pressure

force

density

mass

velocity

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SCHAUM'S outlines

Thermodynamics for Engineers

Third Edition

Merle C. Potter, PhD

Professor Emeritus of Mechanical Engineering
Michigan State University

Craig W. Somerton, PhD

Associate Professor of Mechanical Engineering
Michigan State University

Merle C. Potter has a BS degree in Mechanical Engineering from Michigan Technological University; his MS in Aerospace Engineering and PhD in Engineering Mechanics were received from the University of Michigan. He is the author or coauthor of *The Mechanics of Fluids*, *Fluid Mechanics*, *Thermal Sciences*, *Differential Equations*, *Advanced Engineering Mathematics*, *Fundamentals of Engineering*, and numerous papers in fluid mechanics and energy. He is professor emeritus of Mechanical Engineering at Michigan State University.

Craig W. Somerton studied Engineering at UCLA, where he was awarded the BS, MS, and PhD degrees. He is currently associate professor of Mechanical Engineering at Michigan State University. He has published in the *International Journal of Mechanical Engineering Education* and is a past recipient of the SAE Ralph R. Teetor Education Award.

Thermodynamics
for Engineers

PREFACE

This book is intended for the first course in thermodynamics required by most, if not all, engineering departments. It is designed to supplement the required text selected for the course; it provides a succinct presentation of the material so that the student can more easily determine the major objective of each section of the textbook. If expanded detail is not of importance in this first course, the present Schaum's Outline could itself serve as the required text.

The material presented in a first course in thermodynamics is more or less the same in most engineering schools. Under a quarter system both the first and second laws are covered, with little time left for applications. Under a semester system it is possible to cover some application areas, such as vapor and gas cycles, nonreactive mixtures, or combustion. This book allows such flexibility. In fact, there is sufficient material for a full year of study.

As some U.S. industry continues to avoid the use of SI units, we have written about 20 percent of the examples, solved problems, and supplementary problems in English units. Tables are presented in both systems of units.

The basic thermodynamic principles are liberally illustrated with numerous examples and solved problems that demonstrate how the principles are applied to actual or simulated engineering situations. Supplementary problems that provide students an opportunity to test their problem-solving skills are included at the ends of all chapters. Answers are provided for all these problems at the ends of the chapters. We have also included FE-type questions at the end of most chapters.

In addition, we have included a set of exams that are composed of multiple-choice questions, along with their solutions. The majority of students who take thermodynamics will never see the material again except when they take a national exam (the professional engineers' exams or the GRE/Engineering exam). The national exams are multiple-choice exams with which engineering students are unfamiliar. Thermodynamics provides an excellent opportunity to give these students an experience in taking multiple-choice exams, exams that are typically long and difficult. Studies have shown that grades are independent of the type of exam given, so this may be the course to introduce engineering students to the multiple-choice exam.

The authors wish to thank Mrs. Michelle Gruender for her careful review of the manuscript and Ms. Barbara Gilson for her efficient production of this book.

You, both professors and students, are encouraged to email me at MerleCP@ sbcglobal.net if you have comments/corrections/questions or just want to opine.

<div align="right">

MERLE C. POTTER
CRAIG W. SOMERTON

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SCHAUM'S
OUTLINE OF

THERMODYNAMICS
FOR ENGINEERS

CONTENTS

Concepts, Definitions, and Basic Principles

1.1 INTRODUCTION

Thermodynamics is a science in which the storage, the transformation, and the transfer of energy are studied. Energy is *stored* as internal energy (associated with temperature), kinetic energy (due to motion), potential energy (due to elevation), and chemical energy (due to chemical composition); it is *transformed* from one of these species to another; and it is *transferred* across a boundary as either heat or work. In thermodynamics we will develop mathematical equations that relate the transformations and transfers of energy to material properties such as temperature, pressure, or enthalpy. Substances and their properties thus become an important secondary theme. Much of our work will be based on experimental observations that have been organized into mathematical statements, or *laws*; the first and second laws of thermodynamics are the most widely used.

The engineer's objective in studying thermodynamics is most often the analysis or design of a large-scale system—anything from an air-conditioner to a nuclear power plant. Such a system may be regarded as a continuum in which the activity of the constituent molecules is averaged into measurable quantities such as pressure, temperature, and velocity. This outline, then, will be restricted to *macroscopic* or *engineering thermodynamics*. If the behavior of individual molecules is important, a text in *statistical* thermodynamics must be consulted.

1.2 THERMODYNAMIC SYSTEMS AND CONTROL VOLUME

A thermodynamic *system* is a definite quantity of matter contained within some closed surface. The surface is usually an obvious one like that enclosing the gas in the cylinder of Fig. 1-1; however, it may be an imagined boundary like the deforming boundary of a certain amount of mass as it flows through a pump. In Fig. 1-1 the system is the compressed gas, the *working fluid*, and the system boundary is shown by the dotted line.

1
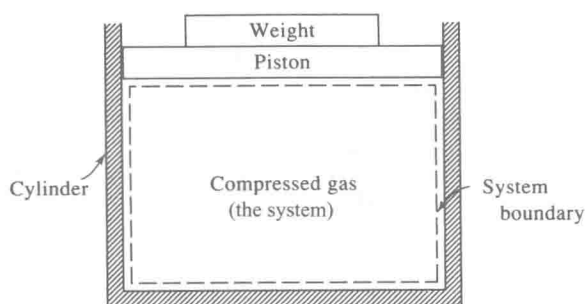
Fig. 1-1 A system.

All matter and space external to a system is collectively called its *surroundings*. Thermodynamics is concerned with the interactions of a system and its surroundings, or one system interacting with another. A system interacts with its surroundings by transferring energy across its boundary. No material crosses the boundary of a given system. If the system does not exchange energy with the surroundings, it is an *isolated* system.

In many cases, an analysis is simplified if attention is focused on a volume in space into which, or from which, a substance flows. Such a volume is a *control volume*. A pump, a turbine, an inflating balloon, are examples of control volumes. The surface that completely surrounds the control volume is called a *control surface*. An example is sketched in Fig. 1-2.
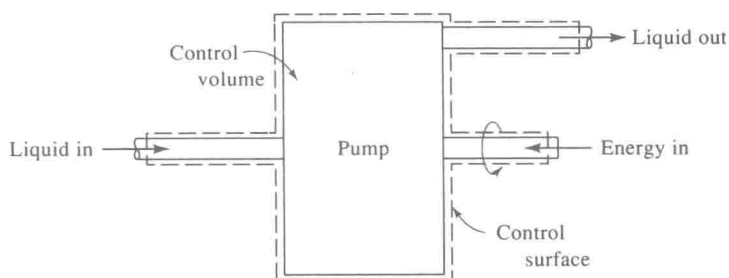
Fig. 1-2 A control volume.

We thus must choose, in a particular problem, whether a system is to be considered or whether a control volume is more useful. If there is mass flux across a boundary of the region, then a control volume is required; otherwise, a system is identified. We will present the analysis of a system first and follow that with a study using the control volume.

1.3 MACROSCOPIC DESCRIPTION

In engineering thermodynamics we postulate that the material in our system or control volume is a *continuum*; that is, it is continuously distributed throughout the region of interest. Such a postulate allows us to describe a system or control volume using only a few measurable properties.

Consider the definition of *density* given by

$$\rho = \lim_{\Delta V \to 0} \frac{\Delta m}{\Delta V} \qquad (1.1)$$

where Δm is the mass contained in the volume ΔV, shown in Fig. 1-3. Physically, ΔV cannot be allowed to shrink to zero since, if ΔV became extremely small, Δm would vary discontinuously, depending on the number of molecules in ΔV. So, the zero in the definition of ρ should be replaced by some quantity ε,

small, but large enough to eliminate molecular effects. Noting that there are about 3×10^{16} molecules in a cubic millimeter of air at standard conditions, ε need not be very large to contain billions and billions of molecules. For most engineering applications ε is sufficiently small that we can let it be zero, as in *(1.1)*.
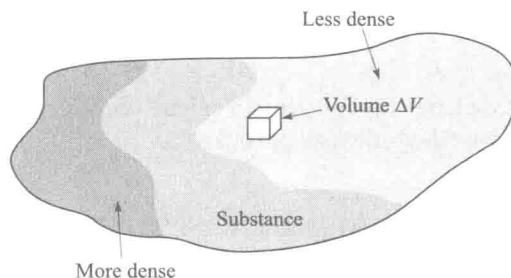
Fig. 1-3 Mass as a continuum.

There are, however, situations where the continuum assumption is not valid, for example, the re-entry of satellites. At an elevation of 100 km the *mean free path*, the average distance a molecule travels before it collides with another molecule, is about 30 mm; the macroscopic approach is already questionable. At 150 km the mean free path exceeds 3 m, which is comparable to the dimensions of the satellite! Under these conditions statistical methods based on molecular activity must be used.

1.4 PROPERTIES AND STATE OF A SYSTEM

The matter in a system may exist in several phases: as a solid, a liquid, or a gas. A *phase* is a quantity of matter that has the same chemical composition throughout; that is, it is homogeneous. Phase boundaries separate the phases, in what, when taken as a whole, is called a *mixture*.

A *property* is any quantity which serves to describe a system. The *state* of a system is its condition as described by giving values to its properties at a particular instant. The common properties are pressure, temperature, volume, velocity, and position; but others must occasionally be considered. Shape is important when surface effects are significant; color is important when radiation heat transfer is being investigated.

The essential feature of a property is that it has a unique value when a system is in a particular state, and this value does not depend on the previous states that the system passed through; that is, it is not a path function. Since a property is not dependent on the path, any change depends only on the initial and final states of the system. Using the symbol ϕ to represent a property, the mathematical equation is

$$\int_{\phi_1}^{\phi_2} d\phi = \phi_2 - \phi_1 \tag{1.2}$$

This requires that $d\phi$ be an exact differential; $\phi_2 - \phi_1$ represents the change in the property as the system changes from state 1 to state 2. There are quantities which we will encounter, such as work, that are path functions for which an exact differential does not exist.

A relatively small number of *independent properties* suffice to fix all other properties and thus the state of the system. If the system is composed of a single phase, free from magnetic, electrical, and surface effects, the state is fixed when any two properties are fixed; this *simple system* receives most attention in engineering thermodynamics.

Thermodynamic properties are divided into two general types, intensive and extensive. An *intensive property* is one which does not depend on the mass of the system; temperature, pressure, density, and velocity are examples since they are the same for the entire system, or for parts of the system. If we bring two systems together, intensive properties are not summed.

An *extensive property* is one which depends on the mass of the system; volume, momentum, and kinetic energy are examples. If two systems are brought together the extensive property of the new system is the sum of the extensive properties of the original two systems.

If we divide an extensive property by the mass a *specific property* results. The *specific volume* is thus defined to be

$$v = \frac{V}{m} \qquad (1.3)$$

We will generally use an uppercase letter to represent an extensive property [exception: m for mass] and a lowercase letter to denote the associated intensive property.

1.5 THERMODYNAMIC EQUILIBRIUM; PROCESSES

When the temperature or the pressure of a system is referred to, it is assumed that all points of the system have the same, or essentially the same, temperature or pressure. When the properties are assumed constant from point to point and when there is no tendency for change with time, a condition of *thermodynamic equilibrium* exists. If the temperature, say, is suddenly increased at some part of the system boundary, spontaneous redistribution is assumed to occur until all parts of the system are at the same temperature.

If a system would undergo a large change in its properties when subjected to some small disturbance, it is said to be in *metastable equilibrium*. A mixture of gasoline and air, or a large bowl on a small table, is such a system.

When a system changes from one equilibrium state to another, the path of successive states through which the system passes is called a *process*. If, in the passing from one state to the next, the deviation from equilibrium is infinitesimal, a *quasiequilibrium* process occurs and each state in the process may be idealized as an equilibrium state. Many processes, such as the compression and expansion of gases in an internal combustion engine, can be approximated by quasiequilibrium processes with no significant loss of accuracy. If a system undergoes a quasiequilibrium process (such as the thermodynamically slow compression of air in a cylinder) it may be sketched on appropriate coordinates by using a solid line, as shown in Fig. 1-4a. If the system, however, goes from one equilibrium state to another through a series of nonequilibrium states (as in combustion) a *nonequilibrium process* occurs. In Fig. 1-4b the dashed curve represents such a process; between (V_1, P_1) and (V_2, P_2) properties are not uniform throughout the system and thus the state of the system cannot be well defined.
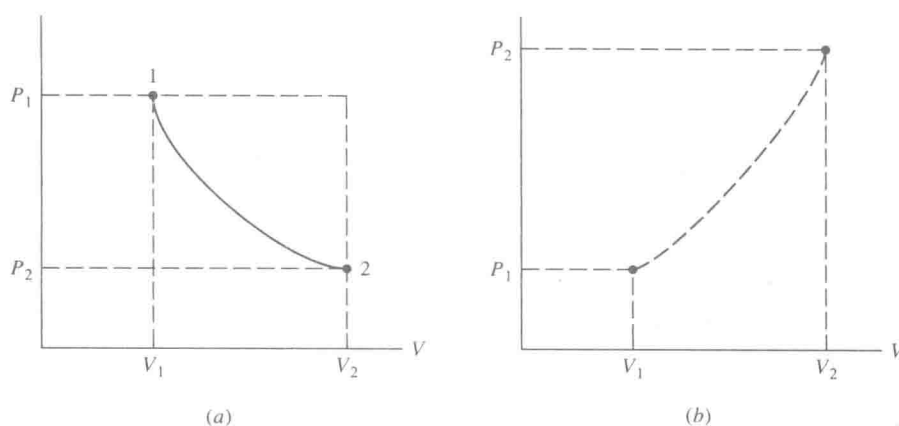

Fig. 1-4 A process.

EXAMPLE 1.1   Whether a particular process may be considered quasiequilibrium or nonequilibrium depends on how the process is carried out. Let us add the weight W to the piston of Fig. 1-5. Explain how W can be added in a nonequilibrium manner and in an equilibrium manner.

   Solution: If it is added suddenly as one large weight, as in part (a), a nonequilibrium process will occur in the gas, the system. If we divide the weight into a large number of small weights and add them one at a time, as in part (b), a quasiequilibrium process will occur.
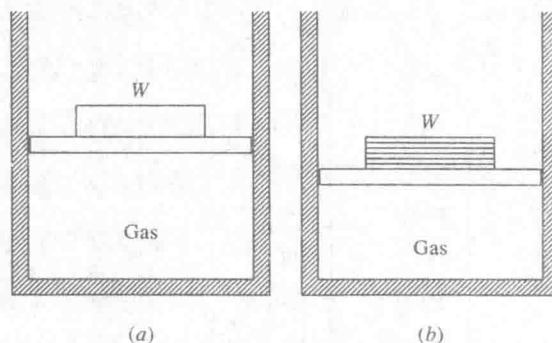

(a)   (b)

Fig. 1-5

   Note that the surroundings play no part in the notion of equilibrium. It is possible that the surroundings do work on the system via friction; for quasiequilibrium it is only required that the properties *of the system* be uniform at any instant during a process.

   When a system in a given initial state experiences a series of quasiequilibrium processes and returns to the initial state, the system undergoes a *cycle*. At the end of the cycle the properties of the system have the same values they had at the beginning; see Fig. 1-6.

   The prefix *iso-* is attached to the name of any property that remains unchanged in a process. An *isothermal* process is one in which the temperature is held constant; in an *isobaric* process the pressure remains constant; an *isometric* process is a constant-volume process. Note the isobaric and the isometric legs in Fig. 1-6.
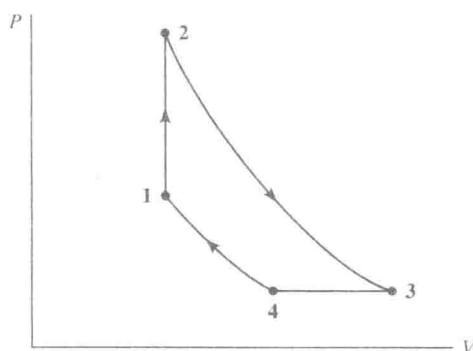
Fig. 1-6   Four processes that make up a cycle.

1.6   UNITS

   While the student is undoubtedly most at home with SI (Système International) units, much of the data gathered in the United States is in English units. Therefore, a certain number of examples and problems will be presented in English units. Table 1-1 lists units of the principal thermodynamic quantities. Observe the dual use of W for weight and work; the context and the units will make clear which quantity is intended.

Table 1-1

Quantity	Symbol	SI Units	English Units	To Convert from English to SI Units Multiply by
Length	L	m	ft	0.3048
Mass	m	kg	lbm	0.4536
Time	t	s	sec	—
Area	A	m^2	ft^2	0.09290
Volume	V	m^3	ft^3	0.02832
Velocity	V	m/s	ft/sec	0.3048
Acceleration	a	m/s^2	ft/sec^2	0.3048
Angular velocity	ω	rad/s	sec^{-1}	—
Force, Weight	F, W	N	lbf	4.448
Density	ρ	kg/m^3	lbm/ft^3	16.02
Specific weight	w	N/m^3	lbf/ft^3	157.1
Pressure, Stress	P, τ	kPa	lbf/ft^2	0.04788
Work, Energy	W, E, U	J	ft-lbf	1.356
Heat transfer	Q	J	Btu	1055
Power	$\dot{W}$	W	ft-lbf/sec	1.356
Heat flux	$\dot{Q}$	W or J/s	Btu/sec	1055
Mass flux	$\dot{m}$	kg/s	lbm/sec	0.4536
Flow rate	$\dot{V}$	m^3/s	ft^3/sec	0.02832
Specific heat	C	kJ/kg·K	Btu/lbm-°R	4.187
Specific enthalpy	h	kJ/kg	Btu/lbm	2.326
Specific entropy	s	kJ/kg·K	Btu/lbm-°R	4.187
Specific volume	v	m^3/kg	ft^3/lbm	0.06242

When expressing a quantity in SI units certain letter prefixes may be used to represent multiplication by a power of 10; see Table 1-2.

The units of various quantities are interrelated via the physical laws obeyed by the quantities. It follows that, in either system, all units may be expressed as algebraic combinations of a selected set of *base units*. There are seven base units in the SI system: m, kg, s, K, mol (mole), A (ampere), cd (candela). The last two are rarely encountered in engineering thermodynamics.

EXAMPLE 1.2   Newton's second law, $F = ma$, relates a net force acting on a body to its mass and acceleration. If a force of one newton accelerates a mass of one kilogram at one m/s^2; or, a force of one lbf accelerates 32.2 lbm (1 slug) at a rate of one ft/sec^2, how are the units related?

   Solution: The units are related as

$$1\,\text{N} = 1\,\text{kg·m/s}^2 \qquad \text{or} \qquad 1\,\text{lbf} = 32.2\,\text{lbm-ft/sec}^2$$

Table 1-2

Multiplication Factor	Prefix	Symbol
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{-2}	centi*	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p

*Discouraged except in cm, cm^2, or cm^3.

EXAMPLE 1.3 *Weight* is the force of gravity; by Newton's second law, $W = mg$. How does weight change with elevation?

Solution: Since mass remains constant, the variation of W with elevation is due to changes in the acceleration of gravity g (from about 9.77 m/s^2 on the highest mountain to 9.83 m/s^2 in the deepest ocean trench). We will use the standard value 9.81 m/s^2 (32.2 ft/sec^2), unless otherwise stated.

EXAMPLE 1.4 Express the energy unit J (joule) in terms of SI base units: mass, length, and time.

Solution: Recall that energy or work is force times distance. Hence, by Example 1.2, the energy unit J (joule) is

$$1\,J = (1\,N)(1\,m) = (1\,kg\cdot m/s^2)(1\,m) = 1\,kg\cdot m^2/s^2$$

In the English system both the lbf and the lbm are base units. As indicated in Table 1-1, the primary energy unit is the ft-lbf. By Example 1.2,

$$1\,ft\text{-}lbf = 32.2\,lbm\text{-}ft^2/sec^2 = 1\,slug\text{-}ft^2/sec^2$$

analogous to the SI relation found above.

1.7 DENSITY, SPECIFIC VOLUME, SPECIFIC WEIGHT

By (*1.1*), density is mass per unit volume; by (*1.3*), specific volume is volume per unit mass. Therefore,

$$v = \frac{1}{\rho} \tag{1.4}$$

Associated with (mass) density is *weight density* or *specific weight w*:

$$w = \frac{W}{V} \tag{1.5}$$

with units N/m^3(lbf/ft^3). [Note that w is volume-specific, not mass-specific.] Specific weight is related to density through $W = mg$ as follows:

$$w = \rho g \tag{1.6}$$