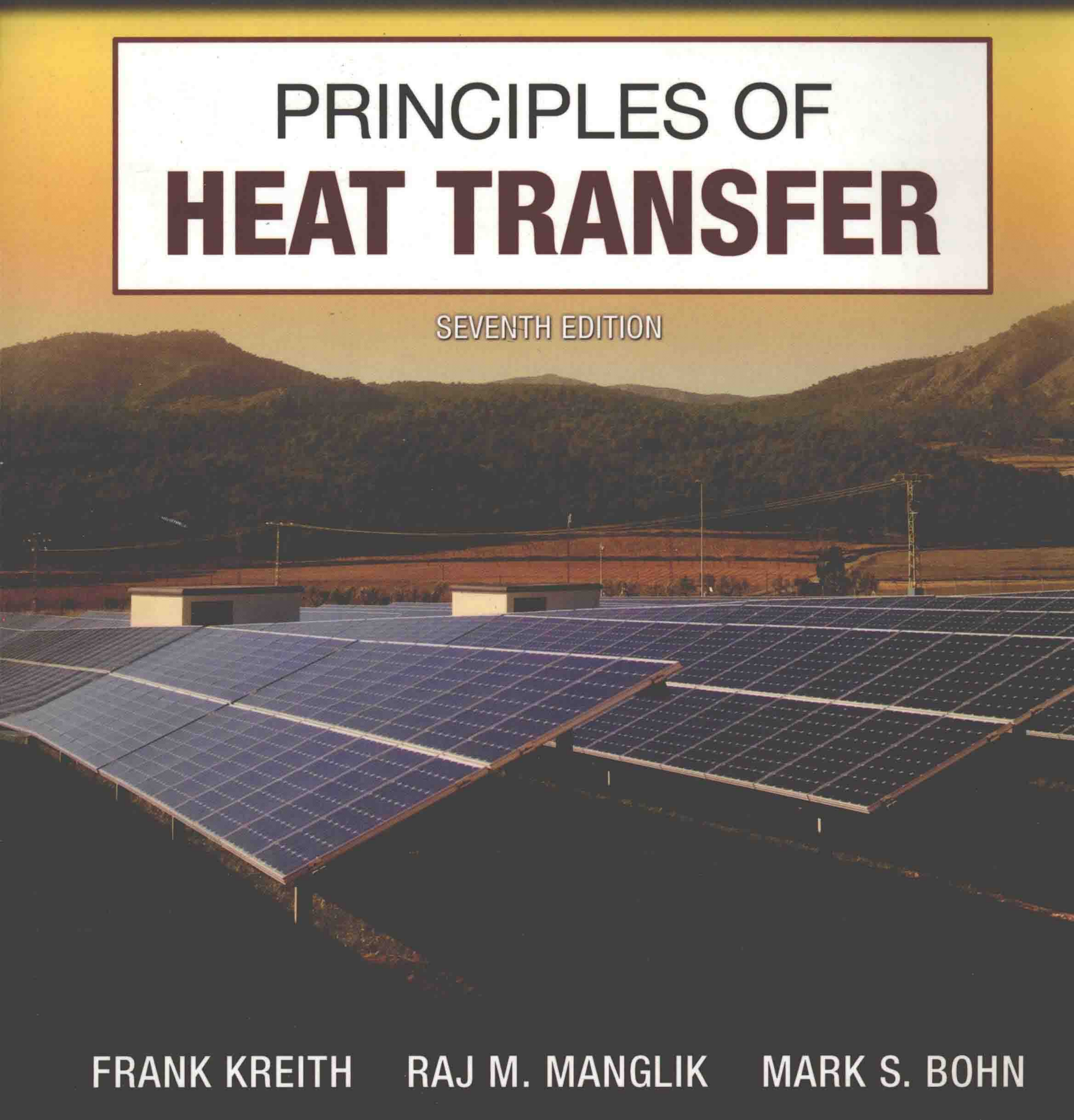
SI EDITION

PRINCIPLES OF HEAT TRANSFER

SEVENTH EDITION



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Principles of

HEAT TRANSFER

Seventh Edition, SI

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To our students
all over the world

PREFACE TO THE SI EDITION

This edition of *Principles of Heat Transfer, Seventh Edition,* has been adapted to incorporate the International System of Units (*Le Système International d'Unités* or SI) throughout the book.

Le Système International d'Unités

The United States Customary System (USCS) of units uses FPS (foot-pound-second) units (also called English or Imperial units). SI units are primarily the units of the MKS (meter-kilogram-second) system. However, CGS (centimeter-gram-second) units are often accepted as SI units, especially in textbooks.

Using SI Units in this Book

In this book, we have used both MKS and CGS units. USCS units or FPS units used in the US Edition of the book have been converted to SI units throughout the text and problems. However, in case of data sourced from handbooks, government standards, and product manuals, it is not only extremely difficult to convert all values to SI, it also encroaches upon the intellectual property of the source. Some data in figures, tables, and references, therefore, remains in FPS units. For readers unfamiliar with the relationship between the FPS and the SI systems, a conversion table has been provided inside the front cover.

To solve problems that require the use of sourced data, the sourced values can be converted from FPS units to SI units just before they are to be used in a calculation. To obtain standardized quantities and manufacturers' data in SI units, the readers may contact the appropriate government agencies or authorities in their countries/regions.

Instructor Resources

The Instructors' Solution Manual in SI units is available through your Sales Representative or online through the book website at www.login.cengage.com.

The readers' feedback on this SI Edition will be highly appreciated and will go a long way in helping us improve subsequent editions.

The Publishers

PREFACE

When a textbook that has been used by more than a million students all over the world reaches its seventh edition, it is natural to ask, "What has prompted the authors to revise the book?" The basic outline of how to teach the subject of heat transfer, which was pioneered by the senior author in its first edition, published 60 years ago, has now been universally accepted by virtually all subsequent authors of heat transfer texts. Thus, the organization of this book has essentially remained the same over the years, but newer experimental data and, in particular the advent of computer technology, have necessitated reorganization, additions, and integration of numerical and computer methods of solution into the text.

The need for a new edition was prompted primarily by the following factors: 1) When a student begins to read a chapter in a textbook covering material that is new to him or her, it is useful to outline the kind of issues that will be important. We have, therefore, introduced at the beginning of each chapter a summary of the key issues to be covered so that the student can recognize those issues when they come up in the chapter. We hope that this pedagogic technique will help the students in their learning of an intricate topic such as heat transfer. 2) An important aspect of learning engineering science is to connect with practical applications, and the appropriate modeling of associated systems or devices. Newer applications, illustrative modeling examples, and more current state-of-the art predictive correlations have, therefore, been added in several chapters in this edition. 3) The sixth edition used MathCAD as the computer method for solving real engineering problems. During the ten years since the sixth edition was published, the teaching and utilization of MathCAD has been supplanted by the use of MATLAB. Therefore, the MathCAD approach has been replaced by MATLAB in the chapter on numerical analysis as well as for the illustrative problems in the real world applications of heat transfer in other chapters. 4) Again, from a pedagogic perspective of assessing student learning performance, it was deemed important to prepare general problems that test the students' ability to absorb the main concepts in a chapter. We have, therefore, provided a set of Concept Review Questions that ask a student to demonstrate his or her ability to understand the new concepts related to a specific area of heat transfer. These review questions are available on the book website in the Student Companion Site at www.cengagebrain.com. Solutions to the Concepts Review Questions are available for Instructors on login.cengage.com. 5) Furthermore, even though the sixth edition had many homework problems for the students, we have introduced some additional problems that deal directly with topics of current interest such as the space program and renewable energy.

The book is designed for a one-semester course in heat transfer at the junior or senior level. However, we have provided some flexibility. Sections marked with asterisks can be omitted without breaking the continuity of the presentation. If all the sections marked with an asterisk are omitted, the material in the book can be covered in a single quarter. For a full semester course, the instructor can select five or six of these sections and thus emphasize his or her own areas of interest and expertise.

The senior author would also like to express his appreciation to Professor Raj M. Manglik, who assisted in the task of updating and refreshing the sixth edition to bring it up to speed for students in the twenty-first century. In turn, Raj Manglik is profoundly grateful for the opportunity to join in the authorship of this revised edition, which should continue to provide students worldwide an engaging learning experience in heat transfer. Although Dr. Mark Bohn decided not to participate in the seventh edition, we wish to express our appreciation for his previous contribution. In addition, the authors would like to acknowledge the contributions by the reviewers of the sixth edition who have provided input and suggestions for the update leading to the new edition of the book: B. Rabi Baliga, McGill University; F.C. Lai, University of Oklahoma; S. Mostafa Ghiaasiaan, Georgia Tech; Michael Pate, Iowa State University; and Forman A. Williams, University of California, San Diego. The authors would also like to thank Hilda Gowans, the Senior Developmental Editor for Engineering at Cengage Learning, who has provided support and encouragement throughout the preparation of the new edition. On a more personal level, Frank Kreith would like to express his appreciation to his assistant, Bev Weiler, who has supported his work in many tangible and intangible ways, and to his wife, Marion Kreith, whose forbearance with the time taken in writing books has been of invaluable help. Raj Manglik would like to thank his graduate students Prashant Patel, Rohit Gupta, and Deepak S. Kalaikadal for the computational solutions and algorithms in the book. Also, he would like to express his fond gratitude to his wife, Vandana Manglik, for her patient encouragement during the long hours needed in this endeavor, and to his children, Aditi and Animaesh, for their affection and willingness to forego some of our shared time.

NOMENCLATURE

Symbol	Quantity	International System of Units
a	velocity of sound	m/s
a	acceleration	m/s^2
A	area; A_c cross-sectional area; A_p, projected area of a body normal to the direction of flow; A_q, area through which rate of heat flow is q; A_s, surface area; A_o, outside surface area; A_i, inside surface area	m^2
b	breadth or width	m
c	specific heat; c_p, specific heat at constant pressure; c_v, specific heat at constant volume	J/kg K
C	constant	
C	thermal capacity	J/K
C	hourly heat capacity rate in Chapter 8; C_c, hourly heat capacity rate of colder fluid in a heat exchanger; C_h, hourly heat capacity rate of warmer fluid in a heat exchanger	W/K
C_D	total drag coefficient	
C_f	skin friction coefficient; C_{fx}, local value of C_f at distance x from leading edge; $\bar{C}_f$, average value of C_f defined by Eq. (4.31)	
d, D	diameter; D_H, hydraulic diameter; D_o, outside diameter; D_i, inside diameter	m
e	base of natural or Napierian logarithm	
e	internal energy per unit mass	J/kg
E	internal energy	J
E	emissive power of a radiating body; E_b, emissive power of blackbody	W/m^2

Symbol	Quantity	International System of Units
E_λ	monochromatic emissive power per micron at wavelength λ	$W/m^2\ \mu m$
$\mathscr{E}$	heat exchanger effectiveness defined by Eq. (8.22)	
f	Darcy friction factor for flow through a pipe or a duct, defined by Eq. (6.13)	
f	friction coefficient for flow over banks of tubes defined by Eq. (7.37)	
F	force	N
F_T	temperature factor defined by Eq. (9.119)	
F_{1-2}	geometric shape factor for radiation from one blackbody to another	
$\mathscr{F}_{1-2}$	geometric shape and emissivity factor for radiation from one graybody to another	
g	acceleration due to gravity	m/s^2
g_c	dimensional conversion factor	$1.0\ kg\ m/N\ s^2$
G	mass flow rate per unit area ($G = \rho U_\infty$)	$kg/m^2\ s$
G	irradiation incident on unit surface in unit time	W/m^2
h	enthalpy per unit mass	J/kg
h_c	local convection heat transfer coefficient	$W/m^2\ K$
$\bar{h}$	combined heat transfer coefficient $\bar{h} = \bar{h}_c + \bar{h}_r$; h_b, heat transfer coefficient of a boiling liquid, defined by Eq. (10.1); $\bar{h}_c$, average convection heat transfer coefficient; $\bar{h}_r$, average heat transfer coefficient for radiation	$W/m^2\ K$
h_{fg}	latent heat of condensation or evaporation	J/kg
i	angle between sun direction and surface normal	rad
i	electric current	amp
I	intensity of radiation	W/sr
I_λ	intensity per unit wavelength	$W/sr\ \mu m$
J	radiosity	W/m^2

(Continued)

Symbol	Quantity	International System of Units
k	thermal conductivity; k_s, thermal conductivity of a solid; k_f, thermal conductivity of a fluid	W/m K
K	thermal conductance; K_k, thermal conductance for conduction heat transfer; K_c, thermal conductance for convection heat transfer; K_r, thermal conductance for radiation heat transfer	W/K
l	length, general	m
L	length along a heat flow path or characteristic length of a body	m
L_f	latent heat of solidification	J/kg
$\dot{m}$	mass flow rate	kg/s
M	mass	kg
$\mathcal{M}$	molecular weight	gm/gm-mole
N	number in general; number of tubes, etc.	
p	static pressure; p_c, critical pressure; p_A, partial pressure of component A	N/m^2
P	wetted perimeter	m
q	rate of heat flow; q_k, rate of heat flow by conduction; q_r, rate of heat flow by radiation; q_c, rate of heat flow by convection; q_b, rate of heat flow by nucleate boiling	W
$\dot{q}_G$	rate of heat generation per unit volume	W/m^3
q''	heat flux	W/m^2
Q	quantity of heat	J
$\dot{Q}$	volumetric rate of fluid flow	m^3/s
r	radius; r_H, hydraulic radius; r_i, inner radius; r_o, outer radius	m
R	thermal resistance; R_c, thermal resistance to convection heat transfer; R_k, thermal resistance to conduction heat transfer; R_r, thermal resistance to radiation heat transfer	K/W
R_e	electrical resistance	ohm
$\mathcal{R}$	perfect gas constant	8.314 J/K kg-mole

Symbol	Quantity	International System of Units
S	shape factor for conduction heat flow	
S	spacing	m
S_L	distance between centerlines of tubes in adjacent longitudinal rows	m
S_T	distance between centerlines of tubes in adjacent transverse rows	m
t	thickness	m
T	temperature; T_b, temperature of bulk of fluid; T_f, mean film temperature; T_s, surface temperature; T_∞, temperature of fluid far removed from heat source or sink; T_m, mean bulk temperature of fluid flowing in a duct; T_{sv}, temperature of saturated vapor; T_{sl}, temperature of a saturated liquid; T_{fr}, freezing temperature; T_l, liquid temperature; T_{as}, adiabatic wall temperature	K or °C
u	internal energy per unit mass	J/kg
u	time average velocity in x direction; u', instantaneous fluctuating x component of velocity; $\bar{u}$, average velocity	m/s
U	overall heat transfer coefficient	W/m^2 K
U_∞	free-stream velocity	m/s
v	specific volume	m^3/kg
v	time average velocity in y direction; v', instantaneous fluctuating y component of velocity	m/s
V	volume	m^3
w	time average velocity in z direction; w', instantaneous fluctuating z component of velocity	m/s
w	width	m
$\dot{W}$	rate of work output	W
x	distance from the leading edge; x_c, distance from the leading edge where flow becomes turbulent	m

(Continued)

Symbol	Quantity	International System of Units
x	coordinate	m
x	quality	
y	coordinate	m
y	distance from a solid boundary measured in direction normal to surface	m
z	coordinate	m
Z	ratio of hourly heat capacity rates in heat exchangers	
	Greek Letters	
α	absorptivity for radiation; α_λ, monochromatic absorptivity at wavelength λ	
α	thermal diffusivity $= k/\rho c$	m^2/s
β	temperature coefficient of volume expansion	1/K
β_k	temperature coefficient of thermal conductivity	1/K
γ	specific heat ratio, c_p/c_v	
Γ	body force per unit mass	N/kg
Γ_c	mass rate of flow of condensate per unit breadth for a vertical tube	kg/s m
δ	boundary-layer thickness; δ_h, hydrodynamic boundary-layer thickness; δ_{th}, thermal boundary-layer thickness	m
Δ	difference between values	
ε	packed bed void fraction	
ε	emissivity for radiation; ε_λ, monochromatic emissivity at wavelength λ; ε_ϕ, emissivity in direction of ϕ	
ε_H	thermal eddy diffusivity	m^2/s
ε_M	momentum eddy diffusivity	m^2/s
ζ	ratio of thermal to hydrodynamic boundary-layer thickness, δ_{th}/δ_h	

Symbol	Quantity	International System of Units
η_f	fin efficiency	
θ	time	s
λ	wavelength; λ_{max}, wavelength at which monochromatic emissive power $E_{b\lambda}$ is a maximum	μm
λ	latent heat of vaporization	J/kg
μ	absolute viscosity	N s/m^2
ν	kinematic viscosity, μ/ρ	m^2/s
ν_r	frequency of radiation	1/s
ρ	mass density, $1/\nu$; ρ_l, density of liquid; ρ_v, density of vapor	kg/m^3
ρ	reflectivity for radiation	
τ	shearing stress; τ_s, shearing stress at surface; τ_w, shear at wall of a tube or a duct	N/m^2
τ	transmissivity for radiation	
σ	Stefan–Boltzmann constant	W/m^2 K^4
σ	surface tension	N/m
ϕ	angle	rad
ω	angular velocity	rad/s
ω	solid angle	sr
	Dimensionless Numbers	
Bi	Biot number $= \bar{h}L/k_s$ or $\bar{h}r_o/k_s$	
Fo	Fourier modulus $= a\theta/L^2$ or $a\theta/r_o^2$	
Gz	Graetz number $= (\pi/4)\mathrm{RePr}(D/L)$	
Gr	Grashof number $= \beta_g L^3\, \Delta T/\nu^2$	
Ja	Jakob number $= (T_\infty - T_{sat})c_{pl}/h_{fg}$	
M	Mach number $= U_\infty/a$	
Nu_x	local Nusselt number at a distance x from leading edge, $h_c x/k_f$	
$\overline{\mathrm{Nu}}_L$	average Nusselt number for blot plate, $\bar{h}_c L/k_f$	
$\overline{\mathrm{Nu}}_D$	average Nusselt number for cylinder, $\bar{h}_c D/k_f$	

(Continued)

Symbol	Quantity
Pe	Peclet number = RePr
Pr	Prandtl number = $c_p\mu/k$ or ν/α
Ra	Rayleigh number = GrPr
Re_L	Reynolds number = $U_\infty \rho L/\mu$;
$\text{Re}_x = U_\infty \rho x/\mu$	Local value of Re at a distance x from leading edge
$\text{Re}_D = U_\infty \rho D/\mu$	Diameter Reynolds number
$\text{Re}_b = D_b G_b/\mu_l$	Bubble Reynolds number
θ	Boundary Fourier modulus = $\bar{h}^2 a\theta/k_s^2$
St	Stanton number = $\bar{h}_c/\rho U_\infty c_p$ or $\overline{\text{Nu}}$/RePr
	Miscellaneous
$a > b$	a greater than b
$a < b$	a smaller than b
$\propto$	proportional sign
$\simeq$	approximately equal sign
∞	infinity sign
Σ	summation sign

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