J. B. JONES / G. A. HAWKINS

ENGINEERING THERMODYNAMICS

AN INTRODUCTORY TEXTBOOK

SECOND EDITION

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Engineering Thermodynamics

AN INTRODUCTORY TEXTBOOK

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John Wiley & Sons, Inc.

New York Chichester Brisbane Toronto Singapore

Library of Congress Cataloging in Publication Data:

Jones, J. B. (James Beverly)
Engineering thermodynamics.

Includes indexes.
1. Thermodynamics. I. Hawkins, George A. (George Andrew), 1907– II. Title.
TJ265.J64 1986 621.402′1 85-17821
ISBN 0-471-81202-1

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

CONVERSION FACTORS

LENGTH

1 ft = 0.3048* m
1 in. = 0.0254* m
1 mi = 5280 ft
1 m = 3.281 ft
1 cm = 0.3937 in.
1 km = 0.6214 mi

AREA

1 ft^2 = 0.0929 m^2
1 $in.^2$ = 645.16 mm^2
1 m^2 = 10.76 ft^2
1 cm^2 = 0.1550 $in.^2$

VOLUME

1 ft^3 = 0.028 317 m^3
1 $in.^3$ = 1.639×10^{-5} m^3
1 gal = 0.003 785 4 m^3
1 l = 0.001 m^3
1 gal/min = 0.002 228 ft^3/s
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1 gal/min = 0.000 063 1 m^3/s

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1 lbm = 0.453 592 kg
1 slug = 14.594 kg
1 ton = 2000 lbm
1 kg = 2.204 62 lbm
1 tonne = 1000 kg

PRESSURE

1 psi = 6.894 757 kPa
1 in. Hg = 3.387 kPa
1 bar = 100* kPa
1 kPa = 0.145 038 psi
1 in. Hg = 0.4912 psi
1 mm Hg = 0.1333 kPa
1 atm = 101.325 kPa = 14.696 psi = 760 mm Hg = 29.92 in. Hg

FORCE

1 lbf = 4.448 222 N
1 dyne = 1×10^{-5} N
1 N = 0.224 809 lbf

*Exact value

ENERGY

1 B = 1.055 056 kJ

1 ft·lbf = 1.3558 J

1 IT cal = 4.1868* J

1 B = 778.169 ft·lbf

1 J = 9.478×10^{-4} B

1 cal = 4.1840* J

SPECIFIC ENERGY

1 B/lbm = 2.326 kJ/kg

1 B/lbmol = 2.326 kJ/kmol

1 kJ/kg = 0.4299 B/lbm

1 kJ/kmol = 0.4299 B/lbmol

SPECIFIC ENTROPY, SPECIFIC HEAT, GAS CONSTANT

1 B/lbm·R = 4.1868* kJ/kg·K

1 B/lbmol·R = 4.1868* kJ/kmol·K

1 kJ/kg·K = 0.2388 B/lbm·R

1 kJ/kmol·K = 0.2388 B/lbm·R

DENSITY

1 lbm/ft^3 = 16.018 kg/m^3

1 kg/m^3 = 0.062 428 lbm/ft^3

SPECIFIC VOLUME

1 ft^3/lbm = 0.062 428 m^3/kg

1 m^3/kg = 16.018 ft^3/lbm

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1 B/s = 1.055 056 kJ/s

1 hp = 550 ft·lbf/s

1 hp = 2545 B/h

1 kW = 1.3410 hp

VELOCITY

1 mph = 1.467 ft/s

1 ft/s = 0.3048* m/s

1 mph = 0.4470 m/s

TEMPERATURE

$$T[°C] = \frac{5}{9}(T[°F] - 32)$$

$$T[°C] = T[K] - 273.15$$

$$T[°F] = \frac{9}{5}T[°C] + 32$$

$$T[°F] = T[R] - 459.67$$

1 K = 1.8 R or 1.8 T[K] = T[R]

*Exact value

ENGINEERING THERMODYNAMICS

PREFACE

This textbook is intended for use in undergraduate engineering courses in thermodynamics. Its purpose is to help develop in the student (1) an understanding of the first law, the second law, and some physical property relationships and (2) competence in the application of these principles to engineering systems. The book is written directly to students; one indication of this is the frequent use of the personal pronoun "you." The intention is to free the teacher from the necessity of interpreting the text to students. The teacher's talents are more effectively used if classroom time is devoted to those teaching activities that require a face-to-face exchange of thoughts and therefore cannot be accomplished by a textbook.

This edition follows the general plan of the first edition where George Hawkins and I expressed our conviction that students need copious explanation and illustration during the early part of a thermodynamics course sequence. A person who has studied thermodynamics at length can state the basic principles concisely and from them deduce many far-reaching conclusions. A thorough familiarity with the subject reveals the simplicity as well as the importance of the fundamentals; but people who have achieved this familiarity may not recognize the need of the neophyte for repeated explanations and illustrations of the fundamentals. Experienced teachers realize this when in subsequent courses they find that too many students are weak precisely on the fundamentals. Consequently, the explanations in the early chapters of this book are often exhaustive, with special emphasis on various points that have been stumbling blocks for students. The early chapters include many fully solved example problems. As the students gain maturity in the subject, they need less explanation, and the instructor can rely more on their reasoning powers; thus, both the amount of explanation and the number of solved example problems decrease in later chapters.

Some derivations are somewhat abbreviated because they are better appreciated after the results have been used enough for the student to recognize their usefulness. Initial derivations that are exhaustive accomplish little with most students, but after one has gained facility with the results, a rigorous examination of derivations can be quite fruitful.

The order of material is based more on pedagogical considerations than on logical economy. (This point is called to the students' attention in Sec. 9·13.) Thus, after the introductory chapter and Chapter 2 on the first law, there are two chapters on physical properties. The problems following these chapters involve extensive applications of the first law and material from the introductory chapter, as well as physical property relationships. The student can thereby practice applying the first law to various systems before taking up the new material on the second law.

Separate chapters are devoted to the second-law statement, reversibility, the Carnot principle and cycle, and entropy in order to emphasize the sequence. Reversibility has meaning only in light of the second law; the Carnot principle and cycle can be established only after reversibility has been defined; and the definition of entropy involves a reversible process and also thermodynamic temperature, which is most easily explained after the Carnot principle is introduced. Chapter 9 then treats physical property relationships that follow from the first and second laws combined, and Chapter 10 introduces availability and irreversibility. A problem posed by the inclusion of availability and irreversibility calculations in an introductory course is that although the conclusions are simple as well as highly useful, the general derivation of these conclusions is somewhat involved. Some instructors may wish to use the conclusions without devoting appreciable time to their derivation.

Chapters 14 through 18 illustrate the application of the basic principles covered in earlier chapters to various systems. The emphasis on fundamentals is maintained by omitting special techniques that are applicable only to certain situations. An instructor can always introduce some of these techniques in the classroom when advisable. It is much easier, in fact, to introduce such special material as a supplement to the basic approach in the textbook than to convince students to rely on the basic approach if their textbook frequently uses more specialized methods.

Chapter 19 on binary mixtures introduces briefly a part of the subject not otherwise mentioned in the book except in connection with absorption refrigeration in Chapter 18. Some teachers may prefer to assign Chapter 19 before Chapter 18. Chapter 20 is a brief introduction to fuel cells and provides additional applications of principles introduced in Chapters 12 and 13.

The final chapter is a short one on the elements of heat transfer. Although heat transfer is not part of the subject of thermodynamics, all engineering students should have some knowledge of this field closely related to thermodynamics. In curricula that do not require a course in heat transfer and even in those that do require one, the chapter on heat transfer may be useful even though it is very brief.

Naturally, many decisions have been made on the selection of material presented. For the most part, in Chapters 1 through 15, no material is introduced unless it is used subsequently or ties in with other material in the book. Some valuable and highly useful concepts (for example, chemical potential, partial molal properties, and fugacity) are not introduced, because covering them to the extent that students could use them effectively would require many additional pages.

Over 1600 problems of varying difficulty are included, and answers to approximately one third are given in the appendix. Many problems are highly "cumulative"; that is, their solutions involve material from several previous chapters. Some simple problems are included so that for illustrating some specific point the teacher can use one of these rather than make up a problem on the spur of the moment and have students end up with solutions in their notes but not the statement of the problem. Some problems involve physical property data that must be obtained from other sources.

This edition includes many problems for which the use of a computer is either required or advisable. However, the problem statements themselves do not indicate this because an essential part of problem solving is the selection of appropriate calculation methods.

For many years to come, engineers in English-speaking countries must be familiar with both SI and English units. Consequently, most of the solved example problems use SI but some use English units. The analysis and early part of a solution are nearly always independent of the system of units used, so the book can be used for courses using either SI or English units alone as may be advisable in some curricula. Doing so is facilitated by the inclusion at the end of each of the first eight chapters of problems similar to each example problem but using the other system of units. The problems that involve units are approximately evenly divided between SI and English units.

The references are for *students*. They have been selected as ones that can be helpful to most students at their current stage in the study of thermodynamics. They may not be the most suitable references for an advanced student reviewing the subject or seeking the greatest rigor in its development. Some of the references use different symbols or conventions from those of this textbook, but students must recognize that they will often encounter this situation in practice.

Many users of the first edition have provided helpful comments. One who has been most helpful in this regard over the years is Robert C. Fellinger of Iowa State University, and I am grateful to him for many excellent suggestions.

Four colleagues have generously helped me by reviewing early versions of various chapter revisions: G. H. Beyer, E. F. Brown, and H. L. Wood of VPI&SU and Professor S. B. Thomason of Memphis State University. I am also indebted to the four reviewers of the nearly completed manuscript: R. C. Fellinger (Iowa State University), Robert J. Heinsohn (Pennsylvania State University), Richard K. Irey (University of Florida), and Michael J. Moran (Ohio State University). Each one made highly perceptive comments and several valuable suggestions. I have considered all of them in detail, and only after careful thought have I chosen not to follow a few of the suggestions.

In preparing this edition, I have been extremely fortunate in having the assistance of two people who have been unsurpassably competent and helpful co-workers. Even when the work was mountainous in extent and tedious or intricate, I appreciated how pleasant it was to work with them. Ada B. Simmons prepared the manuscript, exercising superb judgment not just in the typing, assembling, and organization but also in editorial improvements. Regina D. Rieves performed many of the calculations and read the entire draft manuscript critically. She also solved many of the examples and problems, gathered and organized data, and prepared some of the figures. I warmly thank Mrs. Simmons and Mrs. Rieves for the quality of their work and their enthusiastic dedication to the project.

All of the people at Wiley with whom I have worked on this edition—like their counterparts years ago on the first edition—have been most helpful, offering many sound suggestions and professional guidance.

Again on this edition my wife, Jane Hardcastle Jones, has supported me through long hours of intense work on what sometimes looked like a never-to-be-ended task, and I am grateful to her.

J. B. Jones

Blacksburg, Virginia
June 1985

George Andrew Hawkins

(1907–1978)

George Hawkins earned B.S.M.E., M.S.M.E., and Ph.D. degrees from Purdue University. He served on the Purdue faculty for forty-four years as Professor of Thermodynamics, Dean of Engineering (1953–67), Vice President for Academic Affairs (1967–71), and in other positions. His primary field of research was heat transfer. In 1940 he was awarded the Pi Tau Sigma Gold Medal as the outstanding young mechanical engineer within ten years of the baccalaureate degree. He made numerous contributions to engineering and engineering education through his wisdom and vigor in teaching, research, and administrative leadership. He served as president of the American Society for Engineering Education in 1970 to 1971. Among his many honors was the election to Honorary Membership in the American Society of Mechanical Engineers. His other books include *Elements of Heat Transfer*, Third Edition, written with Max Jakob (Wiley, 1957) and *Thermodynamics*, Second Edition (Wiley, 1951).

SYMBOLS

A	area; Helmholtz function, $U - TS$
a	linear acceleration; specific Helmholtz function, $u - Ts$; velocity of a pressure wave
b	Darrieus function, h $- T_0s$
C	a constant; number of components (in the phase rule)
C_p	molar specific heat at constant pressure
C_v	molar specific heat at constant volume
c	constant-temperature coefficient, $(\partial h/\partial P)_T$; velocity of sound
c_p	specific heat at constant pressure, $(\partial h/\partial T)_P$
c_v	specific heat at constant volume, $(\partial u/\partial T)_V$
E	stored energy
e	specific stored energy, E/m
F	force; maximum number of independent intensive properties (in the phase rule)
F_A	shape factor for radiant heat transfer
F_E	emissivity factor for radiant heat transfer
$\mathfrak{F}$	Faraday constant, 96.487×10^6 coulomb/kmol of electrons
f	number of degrees of freedom of a molecule
G	Gibbs function, $H - TS$
g	gravitational acceleration or the acceleration of a freely falling body; specific Gibbs function, $h - Ts$
g_c	dimensional constant
H	enthalpy, $U + PV$
ΔH_f	enthalpy (change) of formation
ΔH_R	enthalpy (change) of reaction
h	specific enthalpy, $u + Pv$; height of a fluid column; convective heat-transfer coefficient
I	irreversibility
i	specific irreversibility; I/m; electric current
k	ratio of specific heats, c_p/c_v; thermal conductivity
K_p	equilibrium constant
KE	kinetic energy
ke	kinetic energy per unit mass
L	length
M	molar mass; Mach number, V/c
$\dot{m}$	mass rate of flow
m	mass

m'	mass of a molecule (Chapter 4); mass of extracted steam per pound of steam entering turbine
N	number of moles
n	polytropic exponent
P	pressure; number of phases (in the phase rule)
P_R	reduced pressure
p_r	relative pressure
PE	potential energy
pe	potential energy per unit mass
Q	heat
$\dot{Q}$	time rate of heat transfer
g	heat transfer per unit mass
R	gas constant
R_u	universal gas constant
r	radius; compression ratio
r_c	cutoff ratio
S	entropy
s	specific entropy
T	absolute temperature, temperature
T_R	reduced temperature
t	temperature
U	internal energy; overall heat-transfer coefficient
ΔU_R	internal energy (change) of reaction
u	specific internal energy; velocity; velocity of a point on a rotor
V	volume, velocity, voltage (emf)
v	specific volume
v_r	relative specific volume
W	work
$\dot{W}$	power
X	mass fraction (Chapters 18 and 19)
x	quality; mole fraction; a property in general; distance in the direction of heat conduction
Y	stream availability
y	specific stream availability; a property in general
Z	compressibility factor, $Z = PV/mRT$
z	elevation

Greek letters

α	absorptivity
β	coefficient of performance; coefficient of volume expansion, $(\partial v/\partial T)_P/V$
γ	specific weight
ε	emissivity, "fuel cell efficiency"

η	efficiency; number of molecules
Θ	Debye's constant or characteristic temperature
θ	temperature on any nonthermodynamic scale
κ_s	isentropic compressibility, $-(\partial v/\partial P)_s/V$
κ_T	isothermal compressibility, $-(\partial v/\partial P)_T/V$
μ	Joule–Thomson coefficient, $(\partial T/\partial P)_h$
υ	stoichiometric coefficient (number of moles in chemical equation)
ρ	density; reflectivity
σ	Stefan–Boltzmann constant
τ	time; transmissivity
Φ	availability of a closed system
ϕ	specific availability of a closed system, $\frac{\Phi}{m}$; $\int \frac{c_p dT}{T}$; relative humidity
ω	humidity ratio

Subscripts

a	air
c	critical state; (see also g_c in list of symbols)
da	dry air
dg	dry gas
f	final state; saturated liquid; fuel
fg	difference between property of saturated liquid and property of saturated vapor at the same pressure and temperature
g	saturated vapor
H	high temperature (as in T_H and Q_H)
i	initial state; ice point; ideal or isentropic; intermediate (as intermediate pressure in multistage compression)
if	difference between property of saturated solid and saturated liquid at the same pressure and temperature
ig	difference between property of saturated solid and saturated vapor at the same pressure and temperature
L	low temperature (as in T_L and Q_L)
m	mixture
N	molar (as in v_N for molar specific volume)
O	base state; state of the atmosphere
R	reduced coordinate; energy reservoir
r	relative
s	steam point
t	total or stagnation
u	universal (in R_u)
v	vapor (in gas–vapor mixtures)

σ referring to an open-system boundary

1,2,3 referring to different states of a system or different locations in space

Superscripts

$^{\circ}$ standard state

$*$ state used in relating real gas and ideal gas properties; state at which $M(= V/c) = 1$

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1 ft·lbf = 1.3558 J	1 J = 9.478×10^{-4} B
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DENSITY

1 lbm/ft^3 = 16.018 kg/m^3	1 kg/m^3 = 0.062 428 lbm/ft^3

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1 B/s = 1.055 056 kJ/s	1 hp = 2545 B/h
1 hp = 550 ft·lbf/s	1 kW = 1.3410 hp

VELOCITY

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$$T[°C] = T[K] - 273.15 \qquad T[°F] = T[R] - 459.67$$

$$1\ K = 1.8\ R \text{ or } 1.8\ T[K] = T[R]$$

*Exact value

CONTENTS