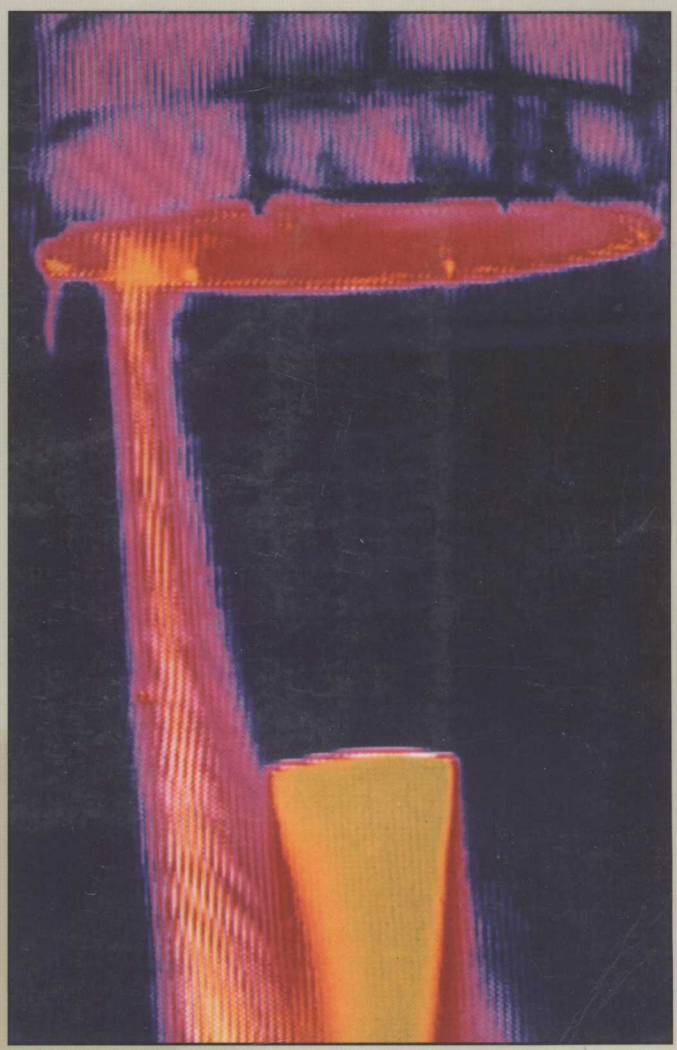
Introduction to
ENGINEERING THERMODYNAMICS

Second Edition



Richard E. Sonntag • Claus Borgnakke

INTRODUCTION TO ENGINEERING THERMODYNAMICS

SECOND EDITION

附 光 盘

RICHARD E. SONNTAG
University of Michigan
Mechanical Engineering

CLAUS BORGNAKKE
University of Michigan
Mechanical Engineering

JOHN WILEY & SONS, INC

ASSOCIATE PUBLISHER Daniel Sayre
ACQUISITIONS EDITOR Joseph Hayton
SENIOR PRODUCTION EDITOR Valerie A. Vargas
MARKETING MANAGER Phyllis Cerys
SENIOR DESIGNER Kevin Murphy
COVER DESIGN David Levy
COVER AND CHAPTER OPENING PHOTOS courtesy of NASA: Left cover image and opener photo (engine test fire) Space Shuttle Main Engine Test Firing, Stennis Space Center, NASA; Right cover image (thermal image) Thermal Image Test of Space Shuttle Main Engine, Stennis Space Center, NASA
EDITORIAL ASSISTANT Mary Moran-McGee
MEDIA EDITOR Stefanie Liebman
PRODUCTION SERVICES mb editorial services

This book was set in "TimesNewRomanPS 10/12" by TechBooks/GTS Companies, York, PA and printed and bound by R.R. Donnelley. The cover was printed by Phoenix Color, Inc.

This book is printed on acid free paper. ♾

ISBN-13 978-0-471-73759-9
ISBN-10 0-471-73759-3

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

INTRODUCTION TO ENGINEERING THERMODYNAMICS

Preface

This book was originally written as a text for two different courses: a one-semester introductory course in engineering thermodynamics for both majors and non-majors; and also, the first course in an introductory sequence in engineering thermal-fluid sciences. This book has also been written to cover a broad range of background, interests, and applications as well as to provide a great deal of flexibility in terms of topics covered and units. In the second edition, we have broadened the coverage somewhat to accommodate a second course for mechanical engineering majors, primarily by inclusion of a chapter on chemical reactions. This chapter focuses on combustion processes, with an introduction to chemical equilibrium.

As in our earlier thermodynamics books, we have deliberately directed our presentation to students. New concepts and definitions are presented in the context where they are first relevant. 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, and entropy with the second law. Many more examples have been included in the second edition 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.

This book is based on our most recent textbook, *Fundaments of Thermodynamics, Sixth Edition,* Richard E. Sonntag, Claus Borgnakke, and Gordon J. Van Wylen, John Wiley & Sons, Inc. (2003). The present book, however, is written at a somewhat lower level, including the chapter-end problems, is directed at a broader audience, and is specifically intended for the multipurpose use mentioned above.

New Features in the Second Edition

New Chapter on Chemical Reactions

A new chapter on chemical reactions, focused on fuels and combustion processes, and including an introduction to chemical equilibrium, has been included especially for a second-semester course.

Revised Coverage of Heat Transfer

The chapter on heat transfer has been rewritten to decrease coverage on conduction, and to emphasize applications involving the cooling of electronic equipment. This material is intended for use in a single course offered to non-majors, or as part of a first course in engineering thermal-fluid sciences.

Inclusion of End-of-Chapter Material from *Fundamentals, Sixth Edition*

End-of-chapter material from the authors' *Fundamentals, Sixth Edition* has been revised and included in this edition: Chapter Summaries; Key Concepts and formulas; and Concept Problems. All this material has been found to be beneficial to and appreciated by the students in their understanding of the subject.

Chapter In-Text Concept Questions and How-To Sections

Groups of In-Text Concept Questions have been included in all chapters having introductory material, to direct basic points and procedures to the students. Also, How-To Sections are included at the end of the chapters to help answer commonly asked questions.

Chapter Examples, Illustrations, and Homework Problems

The number of chapter examples, illustrations, and homework problems have all been expanded and revised; a large number of new problems are included, especially introductory-level problems.

Reorganization of Entropy and Second Law Presentation

A significant change in this edition is the reorganization of material in Chapter 8, Entropy. Following the introduction of the property entropy, its relevance in reversible processes, and the thermodynamic property relation, we now discuss its calculation for various thermodynamic models and its use in certain thermodynamic processes. Then the significance and behavior of entropy in irreversible processes is considered, including a revised development of entropy generation and the general statement of the second law of thermodynamics.

Other New or Revised Material and Developments

There are a number of new or revised developments: separate section on compressibility factor and equations of state in Chapter 3; new section on thermodynamic temperature scale and comparison with ideal-gas scale in Chapter 7; new development of steady-state single flow process in Chapter 9; new development of reversible work and irreversibility in Chapter 9; new section on entropy and chaos in Chapter 9; streamlined discussion of Rankine cycle variables in Chapter 11; new section of reciprocating engine power cycles in Chapter 11.

Expanded Software Included

In this edition we have included the expanded software *Tables of Thermodynamic and Transport Properties* (expanded CATT2) that includes many additional substances besides those included in the printed tables in Appendices B and F. A number of hydrocarbon fuels, refrigerants, and cryogenic fluids are included. The software is available as a download from the student companion site (www.wiley.com/college/sonntag) by using the registration card enclosed in the text. A printed version is available in the book *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 introductory subject matter of engineering 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. We recognize that a number of schools offer a single introductory course in thermodynamics or engineering thermal-fluid sciences for a number of programs, and have tried to cover those topics that the different programs might wish to have included. Recognizing that specific courses vary considerably in background of the students, prerequisites, and level of course introduction, we have arranged the text material, particularly in the later chapters, so that there is considerable flexibility in the amount of material that may be included and also in the order of coverage.

Units

This edition has been organized so that the course or sequence can be taught entirely in SI units (Le Systeme International d'Unites). Thus, all the text examples, complete problem sets, and thermodynamics tables are given in SI units. In recognition of the continuing need for engineering graduates to be familiar with the corresponding Engineering English units, we have included an Appendix that includes an introduction to this system, examples, problems, and several thermodynamics tables, so that this material can be introduced at the appropriate times in the course(s) as desired. When dealing with English units, the force-mass conversion between pound force and pound mass is treated simply as a units conversion, without using an explicit conversion constant. Throughout the text, symbols, units, and sign conversions are all treated as in our previous books.

Supplements and Additional Support

Additional support is available through a companion website at www.wiley.com/college/sonntag. Instructors may want to visit the Web site 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. In particular, we acknowledge the background and roots of this book lying in our earlier efforts with our colleague and co-author Gordon J. Van Wylen and his important contributions to those projects over the years. We also appreciate the contributions and suggestions of many of our former students, who have also been of particular assistance in a number of areas. The comments and suggestions of the several reviewers of an early version of the manuscript were important to us in rethinking the organization and content of the book. We also appreciate the efforts of our editor at John Wiley, Joseph Hayton in the production of this edition. Finally, for each of us, the encouragement and patience of our wives and families have been indispensable, and have made this an enjoyable undertaking.

We hope that this book will contribute to the effective teaching of thermodynamics to students who face significant challenges and opportunities during their professional careers. Your comments, criticism, and suggestions will also be appreciated.

RICHARD E. SONNTAG rsonntag@umich.edu
CLAUS BORGNAKKE claus@umich.edu
Ann Arbor, Michigan
August, 2005

Symbols

a	acceleration
A	area
AF	air-fuel ratio
c	mass fraction
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
h	convection heat transfer coefficient
i	electrical current
I	irreversibility
k	conductivity
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
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
Pr	Prandtl number
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
R	thermal resistance
Re	Reynolds number

s, S	specific entropy and total entropy
S_{gen}	entropy generation
$\dot{S}_{\text{gen}}$	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	temperature coefficient
β	coefficient of performance for a refrigerator
β'	coefficient of performance for a heat pump
η	efficiency
θ	temperature variable
μ	absolute viscosity
ν	stoichiometric coefficient
ν	kinematic viscosity
ρ	density
Φ	equivalence ratio
ϕ	relative humidity
ψ	flow availability or exergy
ω	humidity ratio or specific humidity
ω	acentric factor

SUBSCRIPTS

c	property at the critical point
c	cross-sectional
cond	conduction
conv	convection

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
s	surface value
0	property of the surroundings free stream value

SUPERSCRIPTS

¯	bar over symbol denotes property on a molal basis
°	property at standard-state condition
rev	reversible
′	property per unit length
″	property per unit area
‴	property per unit volume

Contents

Brief Contents