INTRODUCTION TO HEAT TRANSFER

Second Edition

FRANK P. INCROPERA
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SECOND EDITION

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Dedicated to those wonderful women in our lives,

Amy, Andrea, Debbie, Donna, Jody, Karen, Shaunna, and Terri

who, through the years, have blessed us with their love, patience, and understanding.

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PREFACE

With the passage of approximately nine years since publication of the first edition, this text has been transformed from the status of a newcomer to a mature representative of heat transfer pedagogy. Despite this maturation, however, we like to think that, while remaining true to certain basic tenets, our treatment of the subject is constantly evolving.

Preparation of the first edition was strongly motivated by the belief that, above all, a first course in heat transfer should do two things. First, it should instill within the student a genuine appreciation for the physical origins of the subject. It should then establish the relationship of these origins to the behavior of thermal systems. In so doing, it should develop methodologies which facilitate application of the subject to a broad range of practical problems, and it should cultivate the facility to perform the kind of engineering analysis which, if not exact, still provides useful information concerning the design and/or performance of a particular system or process. Requirements of such an analysis include the ability to discern relevant transport processes and simplifying assumptions, identify important dependent and independent variables, develop appropriate expressions from first principles, and introduce requisite material from the heat transfer knowledge base. In the first edition, achievement of this objective was fostered by couching many of the examples and end-of-chapter problems in terms of actual engineering systems.

The second edition was also driven by the foregoing objectives, as well as by input derived from a questionnaire sent to over 100 colleagues who used, or were otherwise familiar with, the first edition. A major consequence of this input was publication of two versions of the book, *Fundamentals of Heat and Mass Transfer* and *Introduction to Heat Transfer*. As in the first edition, the *Fundamentals* version included mass transfer, providing an integrated treatment of heat, mass and momentum transfer by convection and separate treatments of heat and mass transfer by diffusion. The *Introduction* version of the book was intended for users who embraced the treatment of heat transfer but did not wish to cover mass transfer effects. In both versions, significant improvements were made in the treatments of numerical methods and heat transfer with phase change.

In this latest edition, changes have been motivated by the desire to expand the scope of applications and to enhance the exposition of physical principles. Consideration of a broader range of technically important problems is facilitated by increased coverage of existing material on thermal contact resistance, fin performance, convective heat transfer enhancement, and compact heat exchangers, as well as by the addition of new material on submerged jets (Chapter 7) and free convection in open, parallel plate channels (Chapter 9). Submerged jets are widely used for industrial cooling and drying operations, while free convection in parallel plate channels is pertinent to passive cooling and heating systems. Expanded discussions of physical principles are concentrated in the chapters on single-phase convection (Chapters 7 to 9) and relate, for example, to forced convection in tube banks and to free convection on plates and in cavities. Other improvements relate to the methodology of performing a first law analysis, a more generalized lumped capacitance analysis, transient conduction in semi-infinite media, and finite-difference solutions.

In this edition, the old Chapter 14, which dealt with multimode heat transfer problems, has been deleted and many of the problems have been transferred to earlier chapters. This change was motivated by recognition of the importance of multimode effects and the desirability of impacting student consciousness with this importance at the earliest possible time. Hence, problems involving more than just a superficial consideration of multimode effects begin in Chapter 7 and increase in number through Chapter 13.

The last, but certainly not the least important, improvement in this edition is the inclusion of nearly 300 new problems. In the spirit of our past efforts, we have attempted to address contemporary issues in many of the problems. Hence, as well as relating to engineering applications such as energy conversion and conservation, space heating and cooling, and thermal protection, the problems deal with recent interests in electronic cooling, manufacturing, and material processing. Many of the problems are drawn from our accumulated research and consulting experiences; the solutions, which frequently are not obvious, require thoughtful implementation of the *tools* of heat transfer. It is our hope that in addition to reinforcing the student's understanding of principles and applications, the problems serve a motivational role by relating the subject to real engineering needs.

Over the past nine years, we have been fortunate to have received constructive suggestions from many colleagues throughout the United States and Canada. It is with pleasure that we express our gratitude for this input.

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SYMBOLS

A	area, m^2
A_c	cross-sectional area, m^2
A_{ff}	free-flow area in compact heat exchanger core (minimum cross-sectional area available for flow through the core), m^2
A_{fr}	heat exchanger frontal area, m^2
A_p	area of prime (unfinned) surface, m^2
A_r	nozzle area ratio
A_s	surface area, m^2
a	acceleration, m/s^2
Bi	Biot number
Bo	Bond number
C	heat capacity rate, W/K
C_D	drag coefficient
C_f	friction coefficient
C_t	thermal capacitance, J/K
c	specific heat, J/kg · K; speed of light, m/s
c_p	specific heat at constant pressure, J/kg · K
c_v	specific heat at constant volume, J/kg · K
D	diameter, m
D_h	hydraulic diameter, m
E	thermal (sensible) internal energy, J; electric potential, V; emissive power, W/m^2
Ec	Eckert number
$\dot{E}_g$	rate of energy generation, W
$\dot{E}_{in}$	rate of energy transfer into a control volume, W
$\dot{E}_{out}$	rate of energy transfer out of control volume, W
$\dot{E}_{st}$	rate of increase of energy stored within a control volume, W
e	thermal internal energy per unit mass, J/kg; surface roughness, m
F	force, N; heat exchanger correction factor; fraction of blackbody radiation in a wavelength band; view factor
Fo	Fourier number
f	friction factor; similarity variable
G	irradiation, W/m^2; mass velocity, $kg/s \cdot m^2$
Gr	Grashof number
Gz	Graetz number
g	gravitational acceleration, m/s^2
g_c	gravitational constant, $1\ kg \cdot m/N \cdot s^2$ or $32.17\ ft \cdot lb_m/lb_f \cdot s^2$
H	nozzle height, m
h	convection heat transfer coefficient, $W/m^2 \cdot K$; Planck's constant
h_{fg}	latent heat of vaporization, J/kg
h_{rad}	radiation heat transfer coefficient, $W/m^2 \cdot K$
I	electric current, A; radiation intensity, $W/m^2 \cdot sr$
i	electric current density, A/m^2; enthalpy per unit mass, J/kg
J	radiosity, W/m^2
Ja	Jakob number
j_H	Colburn j factor for heat transfer
k	thermal conductivity, W/m · K; Boltzmann's constant
L	characteristic length, m
M	mass, kg; number of heat transfer lanes in a flux plot; reciprocal of the Fourier number for finite-difference solutions
$\mathcal{M}$	molecular weight, kg/kmol
m	mass, kg
$\dot{m}$	mass flow rate, kg/s
N	number of temperature increments in a flux plot; total number of tubes in a tube bank; number of surfaces in an enclosure
N_L, N_T	number of tubes in longitudinal and transverse directions
Nu	Nusselt number
NTU	number of transfer units
P	perimeter, m; general fluid property designation
P_L, P_T	dimensionless longitudinal and transverse pitch of a tube bank
Pe	Peclet number ($RePr$)

Pr	Prandtl number
p	pressure, N/m^2
Q	energy transfer, J
q	heat transfer rate, W
$\dot{q}$	rate of energy generation per unit volume, W/m^3
q'	heat transfer rate per unit length, W/m
q''	heat flux, W/m^2
R	cylinder radius, m
$\mathcal{R}$	universal gas constant
Ra	Rayleigh number
Re	Reynolds number
R_e	electric resistance, Ω
R_f	fouling factor, $m^2 \cdot K/W$
$R_{m,n}$	residual for the m, n nodal point
R_t	thermal resistance, K/W
$R_{t,c}$	thermal contact resistance, K/W
r_o	cylinder or sphere radius, m
r, ϕ, z	cylindrical coordinates
r, θ, ϕ	spherical coordinates
S	shape factor for two-dimensional conduction, m; nozzle pitch, m; plate spacing, m
S_c	solar constant
S_D, S_L, S_T	diagonal, longitudinal, and transverse pitch of a tube bank, m
St	Stanton number
T	temperature, K
t	time, s
U	overall heat transfer coefficient, $W/m^2 \cdot K$
$u, v,$	mass average fluid velocity components, m/s
V	volume, m^3; fluid velocity, m/s
v	specific volume, m^3/kg
W	width of a slot nozzle, m
$\dot{W}$	rate at which work is performed, W
We	Weber number
X, Y, Z	components of the body force per unit volume, N/m^3
x, y, z	rectangular coordinates, m
x_c	critical location for transition to turbulence, m
$x_{fd,h}$	hydrodynamic entry length, m
$x_{fd,t}$	thermal entry length, m

Greek Letters

α	thermal diffusivity, m^2/s; heat exchanger surface area per unit volume, m^2/m^3; absorptivity
β	volumetric thermal expansion coefficient, K^{-1}
Γ	mass flow rate per unit width in film condensation, $kg/s \cdot m$
δ	hydrodynamic boundary layer thickness, m
δ_t	thermal boundary layer thickness, m
ε	emissivity; porosity of a packed bed; heat exchanger effectiveness
ε_f	fin effectiveness
ε_H	turbulent diffusivity for heat transfer, m^2/s
ε_M	turbulent diffusivity for momentum transfer, m^2/s
η	similarity variable
η_f	fin efficiency
η_o	fin temperature effectiveness
θ	zenith angle, rad; temperature difference, K
κ	absorption coefficient, m^{-1}
λ	wavelength, μm
μ	viscosity, $kg/s \cdot m$
ν	kinematic viscosity, m^2/s; frequency of radiation, s^{-1}
ρ	mass density, kg/m^3; reflectivity
σ	Stefan-Boltzmann constant; electrical conductivity, $1/\Omega \cdot m$; normal viscous stress, N/m^2; surface tension, N/m; ratio of heat exchanger minimum cross-sectional area to frontal area
Φ	viscous dissipation function, s^{-2}
ϕ	azimuthal angle, rad
ψ	stream function, m^2/s
τ	shear stress, N/m^2; transmissivity
ω	solid angle, sr

Subscripts

abs	absorbed
adv	advection
am	arithmetic mean
b	base of an extended surface; blackbody
c	cross-sectional; cold fluid
cr	critical insulation thickness
cond	conduction
conv	convection
CF	counterflow
D	diameter; drag
e	excess; emission
evap	evaporation
f	fluid properties; fin conditions; saturated liquid conditions
fd	fully developed conditions

g	saturated vapor conditions
H	heat transfer conditions
h	hydrodynamic; hot fluid
i	inner surface of an annulus; initial condition; tube inlet condition; incident radiation
L	based on characteristic length
l	saturated liquid conditions
lm	log mean condition
M	momentum transfer condition
m	mean value over a tube cross section
max	maximum fluid velocity
o	center or midplane condition; tube outlet condition; outer
R	reradiating surface
r, ref	reflected radiation
rad	radiation
S	solar conditions
s	surface conditions; solid properties
sat	saturated conditions
sky	sky conditions
sur	surroundings
t	thermal
tr	transmitted
v	saturated vapor conditions
x	local conditions on a surface
λ	spectral
∞	freestream conditions

Superscripts

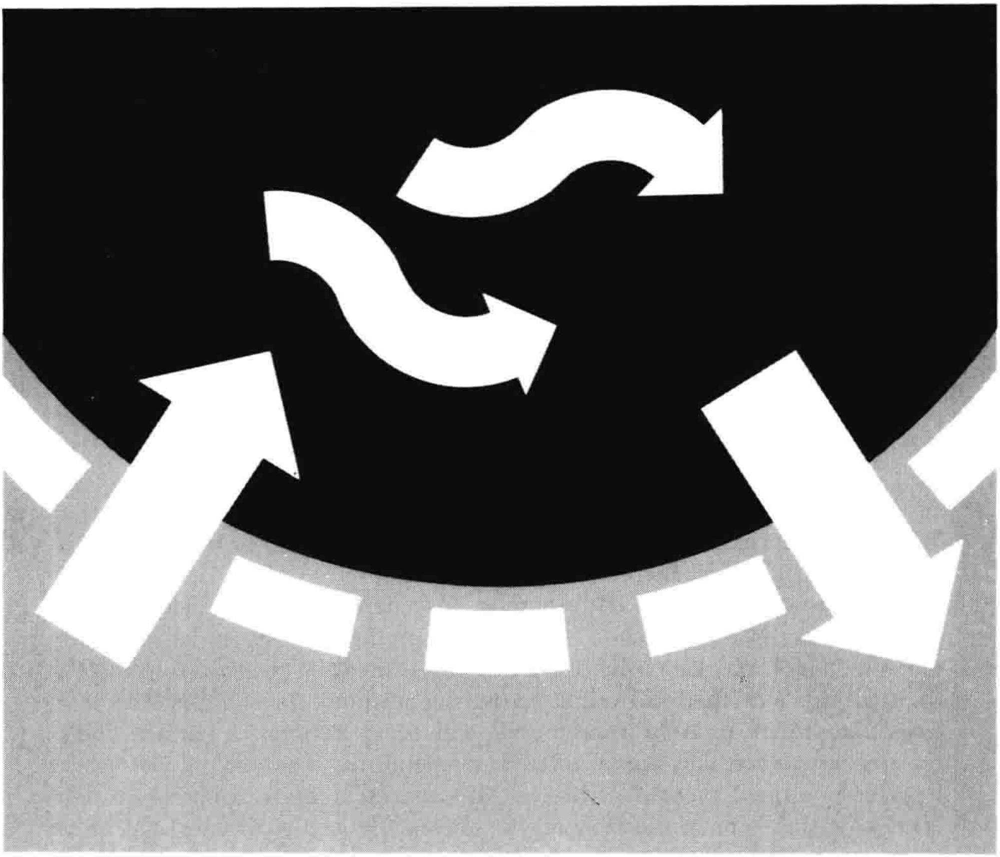
$'$	fluctuating quantity
$*$	dimensionless quantity

Overbar

$\overline{}$	surface average conditions; time mean

CONTENTS

CHAPTER 1



INTRODUCTION