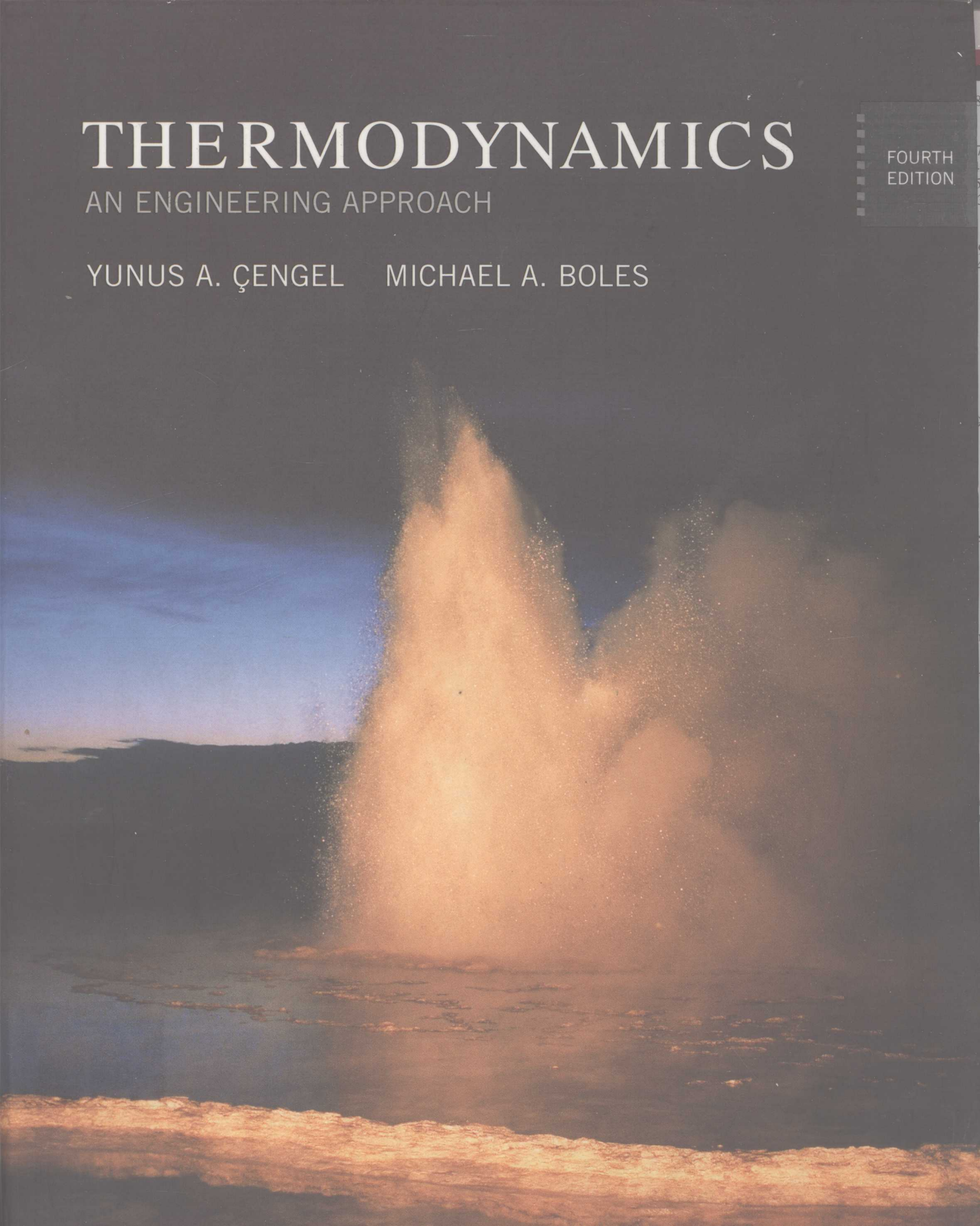
THERMODYNAMICS

AN ENGINEERING APPROACH

FOURTH EDITION

YUNUS A. ÇENGEL MICHAEL A. BOLES



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Thermodynamics is a funny subject. The first time you go through it, you don't understand it at all. The second time you go through it, you think you understand it, except for one or two points. The third time you go through it, you know you don't understand it, but by that time you are so used to the subject, it doesn't bother you anymore.
—Arnold Sommerfeld

There is nothing more practical than a good theory.
—L. Boltzmann

Knowledge and timber shouldn't be much used till they are seasoned.
—Oliver Wendell Holmes

The true scholar-educator becomes a sheep, not a bird. Passes on his knowledge selflessly. The sheep gives its lambs digested pure milk. The bird gives its chicks saliva-soaked feed.
—Said Nursi

Heat cannot, of itself, pass from a colder to a hotter body.
—Rudolf Clausius

Economic activities are inherently dissipative and governed by the second law of thermodynamics.
—Robert U. Ayres

All that is human must retrograde if it does not advance.
—Edward Gibson

Absence of occupation is not rest; a mind quite vacant is a mind distressed.
—William Cowper

There is no point at which having arrived we can remain.
(Author unknown)

The higher the level of expectation, the lower the level of satisfaction.
(Author unknown)

Blessed are those who expect nothing, for they will never be disappointed.
(Author unknown)

A science is any discipline in which the fool of this generation can go beyond the point reached by the genius of last generation.
—Max Gluckman

About the Authors

Yunus A. Çengel is a Professor of Mechanical Engineering at the University of Nevada, Reno. He received his Ph.D. in mechanical engineering from North Carolina State University in 1984. His current research areas are renewable energy, desalination, exergy analysis, and energy conservation. He served as the director of the Industrial Assessment Center (IAC) at the University of Nevada, Reno, from 1996 to 2000. He has led teams of engineering students to numerous manufacturing facilities in Northern Nevada and California to industrial assessments, and has prepared energy conservation, waste minimization, and productivity enhancement reports for them.

Dr. Çengel is also the author of the widely adopted textbooks *Introduction to Thermodynamics and Heat Transfer* (1997), *Heat Transfer: A Practical Approach* (1998), and *Fundamentals of Thermal-Fluid Sciences* (with Dr. Turner, 2001), all published by McGraw-Hill. Some of his textbooks have been translated to Chinese, Japanese, Korean, Spanish, Turkish, Italian, and Greek. Dr. Çengel is the recipient of several outstanding teacher awards, and he has received the ASEE Meriam/Wiley Distinguished Author Award for excellence in authorship in 1992 and again in 2000.

Dr. Çengel is a registered Professional Engineer in the State of Nevada, and is a member of the American Society of Mechanical Engineers (ASME) and the American Society for Engineering Education (ASEE).

Michael A. Boles is Associate Professor of Mechanical and Aerospace Engineering at North Carolina State University where he earned his Ph.D. in mechanical engineering and is an Alumni Distinguished Professor. 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 Education Award and has been twice elected to the NCSU Academy of Outstanding Teachers. On several occasions the ASME student section has recognized him as outstanding teacher and the faculty member having the most impact on mechanical engineering students.

Dr. Boles specializes in heat transfer and has been involved in the analytical and numerical solution of phase change and drying of porous media. He is a member of the American Society of Mechanical Engineers, the American Society for Engineering Education, and Sigma Xi. Dr. Boles received the ASEE Meriam/Wiley Distinguished Author Award in 1992 for excellence in authorship.

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_{HP}	Coefficient of performance of a heat pump
COP_{R}	Coefficient of performance of a refrigerator
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	Convection heat transfer coefficient, W/m^2 · °C
h	Specific enthalpy, $u + Pv$, kJ/kg
H	Total enthalpy, $U + PV$, kJ
$\bar{h}_c$	Enthalpy of combustion, kJ/kmol fuel
$\bar{h}_f$	Enthalpy of formation, kJ/kmol
$\bar{h}_R$	Enthalpy of reaction, kJ/kmol
HHV	Higher heating value, kJ/kg fuel
i	Specific irreversibility, kJ/kg
I	Electric current, A
I	Total irreversibility, kJ
k	Specific heat ratio, C_p/C_v
k_s	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
LHV	Lower heating value, kJ/kg 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
$\dot{Q}$	Heat transfer rate, kW
Q_H	Heat transfer with high-temperature body, kJ
Q_L	Heat transfer with low-temperature body, kJ
r	Compression ratio
R	Gas constant, kJ/kg · K
r_c	Cutoff ratio
r_p	Pressure ratio
R_u	Universal gas constant, kJ/kmol · K
s	Specific entropy, kJ/kg · K
S	Total entropy, kJ/K
s_{gen}	Specific entropy generation, kJ/kg · 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_H	Temperature of high-temperature body, K
T_L	Temperature of low-temperature body, K
T_{R}	Reduced temperature
T_{wb}	Wet-bulb temperature, °C

T_0	Surroundings temperature, °C or 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	Pseudoreduced specific volume
V	Total volume, m^3
$\mathscr{V}$	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
x	Specific exergy, kJ/kg
X	Total exergy, kJ/kg
x_{dest}	Specific exergy destruction, kJ/kg
X_{dest}	Total exergy destruction, kJ
$\dot{X}_{dest}$	Rate of total exergy destruction, kW
y	Mole fraction
z	Elevation, m
Z	Compressibility factor
Z_h	Enthalpy departure factor
Z_s	Entropy departure factor

Greek Letters

α	Absorptivity
α	Isothermal compressibility, 1/kPa
β	Volume expansivity, 1/K
Δ	Finite change in quantity
ε	Emissivity
η_{th}	Thermal efficiency
η_{II}	Second-law efficiency
θ	Total energy of a flowing fluid, kJ/kg
μ_{JT}	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_n	Normal stress, N/m^2
σ_s	Surface tension, N/m
τ	Torque, Nm
ϕ	Relative humidity
ϕ	Specific closed system exergy, kJ/kg
Φ	Total closed system exergy, kJ
ψ	Stream exergy, 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
cv	Control volume
e	Exit conditions
f	Saturated liquid
fg	Difference in property between saturated liquid and saturated vapor
g	Saturated vapor
gen	Generation
H	High temperature (as in T_H and Q_H)
i	Inlet conditions
i	ith component
L	Low temperature (as in T_L and Q_L)
m	Mixture
r	Relative
R	Reduced
rev	Reversible
s	Isentropic
sat	Saturated
surr	Surroundings
sys	System
v	Water vapor
0	Dead state
1	Initial or inlet state
2	Final or exit state

Superscripts

$\dot{}$ (over dot)	Quantity per unit time
$\bar{}$ (over bar)	Quantity per unit mole
$^\circ$ (circle)	Standard reference state

PREFACE

OBJECTIVES

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 contains sufficient material for two sequential courses in thermodynamics, and it is intended for use by *undergraduate* engineering students and by practicing engineers as a reference. The objectives of this text are

- To cover the *basic principles* of thermodynamics.
- To present a wealth of real-world *engineering applications* to give students a feel for engineering practice.
- To develop an *intuitive understanding* of the subject matter by emphasizing the physics and physical arguments.

GENERAL APPROACH

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

The philosophy that contributed to the overwhelming popularity of the prior editions of this book has remained unchanged in this edition. The goal throughout this project has been to offer an engineering textbook that

- Talks directly to the minds of tomorrow's engineers in a *simple yet precise* manner.
- Encourages *creative thinking* and development of a *deeper understanding* of the subject matter.
- Is *read* by students with *interest* and *enthusiasm* rather than being used as an aid to solve problems.

Special effort has been made to appeal to readers' natural curiosity and to help students explore the various facets of the exciting subject area of thermodynamics. The enthusiastic response we received from the users of prior editions—from small colleges to large universities—indicates that our objectives have largely been achieved.

Yesterday's engineer spent a major portion of his or her time substituting values into the formulas and obtaining numerical results. However, now formula manipulations and number crunching are being left mainly to the computers. Tomorrow's engineer will have to have a clear understanding and a firm grasp of the *basic principles* so that he or she can understand even the

most complex problems, formulate them, and interpret the results. A conscious effort is made to emphasize these basic principles while also providing students with a look at how computers are used in engineering practice.

NEW IN THIS EDITION

All the popular features of the previous editions are retained while new ones are added. With the exception of unifying the first law coverage and the addition of some new material, the main body of the text remains largely unchanged. The most significant changes in this edition are highlighted below.

Topics of Special Interest

Most chapters now contain a new section called "Topics of Special Interest" where interesting aspects of thermodynamics are discussed. Some existing sections such as *Thermodynamic Aspects of Biological Systems* in Chapter 1, *Refrigeration and Freezing of Foods* in Chapter 4, and *Second-Law Aspects of Daily Life* in Chapter 7 are moved to these sections as topics of special interest. New sections, such as *Saving Fuel and Money by Driving Sensibly* in Chapter 8 and *Chemical Potential and the Separation Work of Mixtures* in Chapter 12, are added. The topics selected for these sections provide intriguing extensions to thermodynamics, but they can be ignored if desired without a loss in continuity.

Comprehensive Problems with Extensive Parametric Studies

A distinctive feature of this edition is the incorporation of about 200 comprehensive problems that require conducting extensive parametric studies, using the enclosed EES (or other suitable) software. Students are asked to study the effects of certain variables in the problems on some quantities of interest, to plot the results, and to draw conclusions from the results obtained. These problems are designated by a computer icon for easy recognition, and can be ignored if desired. Solutions of these problems are given in the Instructor's Manual.

Fundamentals of Engineering (FE) Exam Problems

To prepare students for the Fundamentals of Engineering Exam (that is becoming more important for the outcome-based ABET 2000 criteria) and to facilitate multiple-choice tests, about 200 new *multiple-choice problems* are added to the end-of-chapter problem sets. They are placed under the title "Fundamentals of Engineering (FE) Exam Problems" for easy recognition. These problems are intended to check the understanding of fundamentals and to help readers avoid common pitfalls.

Unified Coverage of the First Law of Thermodynamics

Now the first law of thermodynamics is covered in a single chapter (Chapter 4) using an intuitive energy balance relation that can be used for any kind of system undergoing any kind of process.

New Coverage of Energy and Environment

To address the growing concerns about the environment, a new section *Energy and Environment* is added to Chapter 1. In this section emissions (especially

from vehicles and power plants), air pollution, smog, acid rain, global warming, etc., and their relation to energy conversion processes are discussed.

Content Changes and Reorganization

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

- In Chapter 1, the section on *Pressure* is revised and extended considerably. The section *Problem Solving Technique* is moved here for early coverage, with an overview of the EES software, and a new section *Energy and Environment* is added. The optional Topic of Special Interest in this chapter is *Thermodynamic Aspects of Biological Systems.*
- Chapter 2 now offers a more comprehensive coverage of thermodynamic properties, including specific heats of both ideal gases and incompressible substances. The section *Vapor Pressure and Phase Equilibrium* is moved to the end of chapter as the Topic of Special Interest.
- Chapter 3 now covers energy interactions by heat, work, and mass. A new section *Conservation of Mass Principle* is added here to provide complete coverage of mass balance. All references to gravitational work and accelerational work are deleted, and examples are done using changes in kinetic and potential energies. Also, the section *Modes of Heat Transfer* is moved to the end of the chapter as the Topic of Special Interest, making it easy to skip by those who desire to do so.
- Chapter 4 now introduces the first law of thermodynamics under one cover for all systems. It presents a unified approach to energy balance calculations. The optional Topic of Special Interest in this chapter is *Refrigeration and Freezing of Foods.*
- The following sections are moved to the end of chapters as the Topics of Special Interest for optional coverage: *Household Refrigerators* in Chapter 5, *Reducing the Cost of Compressed Air* in Chapter 6, *Second-Law Aspects of Daily Life* in Chapter 7, *Binary Vapor Cycles* in Chapter 9, *Thermoelectric Power Generation and Refrigeration Systems* in Chapter 10, and *Fuel Cells* in Chapter 14.
- Chapter 7 is revised, and the exergy content of flowing and nonflowing fluids is determined more directly using an intuitive approach.
- In Chapter 8, a new section *Saving Fuel and Money by Driving Sensibly* is added as a Topic of Special Interest to enhance awareness about fuel efficiency.
- In Chapter 12, a new section *Chemical Potential and the Separation Work of Mixtures* is added as a Topic of Special Interest for those who wish to study thermodynamic aspects of separation processes, with particular emphasis on desalination.
- In Chapter 14, discussions of fuels are expanded.
- In Appendices, the tables on fuel properties are replaced by more extensive ones.

LEARNING TOOLS

Emphasis on Physics

A distinctive feature of this book is its emphasis on the physical aspects of subject matter rather than mathematical representations and manipulations. The authors believe that the emphasis in undergraduate education should remain on *developing a sense of underlying physical mechanism* and a *mastery of solving practical problems* an engineer is likely to face in the real world. Developing an intuitive understanding should also make the course a more pleasant and worthwhile experience for the students.

Effective Use of Association

An observant mind should have no difficulty understanding engineering sciences. After all, the principles of engineering sciences are based on our *everyday experiences* and *experimental observations.* A more physical, intuitive approach is used throughout this text. 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. The process of cooking, for example, serves as an excellent vehicle to demonstrate the basic principles of thermodynamics.

Self-Instructing

The material in the text is introduced at a level that an average student can follow comfortably. It speaks to students, not over students. In fact, it is *self-instructive.* The order of coverage is *from simple to general.* That is, it starts with the simplest case and adds complexities gradually. 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. Noting that the principles of sciences are based on experimental observations, all the derivations in this text are based on physical arguments, and thus they are easy to follow and understand.

Presenting the Material in a Logical Order

The subject matter 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. Following a discussion of energy transfer by heat, work, and mass, the energy balance relation is developed and is applied to various systems. The concepts of entropy, exergy, and second-law efficiency 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.

Extensive Use of Artwork

Figures are important learning tools that help the students "get the picture." The text makes effective use of graphics. It contains more figures and illustrations than any other book in this category. Figures attract attention and stimulate curiosity and interest. Some of the figures in this text are intended to

serve as a means of emphasizing some key concepts that would otherwise go unnoticed; some serve 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 can't be fun?

Chapter Openers and Summaries

Each chapter begins with an overview of the material to be covered and its relation to other chapters. A *summary* is included at the end of each chapter for a quick review of basic concepts and important relations.

Numerous Worked-Out Examples

Each chapter contains several worked-out *examples* that clarify the material and illustrate the use of the basic principles. An *intuitive* 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.

A Wealth of Realistic End-of-Chapter Problems

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 under *Review Problems* are more comprehensive in nature and are not directly tied to any specific section of a chapter. The problems under the *Design and Essay Problems* title are intended to encourage students to make engineering judgments, to conduct independent exploration of topics of interest, and to communicate their findings in a professional manner. Several economics- and safety-related problems are incorporated throughout to enhance cost and safety awareness among engineering students. Answers to selected problems are listed immediately following the problem for convenience to students.

A Systematic Solution Procedure

A well-structured approach is used in problem solving while maintaining an informal conversational style. The problem is first stated and the objectives are identified, and the assumptions made are stated together with their justifications. Numerical values are used together with their units to emphasize that numbers without units are meaningless, and unit manipulations are as important as manipulating the numerical values with a calculator. The significance of the findings is discussed following the solutions. This approach is also used consistently in the solutions presented in the Solutions Manual.

Physically Meaningful Formulas

The physically meaningful forms of the conservation equations rather than formulas are used to foster deeper understanding and to avoid a cookbook approach. The mass, energy, entropy, and exergy balances for *any system* undergoing *any process* are expressed as

Mass balance: $$m_{in} - m_{out} = \Delta m_{system}$$

Energy balance: $$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic, potential, etc., energies}}$$

Entropy balance: $$\underbrace{S_{in} - S_{out}}_{\text{Net entropy transfer by heat and mass}} + \underbrace{S_{gen}}_{\text{Entropy generation}} = \underbrace{\Delta S_{system}}_{\text{Change in entropy}}$$

Exergy balance: $$\underbrace{X_{in} - X_{out}}_{\text{Net exergy transfer by heat, work, and mass}} - \underbrace{X_{destroyed}}_{\text{Exergy destruction}} = \underbrace{\Delta X_{system}}_{\text{Change in exergy}}$$

The relations above reinforce that during an actual process mass and energy are conserved, entropy is generated, and exergy is destroyed. Students are encouraged to use these forms of balances in early chapters after they specify the system, and to simplify them for the particular problem. A more relaxed approach is used in later chapters as students gain mastery.

Relaxed Sign Convention

The use of a formal sign convention for heat and work is abandoned as it often becomes counterproductive. A physically meaningful and engaging approach is adopted for interactions instead of a mechanical approach. Subscripts "in" and "out," rather than the plus and minus signs, are used to indicate the directions of interactions.

A Choice of SI Alone or SI/English Units

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 appendixes 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, and they can be ignored easily by SI users.

Conversion Factors

Frequently used conversion factors and the physical constants are listed on the inner cover pages of the text for easy reference.

SUPPLEMENTS

The following supplements are available to the adopters of the book.

Instructor's Solutions Manual

Available to instructors only, this manual features detailed solutions prepared using an equation editor complete with illustrations. The solutions are suitable for posting or using as handouts in class.

EES Software

Developed by Sanford Klein and William Beckman from the University of Wisconsin—Madison, this software program allows students to solve problems, especially design problems, and to ask "what if" questions. EES (pronounced "ease") is an acronym for Engineering Equation Solver. EES is very easy to master since equations can be entered in any form and in any order. The combination of equation-solving capability and engineering property data makes EES an extremely powerful tool for students.

EES can do optimization, parametric analysis, and linear and nonlinear regression and provides publication-quality plotting capability. Equations can be entered in any form and in any order. EES automatically rearranges the equations to solve them in the most efficient manner. EES is particularly useful for thermodynamics problems since most of the property data needed for solving such problems are provided in the program. For example, the steam tables are implemented such that any thermodynamic property can be obtained from a built-in function call in terms of any two properties. Similar capability is provided for many organic refrigerants, ammonia, methane, carbon dioxide, and many other fluids. Air tables are built-in, as are psychrometric functions and JANAF table data for many common gases. Transport properties are also provided for all substances. EES also allows the user to enter property data or functional relationships with lookup tables, with internal functions written with EES, or with externally compiled functions written in Pascal, C, C++, or Fortran.

The *Student Resources CD* that accompanies the text contains the *Limited Academic Version* of the EES program and the scripted EES solutions of about 50 homework problems (indicated by the "EES" logo in the text). Each EES solution provides detailed comments and on-line help, and can easily be modified to solve similar problems. These solutions should help the student master the important concepts without the calculational burden that has been previously required.

Thermodynamics Tutorial

Also included on the *Student Resources CD* packaged free with the text is the *Interactive Thermodynamics Tutorial* developed by Edward Anderson of Texas Tech University. This tutorial allows students to further explore difficult topics such as Entropy and the Second Law of Thermodynamics.

Online Learning Center

Students and instructors using this book will have access to the text-specific Online Learning Center (OLC) at http://www.mhhe.com/cengel-boles. OLCs are the perfect solution for Internet-based content. These exclusive websites follow the text chapter by chapter and contain additional instructor and student supplements, including a Student Study Guide (developed by text co-author Michael Boles), FE Exam Review style quizzes, and instructional aids including Power Point Presentations.

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CONTENTS