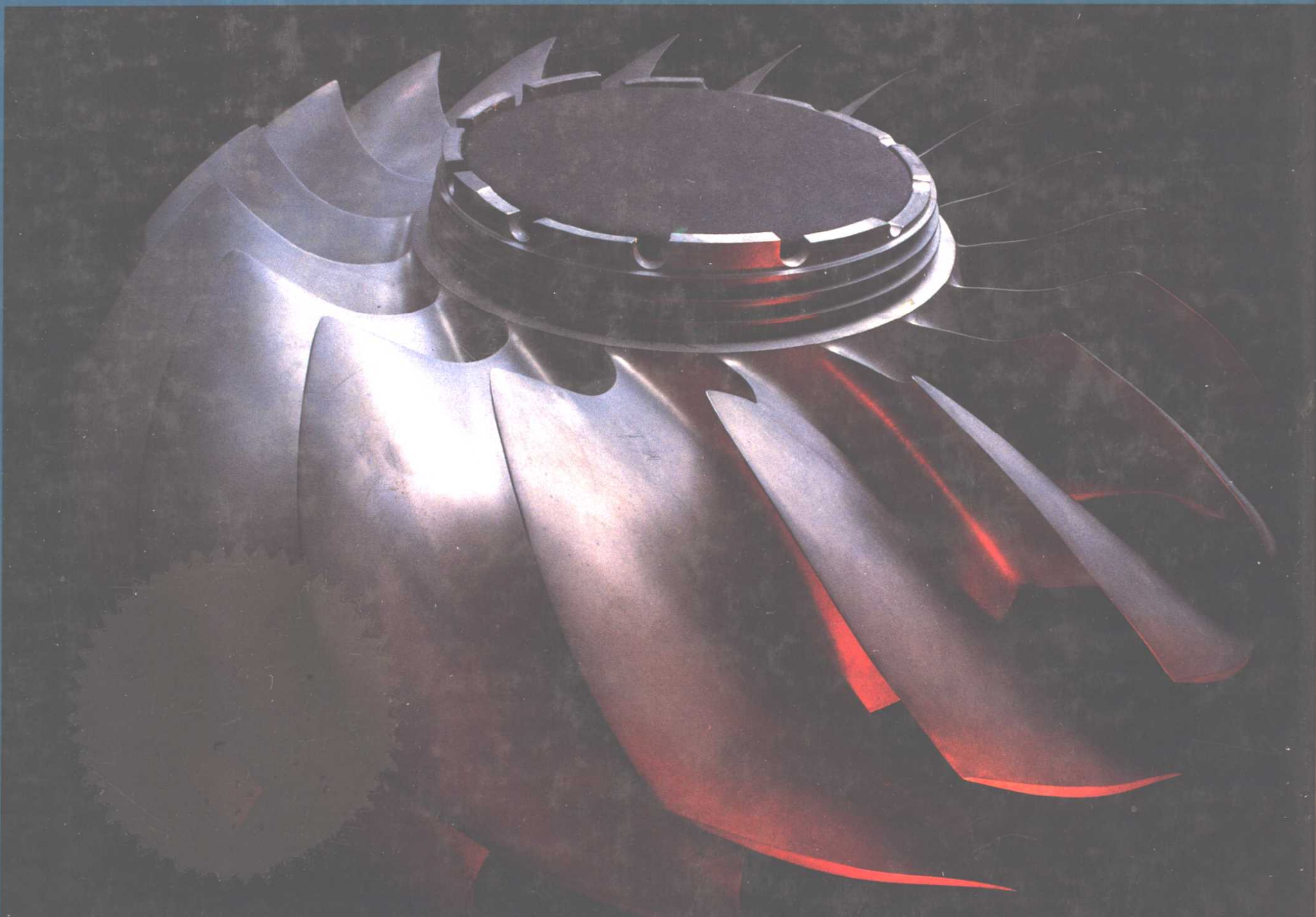
Second Edition

Fundamentals of Engineering Thermodynamics

John R. Howell • Richard O. Buckius



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Fundamentals of Engineering Thermodynamics

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About the Authors

John R. Howell received his B.S. (1958), M.S. (1960), and Ph.D. (1962) in chemical engineering from Case Institute of Technology (now Case Western Reserve University) in Cleveland, Ohio. He worked at the NASA Lewis Research Center in Cleveland on fundamental heat transfer research until 1968, when he joined the Department of mechanical Engineering at the University of Houston, Texas. He joined the Department of Mechanical Engineering at the University of Texas at Austin in 1978, where he is presently Baker-Hughes Professor and has served as Chairman and Director of the Center for Energy Studies.

Dr. Howell has published widely in various areas of heat transfer, including more than 130 technical papers and reports as well as text and reference books. He was awarded the Ralph Coats Roe award as outstanding teacher of mechanical engineering in 1987 by the American Society of Engineering Education, and he received the Thermophysics Award of the American Institute of Aeronautics and Astronautics in 1990. He is a Fellow of ASME.

Richard O. Buckius received his B.S (1972), M.S. (1973), and Ph.D. (1975) in mechanical engineering from the University of California, Berkeley. He then joined the Department of Mechanical and Industrial Engineering at the University of Illinois at Urbana-Champaign as an assistant professor. He has been the associate head of the department, program director with the National Science Foundation, and Associate Vice Chancellor for Research.

Dr. Buckius has published numerous technical articles in the areas of heat transfer and combustion. He has received various teaching awards, including the Campus Award for Excellence in Undergraduate Teaching from the University of Illinois and the Western Electric Fund Award from the American Society for Engineering Education. He is a Fellow of ASME.

Preface to the Second Edition

The attributes of the first edition of this work have been maintained and expanded, particularly the use of worked examples, two-color format to distinguish processes from properties on diagrams and to enhance the perception of availability on equipment diagrams, and the use of contemporary equipment and systems to illustrate the applications of this fascinating subject. As with any work of this kind, however, we have seen ways to improve the usefulness of the text, and we believe that this edition contains some significant improvements for both students and instructors.

A major change has been to convert to the traditional sign convention used in the engineering community that work produced by a system is positive. There are certainly strong arguments for the use of either the positive or the negative sign, or for a system of choice depending on analysis of a particular problem. We have chosen to go with the conventional system based on an overwhelming response by the community.

The continuing and probably never-ending debate on how best to introduce students to the second law of thermodynamics is reflected in our treatment in Chap. 5. We believe that the treatment based on a logical interpretation of commonly observed phenomena as presented in the first edition is an effective method, and we urge others to try it. We still present that method as the primary thrust in this edition, but we also provide a section on the traditional derivation of entropy based on the Carnot cycle for those who believe this to be a more effective presentation.

The number and scope of the homework problems have been enhanced in this edition by the addition of over 500 problems. We wish to acknowledge the United States Military Academy for providing many of these from their storehouse of auxiliary teaching materials.

To aid both instructor and student in having a choice of material, many new and expanded applications sections have been included. Particularly applications to multistage turbines and compressors, nozzles, and other components are treated. The chapter on cycles in the first edition was greatly expanded and split into two chapters that deal with gas cycles and vapor cycles, respectively. This allowed material on internal combustion engines to be expanded to include the concept of mean effective pressure, much more coverage of variable-property effects, and the addition of other gas cycles. In the vapor cycle chapter, additional material on the Kalina cycle and on cogeneration and combined cycle plants is included.

The chapter on second law analysis was revised to include discussions and definitions of the second law efficiency of devices and processes. In the coverage of combustion, a section on combustion chemistry was added. Updated and enhanced material on mixing, chemical reactions, and psychrometry was included.

In the tabular material, the steam tables were revised and all tables, problems, and the computerized tables in this edition are based on the NIST/NRC standard tables, which the authors believe to be the most accurate available. The computerized tables for steam were completely reprogrammed to provide a more useful tool than was available in the first edition.

Because many users of the text do not carry out a review of the mathematical concepts pertinent to thermodynamics, but wish to refer to these concepts as needed throughout the course, the material on mathematical concepts has been removed from Chap. 1 and placed in an appendix for easy reference. Those who wish to use this material as a review will find homework problems at the end of App. H.

Many additional changes, both substantive and cosmetic, have been made. Many of these, such as retaining running titles on multipage property tables, were made to aid in reducing errors or increasing understanding and will not be obvious to the casual user.

We again wish to thank our families for putting up with evening and weekend sessions used in preparing this edition. They make the work worthwhile.

McGraw-Hill and the authors would like to thank the following reviewers for their many helpful comments and suggestions: Nasser Ashgriz, State University of New York, Buffalo; Louis Bermeister, University of Kansas; Sushel Bhavanani, Auburn University; J.C. Cantrell, United States Military Academy, John Francis, University of Oklahoma; Sang Lu Han, Tennessee Technological University; Jai Krishna Kadambi, Case Western Reserve University; Thomas Litzinger, Pennsylvania State University; Jack Lloyd, Michigan State University; David Miller, Drexel University; G.P. Peterson, Texas A&M University; Harold Shock, Michigan State University; and Vijay Varadan, Pennsylvania State University.

John R. Howell
Richard O. Buckius

Preface to the First Edition

This text provides an introduction to engineering thermodynamics from the so-called classical approach. The organization follows a logical sequence which is considerably different from the historical development of thermodynamics. However, we proceed in a manner that allows the student to build an understanding of the fundamentals and applications, proceeding from simple but useful relations and applications from simple substances to the necessarily more complex relations for mixtures and materials with chemical reactions.

We have included many fully worked examples to illustrate the application of the theory presented in the text, and we have found these very helpful to the student. In these examples, we have followed the problem-solving methodology presented in Chaps. 1, 4, and 6. This methodology emphasizes the careful structuring of the problem, the use of property diagrams to visualize the processes involved, and the use of state tables for defining the process end states. These allow the student to see exactly what information is given and what must be generated through use of themodynamic relations. Such an approach can help the student to see to the heart of the problems posed and to develop orderly solution procedures.

Because of the availability of computerized property data for microcomputers, a wide range of problems can be treated by students that were not feasible for an earlier generation. We have provided a mix of problems; most can be solved by "hand" calculation, and others require so much interpolation from tabular data that only the use of computerized tables makes complete solution feasible. These problems have been flagged in the problems sections so that the instructor will not inadvertently assign them. We believe that the "hand" problems, making use of tabular data where necessary, are required to help the student gain the necessary insight into thermodynamics. The problems requiring computerized data generally show the behavior of a particular control mass or device under parametric variations of conditions; such problems also can provide great insight but have often been ignored in introductory texts because of the time formerly involved in solution. However, care must be taken to help the student develop the ability to critically examine what the computer is providing, so that erroneous computer results will not be blindly accepted and used.

The computerized tables available with this text cover the range of properties encompassed by the problems and are discussed in some detail in App. G.

At the beginning of each chapter are photographs, cutaways, and diagrams of the equipment analyzed in the text. These are included because many students entering the engineering curriculum have not seen such equipment and have little concept of its scale and complexity. These pictures give some idea of what lies within the blocks shown on the cycle diagrams in the body of the text.

Two versions of this text are available—this one, which contains both SI and U.S. conventional (USCS) systems of units, and one that is solely in SI.

Although the presentation in the first 11 chapters is generally from the classical viewpoint (with some microscopic interpretations where they appear helpful), Chap. 12 deals with the statistical interpretation of thermodynamics. It is organized so that a more detailed statistical viewpoint can be introduced along with the classical material if the instructor desires. Alternatively, Chap. 12 can be used to review the classical relations from another viewpoint following completion of the first 11 chapters. In any case, the statistical treatment is presented as an aid to understanding how properties can be computed from a fundamental understanding of structure; the interpretation of entropy in terms of uncertainty; the ideas of the increase of the entropy of the universe from the microscopic viewpoint; and a microscopic interpretation of the first and second laws of thermodynamics. No attempt is made to provide a complete treatment of statistical thermodynamics.

Finally, we have observed that thermodynamics is often the first course in which mathematical concepts from courses in partial differential equations are applied to engineering problems. We have tried to aid in the transition from abstract concepts to concrete applications with a section in Chap. 1 on the mathematics needed in this course. Some instructors may wish to omit this section, using it for reference as required.

We are indebted to our colleagues at the University of Texas at Austin and the University of Illinois at Urbana-Champaign. Their comments, criticisms, and suggestions have helped us improve this final product. We are also indebted to the academic reviewers listed on page ii of the first edition. We acknowledge the efforts of Kumbae Lee and Larry Lister for their detailed review of the problems and text. We are also grateful for the excellent typing of the entire manuscript and revisions by Angela Ehrsam.

We now understand the reason that authors invariably thank their families for their encouragement and support. Their contributions is a very real one. We are very grateful to Susan and Kathy, who have endured

many periods of doubt and second thoughts about this project with great grace and understanding. And we are very grateful to our children. Reid, Keli, and David, who have passed to adulthood, and Sarah and Emily, who have passed through their preschool years, during this writing.

John R. Howell
Richard O. Buckius

Nomenclature

a	activity, specific Helmholtz function, acceleration
A	Helmholtz function, area
AFR	air-fuel ratio
c_P	specific heat at constant pressure
c_P^*	temperature mean specific heat at constant pressure
c_P^*, LM	temperature log mean specific heat at constant pressure
c_v	specific heat at constant volume
c_v^*	temperature mean specific heat at constant volume
$c_{v,LM}^*$	temperature log mean specific heat at constant volume
COP	coefficient of performance
d	distance
e	specific energy
E	energy, Young's modulus
E	electric potential
f	fugacity
f^*	ideal solution fugacity
F	vector force
F	force
F	generalized force
FAR	fuel-air ratio
g	acceleration due to gravity, specific Gibbs function, degeneracy
g_c	constant that relates force, mass, length, and time in USCS units
G	Gibbs function
h	specific enthalpy, Planck's constant
H	enthalpy
i	electric current, specific irreversibility
I	irreversibility
k	specific heat ratio c_P/c_v, rate constant, Boltzmann constant
k_s	spring constant
K	equilibrium constant
KE	kinetic energy
L	length
m	mass
$\dot{m}$	mass rate of flow
M	molecular weight
n	number of moles, polytropic exponent

N	number
N_a	Avogadro's number
N_p	number of particles
P	pressure
P_i	partial pressure of component i
PE	potential energy
q	heat transfer per unit mass
Q	heat transfer
$\mathbf{Q}$	charge
$\dot{Q}$	rate of heat transfer
R	particular gas constant
$\overline{R}$	universal gas constant
$\mathbf{s}$	displacement
s	specific entropy
S	entropy
S_{gen}	entropy generation
t	time
T	temperature
u	specific internal energy
U	internal energy
v	specific volume
V	volume
$\mathbf{V}$	velocity
$\mathbf{V}$	speed
$\mathbf{V}_{ref}$	speed with reference to surroundings
w	work per unit mass
W	work
$\dot{W}$	rate of work, or power
W_{rev}	reversible work between two states
x	quality, mass fraction
$\mathbf{X}$	generalized displacement
y	mole fraction
z	compressibility factor
Z	elevation, partition function

Greek Letters

α	residual volume, extent of reaction
β	coefficient of thermal expansion
ε	strain, particle energy
η	efficiency
θ	angle between surface normal and direction of vector
κ	isothermal compressibility
μ	chemical potential, Joule-Thomson coefficient, degree of saturation
υ	stoichiometric coefficient
ρ	density

σ	stress, surface tension
τ	sheer stress
ϕ	nonflow availability per unit mass, relative humidity
Φ	nonflow availability
ψ	flow availability per unit mass, wave function
Ψ	flow availability
ω	humidity ratio, acentric factor

Subscripts

a	actual, air
comb	combustion
c	components, compressor
C	carnot
cr	critical point
CM	control mass
CV	control volume
d	dew point
f	formation, fuel
g	property of saturated vapor
H	high-temperature source
in	state of a substance entering a control volume
i	component
irr	irreversible
j	phase
L	low-temperature source
l	property of saturated liquid
lg	difference in property for saturated vapor and saturated liquid
out	state of a substance leaving a control volume
p	product
ph	phases
pr	properties
r	reduced property, reactant
ref	with surroundings as reference
rev	reversible
s	isentropic process
v	vapor
0	property of the surroundings, zero pressure

Superscripts

$\bar{}$	bar over symbol denotes property on a molal basis, partial molal property
$\circ$	property at standard reference state
$\cdot$	dot over symbol denotes rate

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