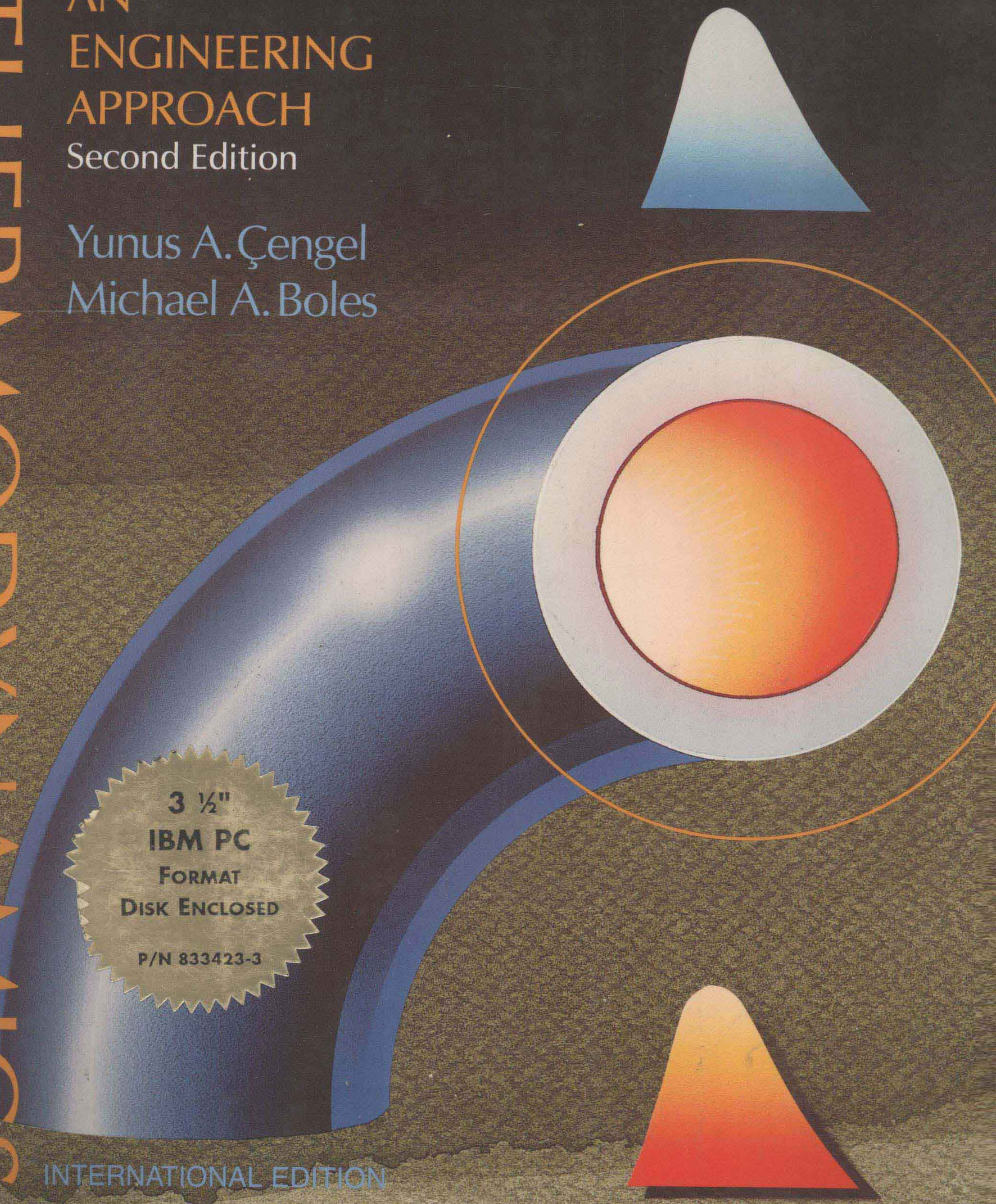
THERMODYNAMICS

AN ENGINEERING APPROACH

Second Edition

Yunus A. Çengel
Michael A. Boles



INTERNATIONAL EDITION

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An Engineering Approach

SECOND EDITION

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Thermodynamics:
An Engineering Approach

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About the Authors

Yunus A. Çengel received his Ph.D. in mechanical engineering from North Carolina State University, and joined the faculty of mechanical engineering at the University of Nevada, Reno, where he has been teaching undergraduate and graduate courses in thermodynamics and heat transfer while conducting research. He has published several papers in the areas of thermodynamics, radiation heat transfer, natural convection, and solar energy. Dr. Çengel has been voted the outstanding teacher by the ASME student sections in both North Carolina State University and the University of Nevada, Reno. He is a member of the American Society of Mechanical Engineers and the American Society for Engineering Education.

Michael A. Boles is Associate Professor of Mechanical and Aerospace Engineering at North Carolina State University. He earned his Ph.D. in mechanical engineering at North Carolina State University. Dr. Boles has received numerous awards and citations for excellence as an engineering educator. He is a past recipient of the SAE Ralph R. Teetor Educational Award and a member of the Academy of Outstanding Teachers at North Carolina State University. Dr. Boles is an Alumni Distinguished Professor at North Carolina State University. Dr. Boles specializes in heat transfer and has been involved in the analytical and numerical solution of phase change and drying of porous media heat transfer. He is a member of the American Society of Mechanical Engineers, the American Society for Engineering Education, and Sigma Xi.

Professors Çengel and Boles received the ASEE Meriam/Wiley Distinguished Author Award in 1992 in recognition of their excellence in the authorship of the first edition of this text.

Preface

Thermodynamics is a basic science that deals with energy and has long been an essential part of engineering curricula all over the world. This introductory text is intended for use in undergraduate engineering courses and contains sufficient material for two sequential courses in thermodynamics.

The traditional classical, or macroscopic, approach is used throughout this text, with microscopic arguments serving in a supporting role where appropriate. This approach is more in line with the students' intuition and makes learning the subject matter much easier.

Our philosophy that contributed to the popularity of the first edition remains unchanged: talk directly to the minds of tomorrow's engineers in a simple yet precise manner, and encourage creative thinking and developing a deeper understanding of the subject matter. Our goal in the first edition was to offer an engineering textbook that is read by the students with interest and enthusiasm instead of one that is used as a reference book to solve problems. We wanted to touch the curious minds and take them to a pleasant journey in the wonderful world of thermodynamics and explore the wonders of this exciting science. The enthusiastic response we received from the users of the first edition from small colleges to large universities indicates that our objectives have been achieved.

NEW IN THE SECOND EDITION

Most users of the first edition who were surveyed expressed a high degree of satisfaction with the text and asked us not to go overboard with the changes. We responded by retaining all the popular features of the first edition while adding new ones. The new features in this second edition can be highlighted as follows:

- Over 250 new problems are added. This brings the total number of the end-of-chapter problems to more than 2000. A special effort is made to incorporate some safety-related problems to enhance awareness of safety in engineering.
- A new *Review Problems* part is added to the problems section of each chapter with about 300 problems to enable instructors to assign more comprehensive problems not tied directly to any specific section of a chapter.
- A new *Computer, Design, and Assay Problems* part is added at the end of each problems section with over 120 problems in response to added emphasis on design, creativity, and computer use in engineering education.
- Some historical perspective is added throughout the text, such as the development of refrigerants in Chapter 10, to enhance the readability of the text and to invoke more student interest.
- New information such as the recent developments on two-stroke engines and turbofans is incorporated in the text, especially in the later chapters dealing with applications.
- A new section entitled *Thermodynamic Aspects of Biological Systems* is added to Chapter 3, complete with tables of metabolizable energy content of common foods and energy consumption during common activities.
- Another new section entitled *Second-Law Aspects of Daily Life* is added to Chapter 7 to draw parallels between the seemingly abstract concepts related to the second law, such as availability, irreversibility, and second-law efficiency, and the common occurrences in ordinary life. Also, the subsection *Entropy and Us* in Chapter 6 is expanded as part of our continued effort to demystify the concept of entropy.
- The software is greatly expanded to allow students to solve design problems and ask "what if" questions. With the enclosed menu-driven user-friendly software, students can now analyze steam and gas power cycles at different levels of complexity, perform combustion analysis of several fuels in closed and steady-flow systems, and evaluate the properties of air–water vapor mixtures as well as the properties of steam, refrigerants, and several gases.
- The tables and charts in the appendix are also reprinted in a separate booklet for use during closed-book examinations.

With the exception of some fine tuning, the main body of the text remained largely unchanged. The noteworthy changes in various chapters are summarized below for those who are familiar with the first edition.

Chapter 1	More discussions are added to Section 1-2 on dimensions and units. Heat and work are introduced briefly as energy interactions in Section 1-5. The constant-volume gas thermometer is described in detail in Section 1-10 in conjunction with absolute temperature scales.
Chapter 2	A table for triple-point properties is added, and the variation of atmospheric pressure and the boiling temperature of water with elevation is tabulated in Section 2-3. A subsection on reference state and reference values is added, and a comprehensive example is given to demonstrate the use of the property tables in Section 2-6. Also, a better approximation for the enthalpy of the compressed liquid is given.
Chapter 3	The discussions on heat are revised, the caloric theory is discussed, and the modes of heat transfer are introduced in Section 3-2. Other forms of work are briefly introduced in Section 3-3 for completeness. A formal statement of the first law is given in Section 3-5. A new section, *Thermodynamic Aspects of Biological Systems,* complete with tables of metabolizable energy content of common foods and energy consumption during common activities, is added to shed some light on dieting and exercise.
Chapter 4	One-dimensional flow is described in Section 4-1. General relations for the control volume mass and energy balances are added to Section 4-4.
Chapter 5	The quantity *Energy Efficiency Rating* (EER) commonly used in practice is defined and its relation to COP is given in Section 5-4. More discussions on perpetual-motion machines are given in Section 5-5. A new subsection, *Quality vs. Quantity in Daily Life,* is added to Section 5-10.
Chapter 6	The Clausius inequality is derived in a formal way in Section 6-1. Section 6-3 on the increase of entropy principle is completely rewritten, emphasizing the entropy balance concept, and a new subsection, *Entropy Generation Associated with a Heat Transfer Process,* is added. The discussions in the subsection *Entropy and Us* in Section 6-5 are expanded.

Chapter 7	A new subsection, *Availability Transfer with Heat and Work Interactions,* is added in Section 7-2. A formal definition for the second-law efficiency is given in Section 7-3, and the discussions are expanded to include various steady-flow devices. A new section, *Second Law Aspects of Daily Life,* is added.
Chapter 8	The discussions on two-stroke engines in Section 8-5 and on turbofan engines in Section 8-11 are updated in the light of new developments.
Chapter 9	The *heat rate* is defined and its relation to thermal efficiency is given in Section 9-2. The material on reheat Rankine cycle in Section 8-5 is revised.
Chapter 10	The discussions on refrigerants in Section 10-5 are expanded, and a historical perspective on the rise and fall of the most widely used refrigerant, Freon-12, is given.
Chapter 13	The discussions on human comfort in Section 13-5 are expanded.
Chapter 14	The subsection *Steady-Flow Systems* in Section 14-4 is rewritten. The entropy change of reacting systems in Section 14-5 is revised.
Appendix	Property tables of nitrogen (Tables A-15, 16, 15E, and 16E) are replaced by the property tables of the ozone-friendly refrigerant-134a. The rest of the tables and charts remained unchanged. The conversion factors on the inner cover page are revised, and a table of frequently used physical constants is added.

Thermodynamics is often perceived as a difficult subject, and the majority of students dread the experience. The authors believe, on the contrary, that thermodynamics is a simple subject, and an observant mind should have no difficulty understanding it. After all, the principles of thermodynamics are based on our everyday experiences and experimental observations. Thermodynamics is a mature basic science, and the topics covered in introductory texts are well established. Primarily, the texts differ only in the approach used. In this text, a more physical, intuitive approach is used throughout. Frequently, parallels are drawn between the subject matter and students' everyday experiences so that they can relate the subject matter to what they already know.

Yesterday's engineer spent a major portion of his or her time substituting values into formulas and obtaining numerical results. But it will not be long before all the formula manipulations and number crunching are left to the computers. Tomorrow's engineer will have to have a clear understanding and firm grasp of the basic principles in order to understand, formulate, and interpret the results of even the most complex problems. A conscious effort is made to lead students in this direction.

The material in the text is introduced at a level that average students can follow comfortably. It speaks *to* the students, not over them. In fact, the material is self-instructive, thus freeing the instructor to use class time more productively.

The order of coverage is from simple to general. That is, it starts with the simplest case and adds complexities one at a time. In this way, the basic principles are repeatedly applied to different systems, and students master how to apply the principles instead of how to simplify a general formula. Since thermodynamic principles are based on experimental observations, all derivations in this text are based on physical grounds; thus they are easy to follow and understand.

Figures are important learning tools that help the students to get the "picture." They attract attention and stimulate curiosity and interest. The text makes effective use of graphics and probably contains more figures and illustrations than any other thermodynamics book. Some of the figures do not function in the traditional sense. Rather, they serve as a means of emphasizing some key statements that would otherwise go unnoticed or as paragraph summaries. The popular cartoon feature "Blondie" is used to make some important points in a humorous way and also to break the ice and ease the nerves. Who says studying thermodynamics cannot be fun?

Each chapter contains numerous worked-out examples that clarify the material and illustrate the use of the basic principles. A consistent and systematic approach is used in the solution of the example problems, with particular attention to the proper use of units. A sketch and a process diagram are included for most examples to clearly illustrate the geometry and the type of process involved.

The subject material is covered in a logical order. First, various concepts are reviewed and some new ones are defined in order to establish a firm basis for the development of thermodynamic principles. Then the properties of pure substances are discussed and the use of property tables is illustrated. At this point the ideal-gas approximation is introduced, together with other equations of state, and the deviation from ideal-gas behavior is examined through the use of compressibility charts. After the introduction of heat and work, the conservation of energy principle is developed for a closed system. Following a discussion of flow energy, the conservation of energy principle for control volumes is developed, first for steady-flow systems and then for general unsteady-flow systems. The development of the second-law relations follow the same order, with special emphasis given to entropy generation. The concepts of availability, reversible work, and irreversibility are developed using familiar examples before they are applied to more complex engineering systems. The principles of thermodynamics are then applied to various areas of engineering.

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A short summary is included at the end of each chapter for a quick overview of basic concepts and important relations; this is followed by a list of references that are appropriate for the level of students studying thermodynamics for the first time. Summaries can also be used as formula sheets during exams by instructors who prefer closed-book tests and yet want to make the equations available to the students.

The end-of-chapter problems are grouped under specific topics in the order they are covered to make problem selection easier for both instructors and students. The problems within each group start with concept questions, indicated by "C," to check the students' level of understanding of basic concepts. The problems involving numerical calculations are arranged in increasing complexity, with the later ones requiring more comprehensive analysis. The problems grouped under *Review Problems* are more comprehensive in nature, and are not directly tied to any specific section of a chapter. The problems under *Computer Design and Assay Problems* are intended to encourage students to use computers in problem solving, to make engineering judgments, to conduct independent searches on topics of interest, and to communicate their findings in a professional manner. Some safety-related problems are incorporated throughout to enhance safety awareness among engineering students. Answers to selected problems are presented immediately following the problem for convenience to the students.

In recognition of the fact that English units are still widely used in some industries, both SI and English units are used in this text, with an emphasis on SI. The material in this text can be covered using combined SI/English units or SI units alone, depending on the preference of the instructor. The property tables and charts in the appendix are presented in both units, except the ones that involve dimensionless quantities. Problems, tables, and charts in English units are designated by "E" after the number for easy recognition. Frequently used conversion factors and physical constants are listed on the inside cover pages of the text for easy reference.

SUPPLEMENTS

The comprehensive software included with this second edition is menu-driven and easy to use. Once the name of a program is typed, the user is guided through the necessary steps. The programs STEAM and REF12 determine the thermodynamic properties of steam and refrigerant-12, respectively, in either SI or English units. Once numerical values for any two independent properties selected from the menu are supplied, the program determines all other properties for the state, and indicates whether the state is in the compressed liquid, saturation, or superheated vapor region. The program GAS determines the thermodynamic properties of several ideal gases at a specified state, at a specified temperature, or at the end of an isentropic process from the specified state for a given volume or pressure ratio. The program PSY determines the properties of moist air using various options for specifying the state. It also calcuates the mixture properties of two moist-air streams after they are mixed. The program SPOWER analyzes simple, reheat, open-regenerative, and reheat-regenerative Rankine cycles by automatically determining the necessary properties, and allows the user to do parametric studies and to solve design problems efficiently. The program GPOWER can be used to analyze Otto and Brayton gas power cycles for both constant and variable specific heat cases. Finally, the program COMB allows the user to perform combustion analysis of several fuels in closed and steady-flow systems. The program determines the heat transfer or the adiabatic-flame temperature together with a balanced combustion equation.

The *Instructor's Manual* is prepared with a scientific word processor, and it provides complete and detailed solutions to end-of-chapter problems. The solutions may be photocopied for posting or preparing transparencies for classroom discussions. A set of *overhead transparencies* is also available to adopters to assist them in lecturing. Booklets that contain reprints of the *tables and charts* in the appendix are also available for use during closed-book examinations.

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We would like to take this opportunity to thank the many users of the first edition at more than 100 colleges and universities in the U.S. and Canada and many others in several countries overseas for their comments, praise, and constructive criticism. Special thanks are due to faculty who took the time to review the first edition with a critical eye to make suggestions for improvements, and to the following who reviewed the revised manuscript for the second edition to evaluate the changes: Joseph Augustus, Manhattan College; Daisie Boettner, United States Military Academy; Frank J. DeLuise, University of Rhode Island; Jerry Dunn, Texas Tech University; Jerry Drummond, The University of Akron; Jeffrey W. Hodgson, University of Tennessee; Vincent J. Lopardo, United States Naval Academy; A. K. MacPherson, Lehigh University; M. Pinar Menguc, University of Kentucky; Alan Parkinson, Brigham Young University; Mardson Queiroz, Brigham Young University; Larry Simmons, University of Portland; and James Strozier, University of Utah. We are grateful to them for their expert advice and suggestions for improvements.

We are most grateful for the enthusiastic response the first edition of this book has received, and we hope that the improvements made in this second edition will please the users even more. Your comments and criticisms are always welcome and will be greatly appreciated.

Yunus A. Çengel
Michael A. Boles

Nomenclature

a	Acceleration, m/s^2
a	Specific Helmholtz function, $u - Ts$, kJ/kg
A	Area, m^2
A	Helmholtz function, $U - TS$, kJ
AF	Air-fuel ratio
c	Speed of sound, m/s
C	Specific heat, kJ/(kg·K)
C_p	Constant pressure specific heat, kJ/(kg · K)
C_v	Constant volume specific heat, kJ/(kg · K)
COP	Coefficient of performance
COP_R	Coefficient of performance of a refrigerator
COP_{HP}	Coefficient of performance of a heat pump
d	Exact differential
d, D	Diameter, m
e	Specific total energy, kJ/kg
E	Total energy, kJ
EER	Energy efficiency rating
F	Force, N
FA	Fuel-air ratio
g	Gravitational acceleration, m/s^2
g	Specific Gibbs function, $h - Ts$, kJ/kg

G	Total Gibbs function, $H - TS$, kJ
h	Height, m
h	Specific enthalpy, $u + Pv$, kJ/kg
h	Convection heat transfer coefficient, $W/(m^2 \cdot C)$
H	Total enthalpy, $U + PV$, kJ
HHV	Higher heating value, kJ/kmol fuel
$\bar{h}_c$	Enthalpy of combustion, kJ/kmol fuel
$\bar{h}_f$	Enthalpy of formation, kJ/kmol
$\bar{h}_R$	Enthalpy of reaction, kJ/kmol
i	Specific irreversibility, kJ/kg
I	Electric current, A
I	Total irreversibility, kJ
k	Specific heat ratio, C_p/C_v
k	Spring constant
k_t	Thermal conductivity
K_p	Equilibrium constant
ke	Specific kinetic energy, $V^2/2$, kJ/kg
KE	Total kinetic energy, $mV^2/2$, kJ
L	Length
LHV	Lower heating value, kJ/kmol fuel
m	Mass, kg
$\dot{m}$	Mass flow rate, kg/s
M	Molar mass, kg/kmol
MEP	Mean effective pressure, kPa
mf	Mass fraction
n	Polytropic exponent
N	Number of moles, kmol
P	Pressure, kPa
P_{cr}	Critical pressure, kPa
P_i	Partial pressure, kPa
P_m	Mixture pressure, kPa
P_r	Relative pressure
P_R	Reduced pressure
P_v	Vapor pressure, kPa
P_0	Surroundings pressure, kPa
pe	Specific potential energy, gz, kJ/kg
PE	Total potential energy, mgz, kJ
q	Heat transfer per unit mass, kJ/kg
Q	Total heat transfer, kJ
Q_H	Heat transfer with high-temperature body, kJ
Q_L	Heat transfer with low-temperature body, kJ

$\dot{Q}$	Heat transfer rate, kW
r	Compression ratio
r_p	Pressure ratio
r_c	Cutoff ratio
R	Gas constant, kJ/(kg · K)
R_u	Universal gas constant, kJ/(kmol · K)
s	Specific entropy, kJ/(kg · K)
s_{gen}	Specific entropy generation, kJ/(kg · K)
S	Total entropy, kJ/K
S_{gen}	Total entropy generation, kJ/K
t	Time, s
T	Temperature, °C or K
T_{cr}	Critical temperature, K
T_{db}	Dry-bulb temperature, °C
T_{dp}	Dew-point temperature, °C
T_f	Bulk fluid temperature, °C
T_{R}	Reduced temperature
T_{wb}	Wet-bulb temperature, °C
T_0	Surroundings temperature, °C or K
T_H	Temperature of high-temperature body, K
T_L	Temperature of low-temperature body, K
u	Specific internal energy, kJ/kg
U	Total internal energy, kJ
v	Specific volume, m^3/kg
v_{cr}	Critical specific volume, m^3/kg
v_r	Relative specific volume
v_{R}	Pseudo-reduced specific volume
V	Total volume, m^3
$\mathbf{V}$	Velocity, m/s
w	Work per unit mass, kJ/kg
W	Total work, kJ
$\dot{W}$	Power, kW
W_{in}	Work input, kJ
W_{out}	Work output, kJ
W_{rev}	Reversible work, kJ
x	Quality
y	Mole fraction
z	Elevation, m
Z	Compressibility factor
Z_h	Enthalpy departure factor
Z_s	Entropy departure factor

Greek Letters

β	Volume expansivity, 1/K
Δ	Finite change in quantity
δ	Differential of a path function
ε	Emissivity
η_{th}	Thermal efficiency
η_{II}	Second-law efficiency
θ	Total energy of a flowing fluid, kJ/kg
α	Absorptivity
α	Isothermal compressibility, 1/kPa
μ	Joule-Thomson coefficient, K/kPa
μ	Chemical potential, kJ/kg
ν	Stoichiometric coefficient
ρ	Density, kg/m^3
ρ_s	Specific weight or relative density
σ	Stefan-Boltzmann constant
σ_s	Surface tension, N/m
σ_n	Normal stress, N/m^2
τ	Torque, Nm
ϕ	Relative humidity
ϕ	Specific closed system availability, kJ/kg
Φ	Total closed system availability, kJ
ψ	Stream availability, kJ/kg
ω	Specific or absolute humidity, kg H_2O/kg dry air

Subscripts

a	Air
abs	Absolute
act	Actual
atm	Atmospheric
av	Average
c	Combustion
cr	Critical point property
cv	Control volume
e	Exit conditions
f	Saturated liquid
fg	Difference in property between saturated liquid and saturated vapor
g	Saturated vapor
gen	Generation

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