FUNDAMENTALS OF HEAT AND MASS TRANSFER

Third Edition

FRANK P. INCROPERA
DAVID P. DE WITT

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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	molar concentration, $kmol/m^3$; heat capacity rate, W/K
C_D	drag coefficient
C_f	friction coefficient
C_t	thermal capacitance, J/K
c	specific heat, $J/kg \cdot K$; speed of light, m/s
c_p	specific heat at constant pressure, $J/kg \cdot K$
c_v	specific heat at constant volume, $J/kg \cdot K$
D	diameter, m
D_{AB}	binary mass diffusion coefficient, m^2/s
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_m	convection mass transfer coefficient, m/s
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_i^*	diffusive molar flux of species i relative to the mixture molar average velocity, $kmol/s \cdot m^2$
j_i	diffusive mass flux of species i relative to the mixture mass average velocity, $kg/s \cdot m^2$
j_H	Colburn j factor for heat transfer
j_m	Colburn j factor for mass transfer
k	thermal conductivity, $W/m \cdot K$; Boltzmann's constant
k_0	zero-order, homogeneous reaction rate constant, $kmol/s \cdot m^3$
k_1	first-order, homogeneous reaction rate constant, s^{-1}
k_1''	first-order, homogeneous reaction rate constant, m/s
L	characteristic length, m
Le	Lewis number
M	mass, kg; number of heat transfer lanes in a flux plot; reciprocal of the Fourier number for finite-difference solutions
$\dot{M}_i$	rate of transfer of mass for species i, kg/s
$\dot{M}_{i,g}$	rate of increase of mass of species i due to chemical reactions, kg/s
$\dot{M}_{in}$	rate at which mass enters a control volume, kg/s

$\dot{M}_{out}$ rate at which mass leaves a control volume, kg/s
$\dot{M}_{st}$ rate of increase of mass stored within a control volume, kg/s
$\mathcal{M}_i$ molecular weight of species i, kg/kmol
m mass, kg
$\dot{m}$ mass flow rate, kg/s
m_i mass fraction of species i, ρ_i/ρ
N number of temperature increments in a flux plot; total number of tubes in a tube bank; number of surfaces in an enclosure
Nu Nusselt number
NTU number of transfer units
N_i molar transfer rate of species i relative to fixed coordinates, kmol/s
N_i'' molar flux of species i relative to fixed coordinates, kmol/s · m^2
$\dot{N}_i$ molar rate of increase of species i per unit volume due to chemical reactions, kmol/s · m^3
$\dot{N}_i''$ surface reaction rate of species i, kmol/s · m^2
n_i'' mass flux of species i relative to fixed coordinates, kg/s · m^2
$\dot{n}_i$ mass rate of increase of species i per unit volume due to chemical reactions, kg/s · m^3
N_L, N_T number of tubes in longitudinal and transverse directions
P_L, P_T dimensionless longitudinal and transverse pitch of a tube bank
P perimeter, m; general fluid property designation
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 · K/W
R_m mass transfer resistance, s/m^3
$R_{m,n}$ 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 solubility, kmol/m^3 · atm; shape factor for two-dimensional conduction, m; nozzle pitch, m; plate spacing, m
S_c solar constant
Sc Schmidt number
Sh Sherwood number
St Stanton number
S_D, S_L, S_T diagonal, longitudinal, and transverse pitch of a tube bank, m
T temperature, K
t time, s
U overall heat transfer coefficient, W/m^2 · K
u, v, w mass average fluid velocity components, m/s
u^*, v^*, w^* molar average 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
$x_{fd,c}$ concentration entry length, m
$x_{fd,h}$ hydrodynamic entry length, m
$x_{fd,t}$ thermal entry length, m
x_i mole fraction of species i, C_i/C

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 · m
δ hydrodynamic boundary layer thickness, m
δ_c concentration 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

ε_m turbulent diffusivity for mass 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 · 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

A, B species in a binary mixture
abs absorbed
am arithmetic mean
b base of an extended surface; blackbody
c cross-sectional; concentration; cold fluid
cr critical insulation thickness
cond conduction
conv convection
CF counterflow
D diameter; drag
dif diffusion
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 general species designation; 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 mass transfer condition; 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
∞ free stream conditions

Superscripts

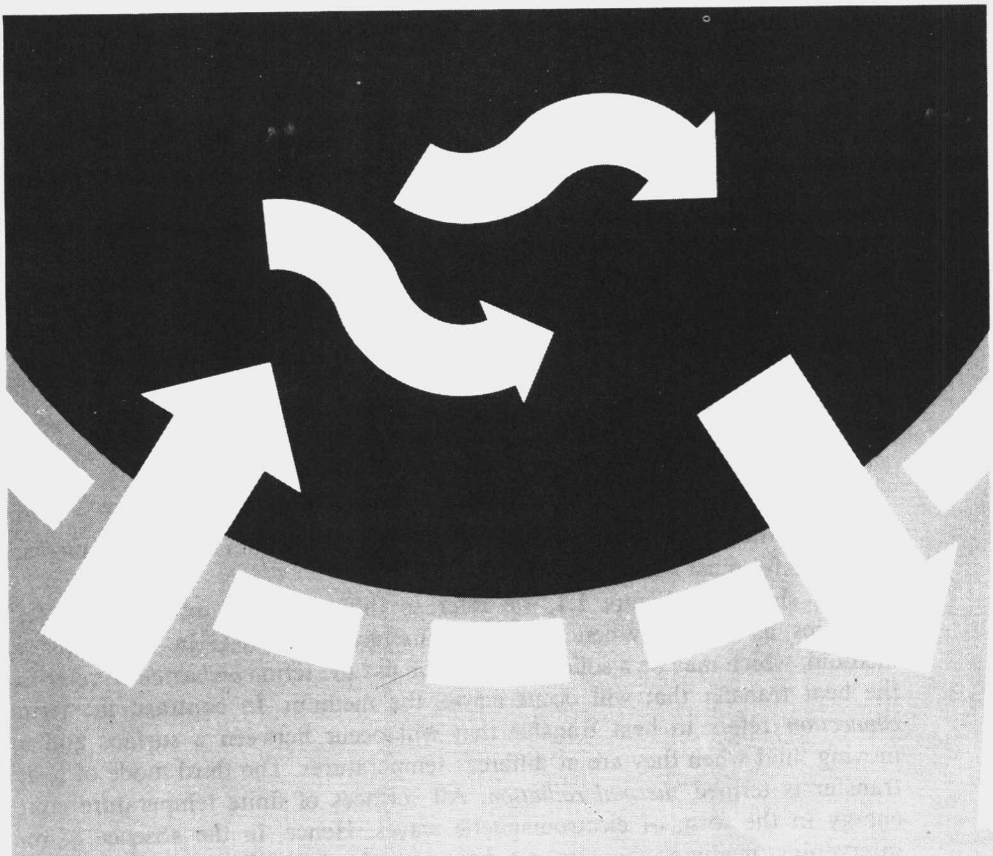
′ fluctuating quantity
* molar average; dimensionless quantity

Overbar

— surface average conditions; time mean

CONTENTS

CHAPTER 1



INTRODUCTION

From the study of thermodynamics, you have learned that energy can be transferred by interactions of a system with its surroundings. These interactions are called work and heat. However, thermodynamics deals with the end states of the process during which an interaction occurs and provides no information concerning the nature of the interaction or the time rate at which it occurs. The objective of this text is to extend thermodynamic analysis through study of the *modes* of heat transfer and through development of relations to calculate heat transfer *rates*. In this chapter we lay the foundation for much of the material treated in the text. We do so by raising several questions. *What is heat transfer? How is heat transferred? Why is it important to study it?* In answering these questions, we will begin to appreciate the physical mechanisms that underlie heat transfer processes and the relevance of these processes to our industrial and environmental problems.

1.1 WHAT AND HOW?

A simple, yet general, definition provides sufficient response to the question: What is heat transfer?

Heat transfer (or heat) is energy in transit due to a temperature difference.

Whenever there exists a temperature difference in a medium or between media, heat transfer must occur.

As shown in Figure 1.1, we refer to different types of heat transfer processes as *modes*. When a temperature gradient exists in a stationary medium, which may be a solid or a fluid, we use the term *conduction* to refer to the heat transfer that will occur across the medium. In contrast, the term *convection* refers to heat transfer that will occur between a surface and a moving fluid when they are at different temperatures. The third mode of heat transfer is termed *thermal radiation*. All surfaces of finite temperature emit energy in the form of electromagnetic waves. Hence, in the absence of an intervening medium, there is net heat transfer by radiation between two surfaces at different temperatures.

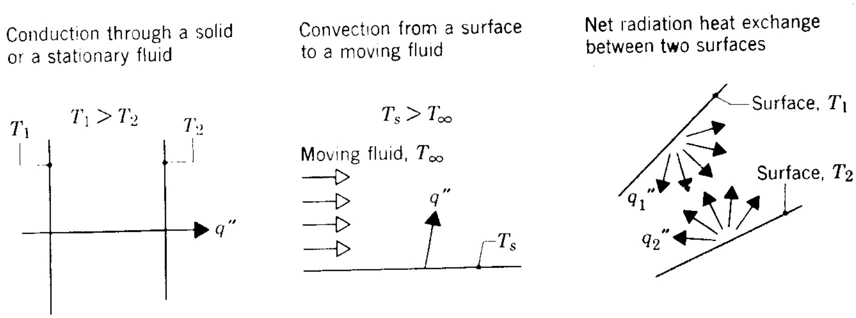


Figure 1.1 Conduction, convection, and radiation heat transfer modes.