressure, what column height difference will it show?

1.51 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_{atm} = 101 kPa. How high a fluid level difference must we plan for?

1.52 A pipe flowing light oil has a manometer attached, as shown in Fig. P1.52. What is the absolute pressure in the pipe flow?

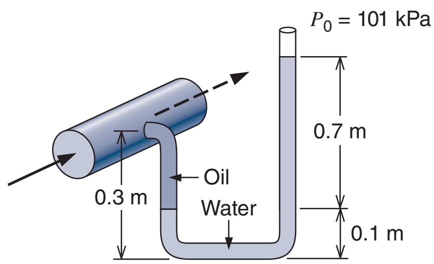

Figure P1.52

1.53 The difference in height between the columns of a manometer is 200 mm, with a fluid of density SS

900 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 kg/m^3) as manometer fluid?

1.54 A piece of experimental apparatus, Fig. P1.54, is located where $g = 9.5$ m/s^2 and the temperature is 5°C. Air flow inside the apparatus is determined by measuring the pressure drop across an orifice with a mercury manometer (density = 13 580 kg/m^3) showing a height difference of 200 mm. What is the pressure drop in kPa?

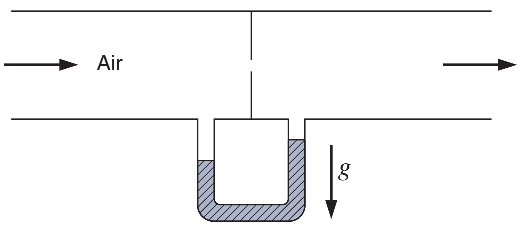

Figure P1.54

Energy and Temperature

1.55 A 0.25 m^3 piece of softwood is lifted up to the top shelf in a storage bin that is 4 m above the ground floor. How much increase in potential energy does the wood get?

SS **1.56** 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?

1.57 What is a temperature of −5°C in degrees Kelvin?

1.58 A mercury thermometer measures temperature by measuring the volume expansion of a fixed mass of liquid mercury due to a change in density as $\rho_{Hg} = 13\,595 - 2.5\,T$ kg/m^3 (T in Celsius). Find the relative change (%) in volume for a change in temperature from 10 to 20°C.

SS **1.59** The density of liquid water is $\rho = 1008 - T/2$ (kg/m^3) with T in °C. If the temperature increases 10°C, how much deeper does a 1-m layer of water become?

Review Problems

1.60 Repeat Problem 1.54 if the flow inside the apparatus is liquid water ($\rho = 1000$ 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.

1.61 A dam retains a lake 6 m deep, as shown in Fig. P1.61. 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.

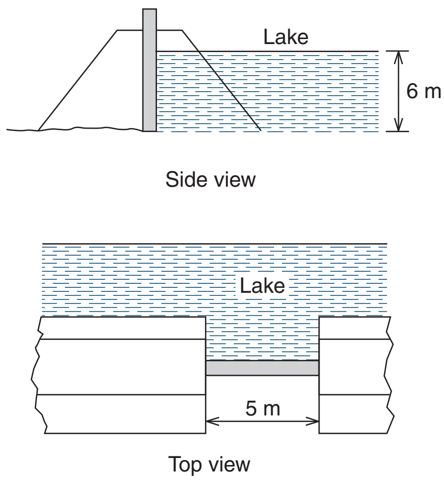

Figure P1.61

1.62 In the city water tower, water is pumped up to a level of 25 m above ground in a pressurized tank with air at 125 kPa over the water surface. This is illustrated in Fig. P1.62. Assuming water density of 1000 kg/m^3 and standard gravity, find the pressure required to pump more water in at ground level.

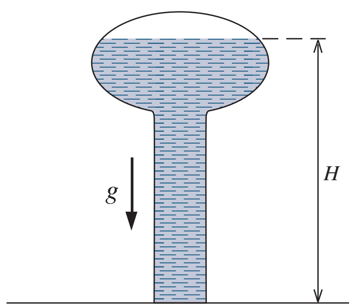

Figure P1.62

1.63 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. P1.63. 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?

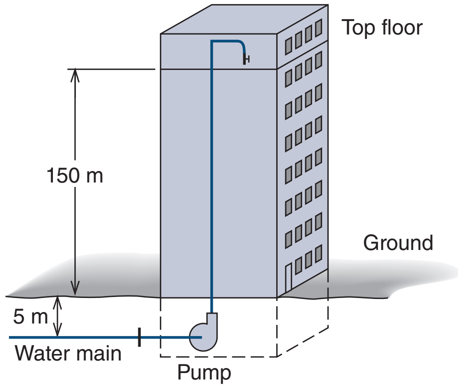

Figure P1.63

ENGLISH UNIT PROBLEMS

English Unit Concept Problems

1.64E A mass of 2 lbm has an acceleration of 5 ft/s^2. What is the needed force in lbf?

1.65E How much mass is in 1 gal of gasoline? In helium in a balloon at atmospheric *P* and *T*?

1.66E Can you easily carry a 1-gal bar of solid gold?

1.67E What is the temperature of −5 F in degrees Rankine?

1.68E What is the lowest possible temperature in degrees Fahrenheit? In degrees Rankine?

1.69E What is the relative magnitude of degree Rankine to degree Kelvin?

English Unit Problems

1.70E The Rover Explorer has a mass of 410 lbm, how much does this "weigh" on the Moon ($g = g_{std}/6$) and on Mars where $g = 12.3$ ft/s^2.

1.71E A 2500-lbm car moving at 25 mi/h is accelerated at a constant rate of 15 ft/s^2 up to a speed of 50 mi/h. What are the force and total time required?

SS **1.72E** 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^2. What is the needed force in the cable?

1.73E A car of mass 4000 lbm travels with a velocity of 60 mi/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?

1.74E A power plant that separates carbon dioxide from the exhaust gases compresses it to a density of 8 lbm/ft^3 and stores it in an unminable coal seam with a porous volume of 3 500 000 ft^3. Find the mass that can be stored.

1.75E The piston cylinder in Fig. P1.29 has a diameter of 4 in., inside pressure 100 psia. What forcemust hold the massless piston up as the piston lower side has P_0 besides the force?

1.76E A laboratory room keeps a vacuum of 1 in. of water due to the exhaust fan. What is the net force on a door of size 6 ft by 3 ft?

1.77E A person, 175 lbm, wants to fly (hoover) on a 4 lbm skateboard of size 2 ft by 0.8 ft. How large a gauge pressure under the board is needed?

1.78E A floating oil rig is anchored in the seabed with cables giving a net pull of 2 250 000 lbf down. How large a water displacement volume does that lead to?

1.79E A container ship is 790 ft long and 72 ft wide. Assume the shape is like a rectangular box. How much mass does the ship carry as load if it is 30 ft down in the water and the mass of the ship itself is 30 000 tons.

1.80E A manometer shows a pressure difference of 3.5 in. of liquid mercury. Find ΔP in psi. SS

1.81E What pressure difference does a 300-ft column of atmospheric air show?

1.82E A piston/cylinder with a cross-sectional area of 0.1 ft^2 has a piston mass of 100 lbm and a force of 180 lbf resting on the stops, as shown in Fig. P1.34. With an outside atmospheric pressure of 1 atm, what should the water pressure be to lift the piston?

1.83E 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?

1.84E A piston, m_p = 10 lbm, is fitted in a cylinder, A = 2.5 $in.^2$, that contains a gas. The setup is in a centrifuge that creates an acceleration of 75 ft/s^2. Assuming standard atmospheric pressure outside the cylinder, find the gas pressure. SS

1.85E The human comfort zone is between 18 and 24°C. What is the range in Fahrenheit?

Summary Objectives

CHAPTER 1

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 ρ, 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 and
  - Sketch the content and identify storage locations for mass
  - Identify mass and energy flows crossing the C.V. surface
- Know properties P–T–v–ρ 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 the difference between (v, ρ) and (V, m) intensive versus extensive.
- Apply a force balance to a given system and relate it to pressure P.
- Know the difference between a relative (gauge) and absolute pressure P.
- Understand the working of a manometer or a barometer and get ΔP or P from height H.
- Know the difference between a relative and absolute temperature T.
- Understand how physics of a device can influence a property.
- You should have an idea about magnitudes (v, ρ, P, T).

Most of these concepts will be repeated and reinforced in the following chapters, such as properties in Chapter 2, energy transfer as heat and work, and internal energy in Chapter 3, together with their applications.

Study guide and Chapter Study Resources

CHAPTER 1

Objectives	Reading, Examples, Eqs & Tables	Concepts, Study, Hw problems
Know properties P-T-v-ρ and their units	Reading: Sec. 1.3, 1.5–1.7, 1.11 Examples: 1.1–1.5 Eqs : 1.2, 1.3, 1.12, 1.13 Tables: A.1	C: 1, 3–10, 14–15 S: 5, 18, 59 Hw: 19–24, 57–58, 65E–69E, 85E
Know that energy is **stored** as kinetic, potential or internal (in molecules)	Reading: Sec. 1.8 Examples: 1.1–1.5 Eqs. : 1.9, 1.10, 1.11	C: 17 Hw: 19–24, 55–56, 73E
Know the difference between (v, ρ) and (V, m) intensive versus extensive	Reading: Sec. 1.3 Examples: 1.2	C: 1, 3 Hw: 20
Apply a force balance to a given system and relate it to pressure P	Reading: Sec. 1.5–1.7, 1.11 Examples: 1.3, 1.4, 1.7 Eqs : 1.1, 1.3–1.7	C: 8–13 S: 13, 31, 38, 40, 84E Hw: 28–41, 84E
Know the difference between a relative (gauge) and absolute pressure P	Reading: Sec. 1.7 Examples: 1.5 – 1.6 Eqs and Tables: 1.3 – 1.4, 1.6	C: 11–12, S: 44, 49, 53 Hw: 42–46, 49, 52, 54
Understand manometer and barometer to get ΔP or P from height H	Reading: Sec. 1.7 Examples: 1.5–1.6 Eqs : 1.3–1.6	C: 11–12 S: 44, 49, 53, 80E Hw: 42–54, 80E–83E
Know the difference between a relative and absolute temperature T	Reading: Sec. 1.11 Examples: 1.5–1.6 Eqs : 1.12, 1.13 Tables: A.1	C: 14–16 S: 59 Hw: 57–59
Understand how physics of a device can influence a property.	Reading: all Examples: 1.2–1.7 Device eqs.: P = C, V = C, T = C	nearly all hw
Have an idea about magnitudes (v, ρ, P, T)	Reading: Sec. 1.7 Examples: 1.5–1.6 Equations: 1.2–1.6 Figure: 1.8	S: 18 Hw: 18, 57, 85E

1 Introduction and Preliminaries

The field of thermodynamics is concerned with the science of energy focusing on energy storage and energy conversion processes. We will study the effects of energy on different substances, as we may expose a mass to heating/cooling or to volumetric compression/expansion. During such processes, we are transferring energy into or out of the mass, so it changes its conditions expressed by properties such as temperature, pressure, and volume. We use several processes similar to this in our daily lives; we heat water to make coffee or tea or cool it in a refrigerator to make cold water or ice cubes in a freezer. In nature, water evaporates from oceans and lakes and mixes with air where the wind can transport it, and later the water may drop out of the air as either rain (liquid water) or snow (solid water). As we study these processes in detail, we will focus on situations that are physically simple and yet typical of real-life situations in industry or nature.

By a combination of processes, we are able to illustrate more complex devices or complete systems—for instance, a simple steam power plant that is the basic system that generates the majority of our electric power. Figure 1.1 shows a power plant that produces electric power and hot water for district heating by burning coal. The coal is supplied by ship, and the district heating pipes are located in underground tunnels and thus are not visible. For a better understanding and a technical description, see the simple schematic of the power plant shown in Fig. 1.2. This includes various outputs from the plant as electric power to the net, warm water for district heating, slag from burning coal, and other materials such as ash and gypsum; the last output is a flow of exhaust gases out of the chimney.

Another set of processes forms a good description of a refrigerator that we use to cool food or apply it at very low temperatures to produce a flow of cold fluid for cryogenic surgery by freezing tissue for minimal bleeding. A simple schematic for such a system is shown in Fig. 1.3. The same system can also function as an air conditioner with the dual purpose of cooling a building in summer and heating it in winter; in this last mode of use, it is also called a *heat pump*. For mobile applications, we can make simple models for gasoline and diesel engines typically used for ground transportation and gas turbines in jet engines used in aircraft, where low weight and volume are of prime concern. These are just a few examples of familiar systems that the theory of thermodynamics allows us to analyze. Once we learn and understand the theory, we will be able to extend the analysis to other cases we may not be familiar with.

Beyond the description of basic processes and systems, thermodynamics is extended to cover special situations like moist atmospheric air, which is a mixture of gases, and the combustion of fuels for use in the burning of coal, oil, or natural gas, which is a chemical and energy conversion process used in nearly all power-generating devices. Many other extensions are known; these can be studied in specialty texts. Since all the processes engineers deal with have an impact on the environment, we must be acutely aware of the ways

FIGURE 1.1 The Avedoere Power Station, Denmark.

(Courtesy of Dong Energy, Denmark.)

in which we can optimize the use of our natural resources and produce the minimal amount of negative consequences for our environment. For this reason, the treatment of efficiencies for processes and devices is important in a modern analysis and is required knowledge for a complete engineering study of system performance and operation.

Before considering the application of the theory, we will cover a few basic concepts and definitions for our analysis and review some material from physics and chemistry that we will need.

1.1 A THERMODYNAMIC SYSTEM AND THE CONTROL VOLUME

A thermodynamic system is a device or combination of devices containing a quantity of matter under study. To define this more precisely, a control volume is chosen so that it

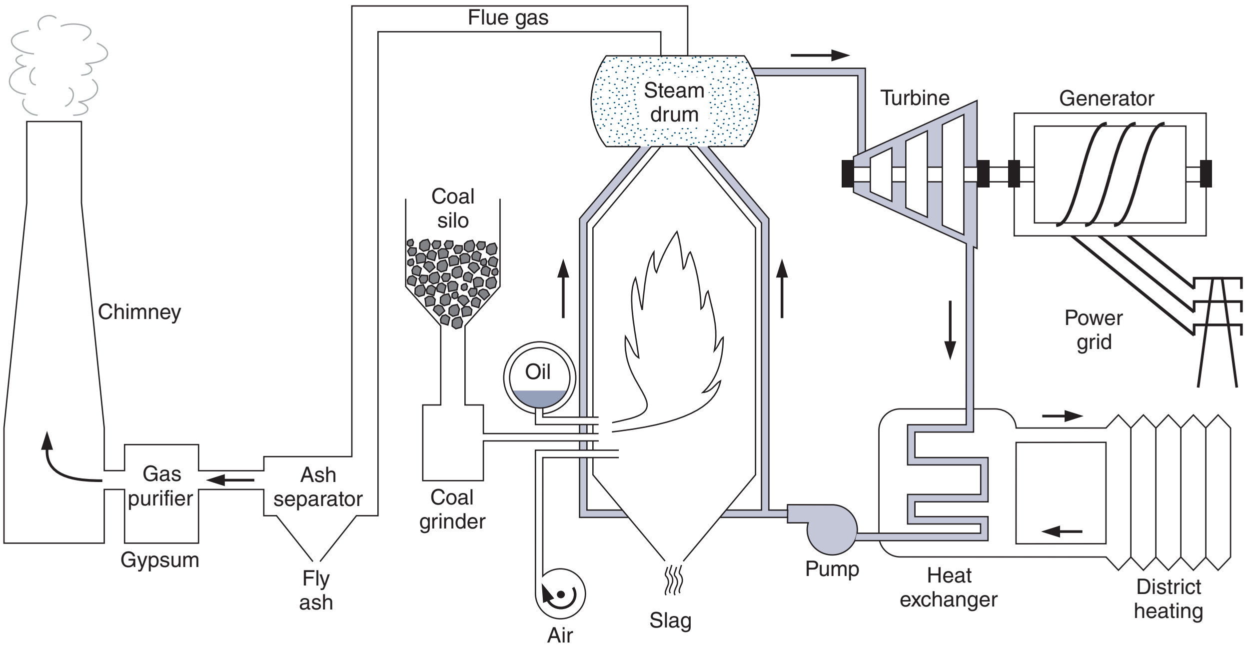

FIGURE 1.2 Schematic diagram of a steam power plant.

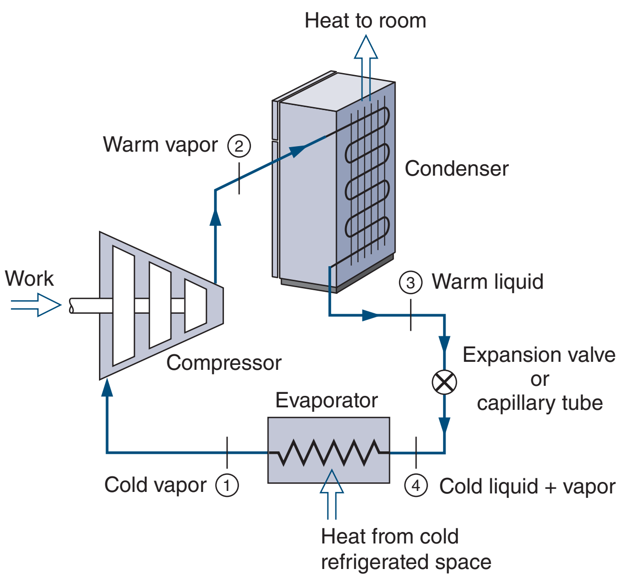

FIGURE 1.3 Schematic diagram of a refrigerator.

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 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.

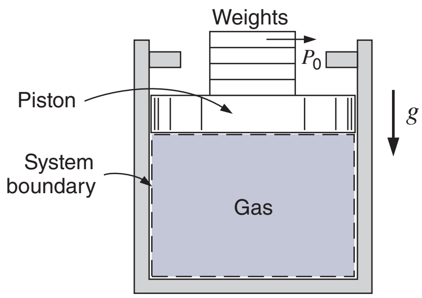

FIGURE 1.4 Example of a control mass.

Selecting the gas in the cylinder of Fig. 1.4 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 move out. As the piston moves, the boundary of the control mass also changes. 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 so that no mass, heat, or work is transferred across the boundary of the system. In a more typical case, a thermodynamic analysis should be conducted for a device such as an air compressor in which mass flows in and out, as shown schematically in Fig. 1.5. The real system includes possibly a storage tank, as shown in Fig. 1.20. In such an analysis, we specify a control volume that surrounds the compressor with a surface called the control surface, across which there may be a transfer of mass and momentum as well as heat and work.

Thus, the more general control surface defines a control volume, where mass may flow in or out, while a control mass is the special case of no mass flowing in or out. Hence, the control mass contains a fixed mass at all times, which explains its name. The general formulation of the analysis is considered in detail in Chapter 4. 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

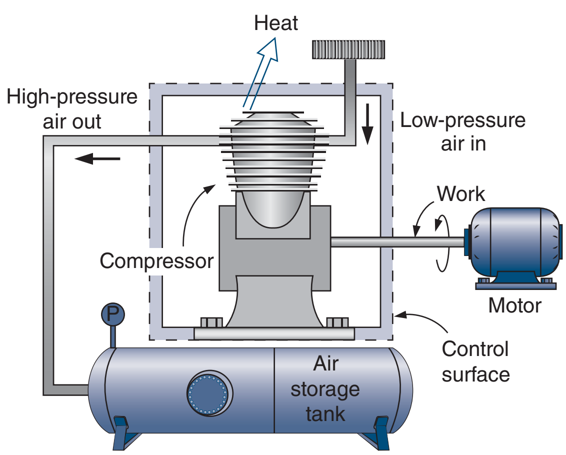

FIGURE 1.5 Example of a control volume.

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.

1.2 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 each 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 6×10^{20} equations. Even with a modern 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 relatively easily involves 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 also should be made regarding the continuum approach. We are normally concerned with volumes that are very large compared to molecular dimensions and with time scales that are very large compared to intermolecular collision frequencies. For this reason, we deal with very large numbers of molecules that interact extremely often during our observation period, so we view the system as a simple uniformly distributed mass in the volume called a continuum. This 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, consistent with the macroscopic point of view.

1.3 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 describing a condition of matter that is homogeneous throughout, commonly referred to as solid, liquid, or gas phases. 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 (i.e., 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, see Section 1.6, 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. 1.4 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 14. When a system is in equilibrium regarding all possible changes of state, we say that the system is in thermodynamic equilibrium.

1.4 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 the crank moves as shown in Fig. 1.6, the piston moves to give a larger cylinder volume so a change in state occurs toward a lower pressure and higher specific volume. The path of the succession of states through which the system passes is called the process.

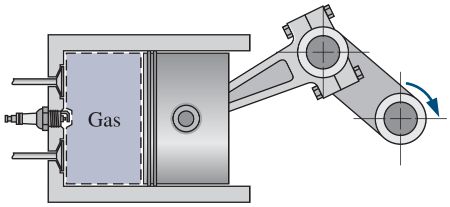

FIGURE 1.6 Example of a system that may undergo a quasi-equilibrium process.

Let us consider the equilibrium of a system as it undergoes a change in state. The moment the piston in Fig. 1.6 is moved, mechanical equilibrium does not exist; as a result, the volume and pressure change until mechanical equilibrium is restored. 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 piston moves slowly, the process could be considered quasi-equilibrium. However, if the piston moves fast, there will be a nonuniform pressure distribution in the gas. 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 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.

1.5 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, and they are all shown in appendix Table A.1. 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 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. 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*, *pico*, or *femto*, as listed in Table A.0, 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 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), which used to be marked on a platinum–iridium bar. Currently, the CGPM has 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, 1 mol 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 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. The unit conversions are shown in Table A.1 and covers most of the commonly used ones in SI and English unit systems.

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

$$F = ma \tag{1.1}$$

The unit of force is the newton (N), which by definition is the force required to accelerate a mass of 1 kg at the rate of 1 m/s^2:

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

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

$$1 \text{ ft} = 0.3048 \text{ m} = 12 \text{ in.}$$

and therefore also relates to the inch (in.). 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^2 or 32.1740 ft/s^2. 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 an lbm and an 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 1.1

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

Solution

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

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