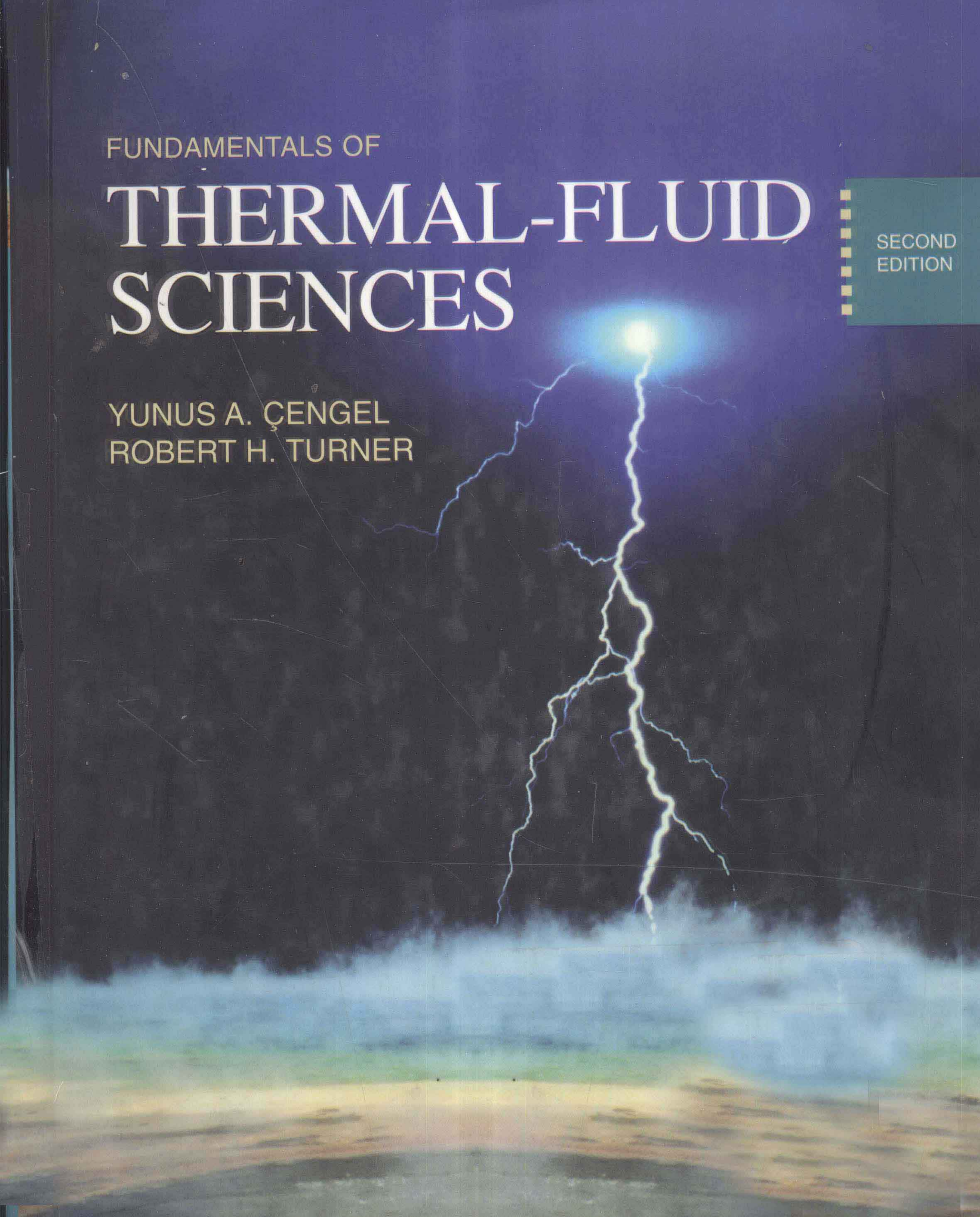
FUNDAMENTALS OF

THERMAL-FLUID SCIENCES

SECOND EDITION

YUNUS A. ÇENGEL
ROBERT H. TURNER



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both of the Department of Mechanical Engineering University of Nevada, Reno

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Dedication

In the future mankind will turn to sciences and learning. It will obtain all its power from sciences. Power and rule will then pass to the hands of sciences and knowledge. Eloquence and beauty of expression, the most brilliant of all arts and sciences, will be the most sought after in all their varieties. Even, in order to make one another accept their ideas and carry out their word, people will find their most effective weapon in eloquent expression, and their most irresistible force in fine oratory.

—Said Nursi, 1930

About the Authors

Yunus A. Çengel is Professor Emeritus of Mechanical Engineering at the University of Nevada, Reno. He received his Ph.D. in mechanical engineering from North Carolina State University. His research areas are renewable energy, desalination, exergy analysis, heat transfer enhancement, radiation heat transfer, 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 the coauthor of the widely adopted textbook *Thermodynamics: An Engineering Approach,* 4th edition (2002), published by McGraw-Hill. He is also the author of the textbooks *Heat Transfer: A Practical Approach,* 2nd edition (2003), and *Introduction to Thermodynamics and Heat Transfer* (1997), both 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).

Robert H. Turner is Professor Emeritus of Mechanical Engineering at the University of Nevada, Reno (UNR). He earned a B.S. and M.S. from the University of California at Berkeley, and his Ph.D. from UCLA, all in mechanical engineering. He worked in industry for 18 years, including nine years at Cal Tech's Jet Propulsion Laboratory (JPL). Dr. Turner then joined the University of Nevada in 1983. His research interests include solar and renewable energy applications, thermal sciences, and energy conservation. He established and was the first director of the Industrial Assessment Center at the University of Nevada.

For 20 years Dr. Turner has designed the solar components of many houses. In 1994–95, in a cooperative effort between UNR and Erciyes University in Kayseri, Turkey, he designed and oversaw construction of the fully instrumented Solar Research Laboratory at Erciyes University, featuring 130 square meters of site-integrated solar collectors. His interest in applications has led Dr. Turner to maintain an active consulting practice.

Dr. Turner is a registered Professional Engineer and is a member of the American Society of Mechanical Engineers (ASME) and the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE).

PREFACE

BACKGROUND

This text is an abbreviated version of standard thermodynamics, fluid mechanics, and heat transfer texts, covering topics that engineering students are most likely to need in their professional lives. The thermodynamics portion of this text is based on the text *Thermodynamics: An Engineering Approach* by Y. A. Çengel and M. A. Boles, the fluid mechanics portion is based on *Fluid Mechanics: Fundamentals and Applications* by Y. A. Çengel and J. M. Cimbala, and the heat transfer portion is based on *Heat Transfer: A Practical Approach* by Y. A. Çengel, all published by McGraw-Hill. Most chapters are practically independent of each other and can be covered in any order. The text is well suited for curriculums that have a common introductory course or a two-course sequence on thermal-fluid sciences.

It is recognized that all topics of thermodynamics, fluid mechanics, and heat transfer cannot be covered adequately in a typical three-semester-hour course, and therefore, sacrifices must be made from depth if not from the breadth. Selecting the right topics and finding the proper level of depth and breadth are no small challenge for the instructors, and this text is intended to serve as the ground for such selection. Students in a combined thermal-fluids course can gain a basic understanding of energy and energy interactions, various mechanisms of heat transfer, and fundamentals of fluid flow. Such a course can also instill in students the confidence and the background to do further reading of their own and to be able to communicate effectively with specialists in thermal-fluid sciences.

OBJECTIVES

This book is intended for use as a textbook in a first course in thermal-fluid sciences for undergraduate engineering students in their junior or senior year, and as a reference book for practicing engineers. Students are assumed to have an adequate background in calculus, physics, and engineering mechanics. The objectives of this text are

- To cover the *basic principles* of thermodynamics, fluid mechanics, and heat transfer.
- To present numerous and diverse real-world *engineering examples* to give students a feel for how thermal-fluid sciences are applied in engineering practice.
- To develop an *intuitive understanding* of thermal-fluid sciences by emphasizing the physics and physical arguments.

The text contains sufficient material to give instructors flexibility and to accommodate their preferences on the right blend of thermodynamics, fluid mechanics, and heat transfer for their students. By careful selection of topics, an instructor can spend one-third, one-half, or two-thirds of the course on thermodynamics and the rest on selected topics of fluid mechanics and heat transfer.

PHILOSOPHY AND GOAL

The philosophy that contributed to the warm reception of the first edition of this book has remained unchanged. Namely, our goal is to offer an engineering textbook that

- Communicates directly to the minds of tomorrow's engineers in a *simple yet precise* manner.
- Leads students toward a clear understanding and firm grasp of the *basic principles* of thermal-fluid sciences without getting bogged down in mathematical detail.
- Encourages *creative thinking* and development of a *deeper understanding* and *intuitive feel* for thermal-fluid sciences.
- Is *read* by students with *interest* and *enthusiasm* rather than being used as an aid to solving 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 thermal-fluid sciences. The enthusiastic response we received from the users of the first edition all over the world indicates that our objectives have largely been achieved.

Yesterday's engineers spent a major portion of their time substituting values into the formulas and obtaining numerical results. Now, however, formula manipulations and number crunching are being left to 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 modern tools are used in engineering practice.

NEW IN THIS EDITION

All the popular features of the previous edition are retained while new ones are added. The main body of the text remains largely unchanged except that three new chapters are added, and a fourth one is available on the Web. The most significant changes in this edition are highlighted next.

FOUR NEW CHAPTERS

The thermodynamics part of the text now contains a new chapter *Gas Mixtures and Psychrometrics* (Chapter 9), where the properties of nonreacting ideal-gas mixtures are discussed, and common air-conditioning processes are examined. The fluid mechanics part of the text contains two additional chapters: *Momentum Analysis of Flow Systems* (Chapter 13) where the linear and angular momentum equations are discussed, and *Dimensional Analysis and Modeling* (available as a web chapter) contributed by John M. Cimbala. The additional chapter in the heat transfer part of the text is *Fundamentals of Thermal Radiation* (Chapter 21), where the basic concepts of radiation and radiation properties are discussed. The most significant changes in this edition are highlighted next.

COMPREHENSIVE PROBLEMS WITH PARAMETRIC STUDIES

A distinctive feature of this edition is the incorporation of about 230 comprehensive problems that require conducting extensive parametric studies, using the enclosed Engineering Equation Solver (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-EES icon for easy recognition, and can be ignored if desired. Solutions of these problems are given in the *Instructor's Solutions Manual.*

CONTENT CHANGES AND REORGANIZATION

With the exception of the changes already mentioned, the main body of the text remains largely unchanged. This edition involves over 500 new or revised problems. The noteworthy changes in various chapters are summarized here for those who are familiar with the previous edition.

- In Chapter 1, the sections on *Closed and Open Systems* and *Properties of a System* are moved to Chapter 2, and the *Conservation of Mass Principle* is moved to Chapter 4. A new section *Accuracy, Precision, and Significant Digits* is added.
- In Chapter 2, a new section *Energy and Environment* is added in addition to the two sections moved from Chapter 1.
- In Chapter 3, the section *Vapor Pressure and Phase Equilibrium* is deleted since it is now covered in Chapter 9, and a new section *Compressibility Factor* is added to complement the discussions of ideal gas.
- In Chapter 4, a new section *Conservation of Mass Principle* (moved from Chapter 1) is added.
- In Chapter 6, the section *Household Refrigerators* is deleted.
- In Chapter 7, a new section *Entropy Balance* is added.
- In Chapter 10 (old Chapter 9), a new section *Vapor Pressure and Cavitation* is added, and the section *Viscosity* is greatly revised.
- In Chapter 11 (old Chapter 10), a new section *Fluids in Rigid-Body Motion* is added, and the section *Buoyancy and Stability* is greatly revised.
- In Chapter 13 (old Chapter 11), four new sections *Basic Conservation Relations, Choosing a Control Volume, Forces Acting on a Control Volume,* and *The Angular Momentum Equation* are added. All other sections are greatly revised.
- In Chapter 14 (old Chapter 12), a new section *The Entrance Region* is added, the section *Laminar Flow in Pipes* is greatly revised.
- In Chapter 15 (old Chapter 13), the first three sections are greatly revised.
- In Chapter 17 (old Chapter 15), the section *Thermal Insulation* is deleted and a new section *Heat Transfer in Common Configurations* is added.
- In Chapter 19 (old Chapter 17), the covered topics remain the same, but the material in all sections is greatly revised.

- In Chapter 20 (old Chapter 18), two new sections *Equation of Motion and the Grashof Number* and *Natural Convection from Finned Surfaces and PCBs* are added. The remaining part of the chapter is completely rewritten, and the Nusselt number relations for rectangular enclosures are updated.
- In Chapters 21 and 22 (old Chapter 19), a new section *Radiation Intensity* is added, and the section *Radiation Properties* is rewritten. The basic concepts associated with thermal radiation are covered in Chapter 21 *Fundamentals of Thermal Radiation,* while radiation exchange between surfaces is discussed in Chapter 22 *Radiation Heat Transfer*.
- In the appendixes, the values of the physical constants are updated; new tables for the properties of saturated ammonia and propane are added; and the tables on the properties of air, gases, and liquids (including liquid metals) are replaced by those obtained using EES. Therefore, property values in tables for air, other ideal gases, ammonia, propane, and liquids are identical to those obtained from EES.

LEARNING TOOLS

EMPHASIS ON PHYSICS

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

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.* Noting that the principles of sciences are based on experimental observations, most of the derivations in this text are largely based on physical arguments, and thus they are easy to follow and understand.

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 page summaries.

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 WEALTH OF REAL-WORLD 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. Within each group of problems are *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—in some cases they require review of material learned in previous chapters. 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. The properties needed to solve the problem are listed separately. 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 *Instructor's Solutions Manual.*

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 the SI users.

CONVERSION FACTORS

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

SUPPLEMENTS

These supplements are available to the adopters of the book.

EES SOFTWARE

Developed by Sanford Klein and William Beckman from the University of Wisconsin–Madison, this software program enables 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 heat transfer 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 enables the user to enter property data or functional relationships with look-up 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 30 homework problems (indicated by the "EES-CD" logo in the text). Each EES solution provides detailed comments and online help, and can easily be modified to solve similar problems. These solutions should help students master the important concepts without the calculational burden that has been previously required. The full Academic Version of EES is available free to departments of educational institutions who adopt the text. Instructors should contact their McGraw-Hill sales representative or go to the Online Learning Center for further download instructions.

BOOK-SPECIFIC ONLINE LEARNING CENTER (OLC)

The book website can be found at www.mhhe.com/cengel/. Visit this site for book and supplement information, author information, and resources for further study or reference.

THREE WEB-BASED CHAPTERS

Three web-based chapters are available on the Online Learning Center (www.mhhe.com/cengel/). These chapters are *Dimensional Analysis and Modeling, Heating and Cooling of Buildings,* and *Cooling of Electronic Equipment.*

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Yunus A. Çengel
Robert H. Turner

NOMENCLATURE

a	Acceleration, m/s^2
A_s	Surface area, m^2
A_c	Cross-sectional area, m^2
Bi	Biot number
C	Speed of sound, m/s
C	Specific heat, kJ/kg · K
C_c, C_h	Heat capacity rate, W/°C
C_D	Drag coefficient
C_f	Friction coefficient
C_L	Lift coefficient
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
D_h	Hydraulic diameter, m
e	Specific total energy, kJ/kg
erfc	Complementary error function
E	Total energy, kJ
E_b	Blackbody emissive flux
EER	Energy efficiency rating
f	Friction factor
f_λ	Blackbody radiation function
F	Force, N
F_D	Drag force, N
F_{ij}, $F_{i \to j}$	View factor
F_L	Lift force, N
g	Gravitational acceleration, m/s^2
G	Incident radiation, W/m^2
Gr	Grashof number
h	Convection heat transfer coefficient, W/m^2 · °C
h	Specific enthalpy, $u + Pv$, kJ/kg
h_c	Thermal contact conductance, W/m^2 · °C
h_{fg}	Enthalpy of vaporization, kJ/kg
h_L	Head loss, m
H	Total enthalpy, $U + PV$, kJ
I	Electric current, A; Radiation intensity, W/m^2 · sr
J	Radiosity, W/m^2; Bessel function
k	Specific heat ratio, C_p/C_v
k	Thermal conductivity
k_{eff}	Effective thermal conductivity, W/m · °C
k_s	Spring constant
ke	Specific kinetic energy, $\mathcal{V}^2/2$, kJ/kg
K_{loss}	Loss coefficient
KE	Total kinetic energy, $m\mathcal{V}^2/2$, kJ
L	Length; half thickness of a plane wall
L_c	Characteristic or corrected length
L_h	Hydrodynamic entry length
L_t	Thermal entry length
m	Mass, kg
$\dot{m}$	Mass flow rate, kg/s
M	Molar mass, kg/kmol
MEP	Mean effective pressure, kPa
n	Polytropic exponent
N	Number of moles, kmol
NTU	Number of transfer units
Nu	Nusselt number

p	Perimeter, m
pe	Specific potential energy, gz, kJ/kg
P	Pressure, kPa
P_{cr}	Critical pressure, kPa
P_r	Relative pressure
P_R	Reduced pressure
P_v	Vapor pressure, kPa
PE	Total potential energy, mgz, kJ
Pr	Prandtl number
q	Heat transfer per unit mass, kJ/kg
$\dot{q}$	Heat flux, W/m^2
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_c	Cutoff ratio
r_{cr}	Critical radius of insulation, m
r_p	Pressure ratio
R	Gas constant, kJ/kg · K
R	Radius, m; Thermal resistance, °C/W
R_c	Thermal contact resistance, m^2 · °C/W
R_f	Fouling factor
R_u	Universal gas constant, kJ/kmol · K
R-value	R-value of insulation
Ra	Rayleigh number
Re	Reynolds number
s	Specific entropy, kJ/kg · K
s_{gen}	Specific entropy generation, kJ/kg · K
S	Total entropy, kJ/K; Conduction shape factor
S_{gen}	Total entropy generation, kJ/K
t	Time, s; Thickness, m
T	Temperature, °C or K
T	Torque, N · m
T_b	Bulk fluid temperature, °C
T_{cr}	Critical temperature, K
T_f	Film temperature, °C
T_H	Temperature of high-temperature body, K
T_L	Temperature of low-temperature body, K
T_R	Reduced temperature
T_s	Surface temperature, °C or K
T_{sat}	Saturation temperature, °C
u	Specific internal energy, kJ/kg
u, v	x- and y-components of velocity
U	Total internal energy, kJ
U	Overall heat transfer coefficient, W/m^2 · °C
v	Specific volume, m^3/kg
v_{cr}	Critical specific volume, m^3/kg
v_r	Relative specific volume
V	Total volume, m^3
$\dot{V}$	Volume flow rate, m^3/s
$\mathcal{V}$	Velocity, m/s
$\mathcal{V}_m$	Mean velocity, m/s
$\mathcal{V}_\infty$	Free-stream 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
x	Quality
z	Elevation, m
Z	Compressibility factor

Greek Letters

α	Absorptivity
α	Thermal diffusivity, m^2/s
α_s	Solar absorptivity

β	Volume expansivity, 1/K
δ	Velocity boundary layer thickness, m
ΔP	Pressure drop, Pa
ΔT_{lm}	Log mean temperature difference
ε	Emissivity; heat exchanger or fin effectiveness
ε	Roughness size, m
η_{fin}	Fin efficiency
η_{th}	Thermal efficiency
θ	Total energy of a flowing fluid, kJ/kg
μ	Dynamic viscosity, kg/m · s or N · s/m^2
υ	Kinematic viscosity $= \mu/\rho$, m^2/s; frequency, 1/s
ρ	Density, kg/m^3
ρ_s	Relative density
σ	Stefan–Boltzmann constant
σ_n	Normal stress, N/m^2
σ_s	Surface tension, N/m
τ	Shear stress, N/m^2
τ	Transmissivity; Fourier number
τ_w	Wall shear stress, N/m^2
ϕ	Relative humidity
θ	Dimensionless temperature
ω	Specific or absolute humidity, kg H_2O/kg dry air

Subscripts

a	Air
abs	Absolute
act	Actual
atm	Atmospheric
b	Boundary; bulk fluid
cond	Conduction
conv	Convection
cr	Critical point
cv	Control volume
e	Exit conditions
f	Saturated liquid; film
fg	Difference in property between saturated liquid and saturated vapor
g	Saturated vapor
H	High temperature as in T_H and Q_H
i	Inlet, initial, or indoor conditions
L	Low temperature as in T_L and Q_L
o	Outlet or outdoor conditions
r	Relative
rad	Radiation
s	Surface
surr	Surrounding surfaces
sat	Saturated
sys	System
υ	Water vapor
1	Initial or inlet state
2	Final or exit state
∞	Far from a surface; free-flow conditions

Superscripts

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

CONTENTS