GLOBAL EDITION

Borgnakke's FUNDAMENTALS OF THERMODYNAMICS

SI VERSION

CLAUS BORGNAKKE
RICHARD E. SONNTAG

WILEY

Borgnakke's
FUNDAMENTALS OF THERMODYNAMICS

Borgnakke's Fundamentals of Thermodynamics continues to offer a comprehensive and rigorous treatment of classical thermodynamics, while retaining an engineering perspective. With concise, applications-oriented discussion of topics and self-test problems, this text encourages students to monitor their own learning. This classic text provides a solid foundation for subsequent studies in fields such as fluid mechanics, heat transfer and statistical thermodynamics, and prepares students to effectively apply thermodynamics in the practice of engineering.

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Preface

In this Global 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 IN THIS EDITION

Chapter Reorganization and Revisions

The majority of the changes for the Global 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. 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.

Chapter 1 still contains the most important concepts from physics and the concepts of thermodynamic properties that describe the condition of the substance included in the analysis. To have the tools for the analysis, the order of the presentation has been maintained, 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 it is still available from Wiley's website 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 used in modern societies. Together with the mention 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 process 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 deal with analysis of processes and devices which relate to this and include a special section of the homework problems where appropriate. 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 and 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 require 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 volume is retained from the previous edition that includes 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 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 includes all of 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 applying the energy and entropy equations to heat engines and heat pumps. This demonstrates 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 improve the students understanding of the material.

The application section in Chapter 7 has been expanded somewhat to include descriptions 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 section has about 30 homework 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 to reduce the mathematical manipulation of the equations and a small application section with the second law efficiency for cycles has been added. This section illustrates 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 in to industrial applications with real systems. The same is done for Chapter 13 with combustion to emphasize an understanding of the basic physics of what happens, which may not be so evident in the more abstract definition terms like enthalpy of combustion.

The property relations in Chapter 12 has been updated to include effects of dilution, 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 includes the Helmholtz function based development.

Web-Based Material

Several documents will be available from Wiley's website for the book. The following material will be accessible for students, with additional material reserved for instructors of the course.

A Note for Fundamentals of 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, and so on. It also covers a short step by step procedure to formulate a thermodynamic problem. This is useful for students doing review of the course or for exam preparation, as it gives a comprehensive presentation in a condensed form.

Extended set of study examples. This document includes a updated collection of additional examples for students to study. These examples have slightly longer and more detailed solutions than the examples printed in the book and thus are excellent for self-study.

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 accommodate in the book. Examples:

How do 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 the ideal gas law?

Instructor material. A complete set of PowerPoint lecture presentations. These also include repeat copies of most book examples with specific heat redone with the ideal gas tables and vice versa. The material for instructors covers typical syllabus and homework assignments for a first and a second course in thermodynamics. Additionally, examples of two standard 1-hour midterm exam, and a 2-hour final exam are given for typical Thermodynamics I and Thermodynamics II classes.

FEATURES

In-Text-Concept Questions

The in-text concept questions appear in the text after major sections of material to allow students to reflect on the material just presented. These questions are intended to be quick self-tests for students or used by teachers as wrap-up checks for each of the subjects covered, and most of them emphasize the understanding of the material without being memory facts.

End-of-Chapter Engineering Applications

The last section in each chapter, called "Engineering Applications", has been revised with updated illustrations and a few more examples. These sections are intended to be motivating material, consisting mostly of informative examples of how this particular chapter material is being used in actual engineering. Many of these sections contains limited material with equations or developments of theory, but focus on figures and explanations of a few real physical systems where the chapter material is relevant for the engineering analysis and design. These sections are deliberately kept short and not all the details in the devices shown are explained, but the reader can get an idea about the applications relatively quickly.

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. To further enhance the summary, a list of skills that the student should have mastered after studying the chapter is presented. Main concepts and formulas are included after the summary for reference, and a collection of these will be available on Wiley's website. The main summary of the general control volume analysis has been removed from Chapter 7 and placed 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 like homework problems with numbers to provide a quick check of the chapter material. These questions are short and directed toward very specific concepts. Students 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 for use with the rest of the homework problems in assignments and are included in the solution manual.

Homework Problems

The number of homework problems has been reduced with many new and modified problems. A large number of introductory problems cover all aspects of the chapter material and are listed according to the subject sections for easy selection according to the particular coverage given. They are generally ordered to be progressively more complex and involved. The later problems in many sections are related to real industrial processes and devices, and labeled 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.

Tables

The tables of the substances have been carried over from the previous 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.

Software Included

The software **CATT3** includes a number of additional substances besides those included in the printed tables in Appendix B. The current set of substances for which the software can provide the complete tables are:

Water Refrigerants:	R-11, 12, 13, 14, 21, 22, 23, 113, 114, 123, 134a, 152a, 404a, 407c, 410A, 500, 502, 507a, and C318
Cryogenics:	Ammonia, argon, ethane, ethylene, isobutane, methane, neon, nitrogen, oxygen, and propane
Ideal Gases:	air, CO_2, CO, N, N_2, NO, NO_2, H, H_2, H_2O, O, O_2, and OH

Besides the properties of the substances just mentioned, the software can provide the psychrometric chart and the compressibility and generalized charts using the Lee-Kesler's equation-of-state including an extension for increased accuracy with the acentric factor. The software can also plot a limited number of processes in the *T*–*s* and log *P*–log *v* diagrams, giving the real process curves instead of the sketches presented in the text material.

FLEXIBILITY IN COVERAGE AND SCOPE

The book attempts to cover fairly comprehensively the basic subject matter of classical thermodynamics, and I believe that it 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 I 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/college/borgnakke for information and suggestions on possible course structure and schedules, and the additional material mentioned as Web material that will be updated to include current errata for the book.

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the book. Both undergraduate and graduate students have been of particular assistance, for their perceptive questions have often caused me 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, the encouragement and patience of my wife and family 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 earlier editions of the book and provided input to the revisions. Some of the reviewers are

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I also wish to welcome the new editor, Chris Nelson, and thank him for his encouragement and help during the production of this edition.

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
September 2016

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	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}	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	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)
$^\circ$	property at standard-state condition
*	ideal gas
*	property at the throat of a nozzle
irr	irreversible
r	real gas part
rev	reversible

Contents