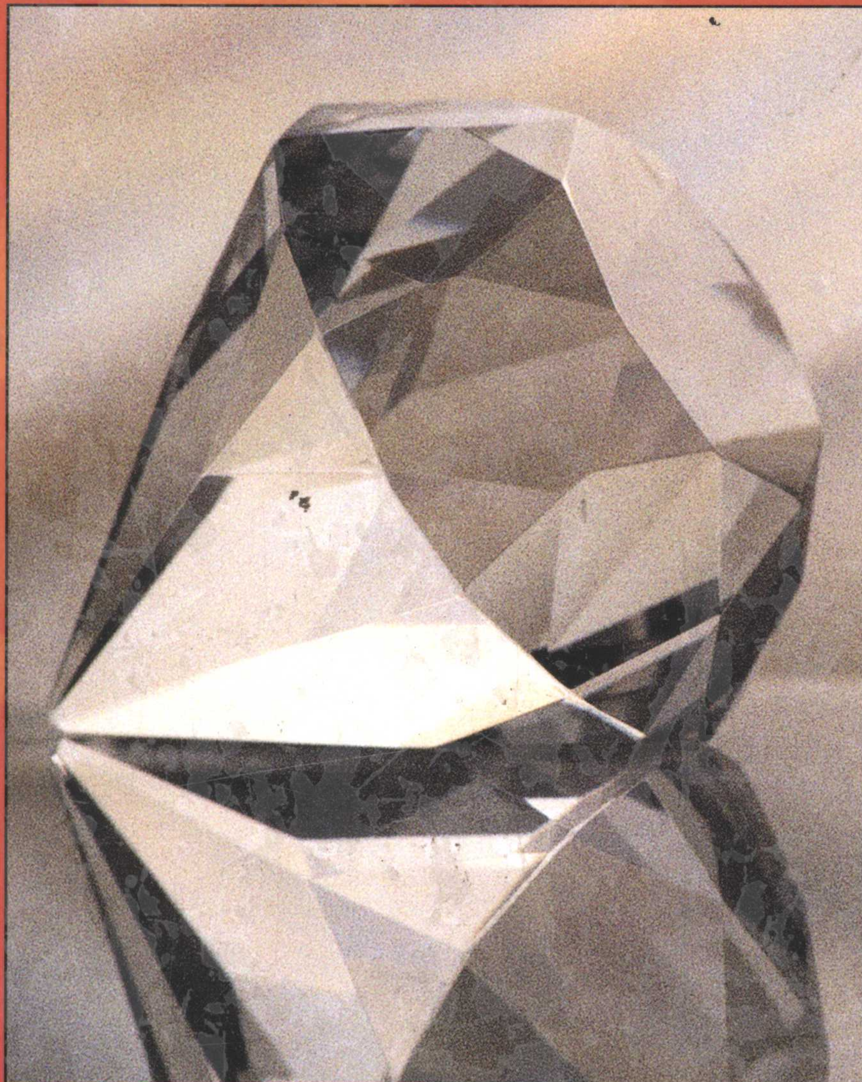
SONNTAG • BORGNAKKE • VAN WYLEN



FUNDAMENTALS of Thermodynamics

Sixth Edition

FUNDAMENTALS OF THERMODYNAMICS

SIXTH EDITION

RICHARD E. SONNTAG
CLAUS BORGNAKKE
University of Michigan

GORDON J. VAN WYLEN
Hope College (emeritus)

JOHN WILEY & SONS, INC.

Acquisitions Editor	Joseph Hayton
Production Editor	Sandra Russell
Marketing Manager	Katherine Hepburn
Senior Designer	Dawn L. Stanley
Production Management Services	UG / GGS Information Services, Inc.
Cover Photo	© Judy Dole/The Image Bank

This book was typeset in 10/12 Times New Roman By UG / GGS Information Services, Inc. and printed and bound by R. R. Donnelley and Sons (Willard). The cover was printed by Phoenix Color Corp.

The paper in this book was manufactured by a mill whose forest management programs include sustained yield harvesting of its timberlands. Sustained yield harvesting principles ensure that the number of trees cut each year does not exceed the amount of new growth.

This book is printed on acid-free paper.

Richard E. Sonntag, Claus Borgnakke, and Gordon J. Van Wylen
Fundamentals of Thermodynamics, sixth edition

ISBN 0-471-15232-3

Printed in the United States of America.

10 9 8 7 6 5 4 3 2

Fundamental Physical Constants

Avogadro	$N_0 = 6.022\ 136 \times 10^{23}$ l/mol
Boltzmann	$k = 1.380\ 658 \times 10^{-23}$ J/K
Planck	$h = 6.626\ 076 \times 10^{-34}$ Js
Gas Constant	$\bar{R} = N_0 k = 8.314\ 51$ J/mol K
Atomic Mass Unit	$m_0 = 1.660\ 540 \times 10^{-27}$ kg
Velocity of light	$c = 2.997\ 925 \times 10^{8}$ m/s
Electron Charge	$e = 1.602\ 177 \times 10^{-19}$ C
Electron Mass	$m_e = 9.109\ 389 \times 10^{-31}$ kg
Proton Mass	$m_p = 1.672\ 623 \times 10^{-27}$ kg
Gravitation (Std.)	$g = 9.806\ 65\ m/s^2$
Stefan Boltzmann	$\sigma = 5.670\ 51 \times 10^{-8}\ W/m^2\ K^4$

Prefixes

10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
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

FUNDAMENTALS OF THERMODYNAMICS

SIXTH EDITION

PREFACE

In this sixth 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

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.

Study Guide Problems

We have made a 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 2,400. 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 the specific internal energy in the superheated vapor region. 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, then the compressibility factor and equations of state. 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. Coverage of ideal gas and ideal gas mixtures focuses on unit mass basis, instead of mole basis, and is simpler. Development of availability and reversible work in Chapter 10 focuses on the steady-state process, and leads to the general expression for exergy. We have therefore included a new section on the general exergy balance to amplify the concept of transport and destruction of exergy. The chapter with property relations is slightly reorganized and streamlined to also focus on properties on a mass basis. Due to current technology developments we have expanded our discussion of the fuel cells and also updated the chapter with combustion.

Expanded Software Included

In this edition we have included the expanded software CATT2 that includes a number of additional substances besides those included in the printed tables in Appendix B. A number of hydrocarbon fuels, refrigerants, and cryogenic fluids are included and a printed version is available in the booklet *Thermodynamic and Transport Properties*, Claus Borgnakke and Richard E. Sonntag, John Wiley & Sons, Inc. (1997).

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.

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 a companion website at **www.wiley.com/college/sonntag**. Tutorials and reviews of all the basic material as indicated in the main text by the ThermoNet icon are accessible through the companion website. The website 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.

The chapter on compressible flow is also available at **www.wiley.com/college/sonntag** and revised with summary, study guide problems, and new homework problems. We recognize that in many cases this chapter is not included in the thermodynamics courses, but may instead be covered elsewhere in the curriculum.

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 companion website at **www.wiley.com/college/sonntag** for information and suggestions on possible course structure and schedules, additional study problem material, and current errata for the book.

ACKNOWLEDGMENTS

We acknowledge with appreciation the suggestions, counsel, and encouragement of many colleagues, both at the University of Michigan and elsewhere. This assistance has been very helpful to us during the writing of this edition, as it was with the earlier editions of the book. Both undergraduate and graduate students have been of particular assistance, for their perceptive questions have often caused us to rewrite or rethink a given portion of the text, or to try to develop a better way of presenting the material in order to anticipate such questions or difficulties. Finally, for each of us, the encouragement and patience of our wives and families have been indispensable and have made this time of writing pleasant and enjoyable, in spite of the pressures of the project. A special thanks to a number of colleagues at other institutions, who have reviewed the book and provided input to the revisions. Some of the reviewers are

Edward E. Anderson, Texas Tech University
Haim H. Bau, University of Pennsylvania
Pei-Feng Hsu, Florida Institute of Technology
Gerald J. Micklow, University of Alabama
Jayathi Y. Murthy, Carnegie Mellon University
Anthony J. Wheeler, San Francisco State University

We also wish to thank our editor, Joseph Hayton, for his effort in the planning and the support and encouragement 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.

RICHARD E. SONNTAG
CLAUS BORGNAKKE
GORDON J. VAN WYLEN
Ann Arbor, Michigan
April 2002

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
e, E	specific energy and total energy
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
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 weight
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	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_{gen}	entropy generation
$\dot{S}_{gen}$	rate of entropy generation
t	time
T	temperature
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^{rev}	reversible work between two states
x	quality
y	gas-phase mole fraction
Z	elevation
Z	compressibility factor
Z	electrical charge

SCRIPT LETTERS

$\mathscr{E}$	electrical potential
$\mathscr{S}$	surface tension
$\mathscr{T}$	tension

GREEK LETTERS

α	residual volume
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
η	efficiency
μ	chemical potential
ν	stoichiometric coefficient
ρ	density
Φ	equivalence ratio
ϕ	relative humidity
ϕ, Φ	exergy or availability for a control mass
ψ	flow availability
ω	humidity ratio or specific humidity
ω	a centric 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
rev	reversible

FUNDAMENTALS OF THERMODYNAMICS

SIXTH EDITION

CONTENTS