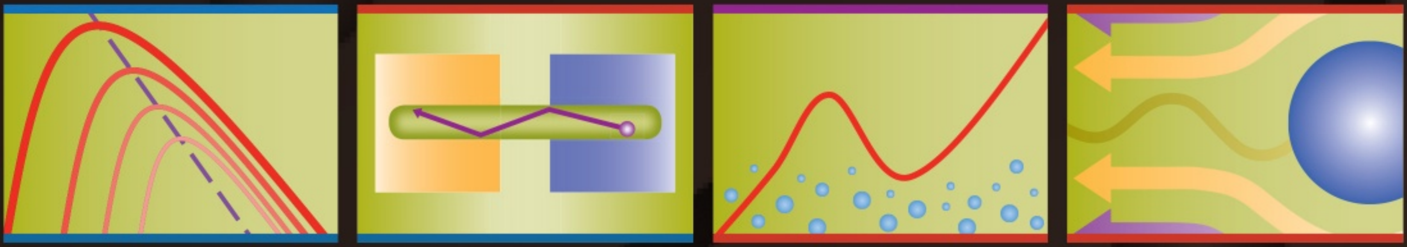
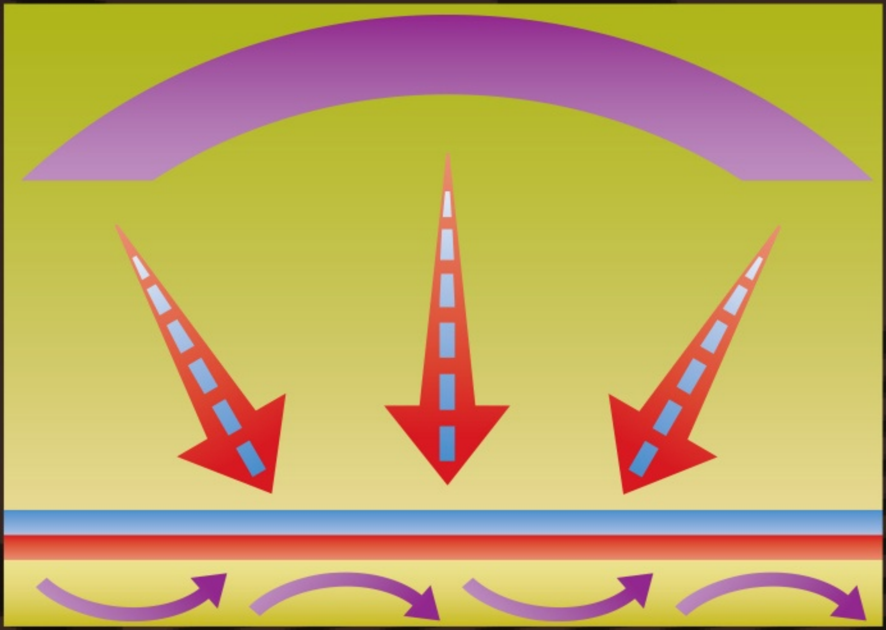


THEODORE L. BERGMAN | ADRIENNE S. LAVINE

FUNDAMENTALS OF HEAT and MASS TRANSFER

EIGHTH EDITION



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EIGHTH EDITION

Fundamentals of Heat and Mass Transfer

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ISBN: 978-1-119-32042-5

The inside back cover will contain printing identification and country of origin if omitted from this page. In addition, if the ISBN on the back cover differs from the ISBN on this page, the one on the back cover is correct.

Library of Congress Cataloging-in-Publication Data

Names: Bergman, Theodore L. | Lavine, Adrienne S.
Title: Fundamentals of heat and mass transfer.
Description: 8th edition / Theodore L. Bergman, Department of Mechanical Engineering, University of Kansas, Adrienne S. Lavine, Mechanical and Aerospace Engineering Department, University of California, Los Angeles. | Hoboken, NJ : John Wiley & Sons, Inc., [2017] | Includes bibliographical references and index.
Identifiers: LCCN 2016053414 (print) | LCCN 2016053784 (ebook) | ISBN 9781119330103 (looseleaf) | ISBN 9781119337676 (pdf) | ISBN 9781119320425 (epub)
Subjects: LCSH: Heat—Transmission. | Mass transfer.
Classification: LCC QC320 .I45 2017 (print) | LCC QC320 (ebook) | DDC 621.402/2—dc23
LC record available at https://lccn.loc.gov/2016053414

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

Preface

In his *Forward to Preface* of the sixth edition of this work, Frank Incropera shared with readers the timeline for the multi-edition transition of authorship from Incropera and DeWitt to Bergman and Lavine. Throughout the 15 years of our involvement with the text, we have been inspired by, and mindful of, Frank's insistence that the quality of the expository material be of paramount importance. We have also attempted to demonstrate the relevance of heat transfer by providing a multitude of examples, ranging from traditional and non-traditional energy generation to potential climate change, where heat transfer plays a vital role.

Since our initial participation in the sixth edition, unexpected developments have evolved in engineering education. For example, the escalating cost of higher education is now debated at all levels of political leadership. As classroom instructors and parents of college students, this concern is not lost on us. In response, we have taken steps to hold the cost of the text in check by reducing its page count and forgoing production of a new edition of the companion text, *Introduction to Heat Transfer*. On the pedagogical front, we have reduced the complexity of many example and end-of-chapter problems. In addition to introducing new end-of-chapter problems, we have modified a significant number of existing problems, often necessitating modified solution approaches.

As in the previous two editions, we have retained a rigorous and systematic problem-solving methodology, and provide a broad range of fundamental as well as applications-motivated end-of-chapter problems that require students to hone and exercise the concepts of heat and mass transfer. We continue to strive to provide a text that will serve as a valuable resource for students and practicing engineers throughout their careers.

Approach and Organization

As in previous editions, we continue to adhere to four broad learning objectives:

1. The student should internalize the meaning of the terminology and physical principles associated with the subject.
2. The student should be able to delineate pertinent transport phenomena for any process or system involving heat or mass transfer.

3. The student should be able to use requisite inputs for computing heat or mass transfer rates and/or material temperatures or concentrations.
4. The student should be able to develop representative models of real processes and systems and draw conclusions concerning process/system design or performance from the attendant analysis.

Also as in previous editions, key concepts are reviewed and questions to test student understanding of the concepts are posed at the end of each chapter.

It is recommended that problems involving complex models and/or parameter sensitivity considerations be addressed using the *Interactive Heat Transfer* (*IHT*) software package that has been developed and refined in conjunction with the text. With its intuitive user interface, extensive built-in thermophysical property database, embedded convection correlations taken from the text, and other useful features, students can master the basic usage of *IHT* in about one hour. To facilitate use of *IHT*, selected example problems in the expository material are identified with an "IHT" icon as shown to the left. These problems are included as demonstrations in the *IHT* software, allowing students to observe how these problems can be solved easily and quickly. More information regarding *IHT* is available later in this preface. Due to the preponderance of readily available software packages capable of solving multi-dimensional conduction problems, the finite-element software package previously made available to students has been discontinued.

Some homework problems require a computer-based solution. Other problems include both a hand calculation and an extension that is computer based. The latter approach is time-tested and promotes the habit of checking computer-generated solutions with hand calculations. Once validated, the computer solution can be utilized to conduct parametric calculations. Problems involving both hand- and computer-generated solutions are identified by enclosing the exploratory part in a red rectangle, as, for example, $\boxed{\text{(b)}}$, $\boxed{\text{(c)}}$, or $\boxed{\text{(d)}}$. This feature also allows instructors to focus their assignments on problems amenable to solution using hand calculations, and benefit from the richness of these problems without assigning the computer-based parts. Problems with a boxed number (for example, $\boxed{1.25}$) require an entirely computer-based solution.

What's New to the 8th Edition

Although the size of the text has been reduced, we have added approximately 90 new and 225 revised end-of-chapter problems, with an emphasis on problems amenable to analytical solutions. Many of the revised problems require modified solution approaches. Within the text, the treatment of thermodynamics has been improved, with clarification of the various forms of energy and their relation to heat transfer. New material on micro- and nanoscale heat transfer and thermal boundary resistances has been added. Mixed convection is presented in a more rigorous manner.

Classroom Coverage

The content of the text has evolved over many years in response to the development of new, fundamental concepts of heat (and mass) transfer and novel ways that the principles of heat transfer are applied. A broad range of engineering disciplines and institutions, with varying missions, make use of this text. Moreover, it is used not only in introductory courses, but also in advanced courses at many colleges and universities. Mindful of this diversity, the authors' intent is *not* to assemble a text whose content is to be covered, in entirety, during a single semester- or quarter-long course. Rather, the text includes fundamental material that should be covered in any introductory heat transfer course, and optional material that can be covered, depending on the mission of the institution, the time available, or the interests of the instructor or practitioner.

Heat and Mass Transfer To assist instructors in preparing a syllabus for a *first course in heat and mass transfer*, we suggest the following (with suggestions for a *first course in heat transfer* further below).

Chapter 1 Introduction sets the stage for any discussion of heat transfer. It explains the science-based linkage between thermodynamics and heat transfer, and the relevance of heat transfer. It should be covered in its entirety. Much of the content of *Chapter 2 Introduction to Conduction* is critical in a first course, especially Section 2.1 The Conduction Rate Equation, Section 2.3 The Heat Diffusion Equation, and Section 2.4 Boundary and Initial Conditions. Section 2.2 The Thermal Properties of Matter need not be covered in depth in a first course.

Chapter 3 One-Dimensional, Steady-State Conduction includes some material that can be assigned depending on the instructor's interest. The optional material includes Section 3.1.5 Porous Media, and Section 3.7 Other Applications of One-Dimensional Steady-State Conduction. The content of *Chapter 4 Two-Dimensional, Steady-State Conduction* is important in that both fundamental concepts and approximate techniques are presented. We recommend that all of Chapter 4 be covered, although some instructors may elect to not include Section 4.4 Finite-Difference Equations and Section 4.5 Solving the Finite-Difference Equations if time is short. It is recommended that *Chapter 5 Transient Conduction* be covered in entirety, although some instructors may prefer to cover only some aspects of Sections 5.8 through 5.10.

The content of *Chapter 6 Introduction to Convection* is often difficult for students to absorb. However, Chapter 6 introduces fundamental concepts in a rigorous manner and sets the stage for Chapters 7 through 11. Chapter 6 should be covered in entirety in an introductory heat and mass transfer course.

Chapter 7 External Flow builds on Chapter 6, introduces several important concepts, and presents convection correlations that students will utilize throughout the remainder of the text and in subsequent professional practice. We recommend Sections 7.1 through 7.5 be included in any first course in heat and mass transfer. However, Sections 7.6 through 7.8 are optional. Likewise, *Chapter 8, Internal Flow* includes matter used in the remainder of the text and in professional practice. However, Sections 8.6 through 8.8 may be viewed as optional in a first course.

Buoyancy-induced flow is covered in *Chapter 9 Free Convection*. Most of Chapter 9 should be covered in a first course, although optional material includes Section 9.7 Free Convection Within Parallel Plate Channels. The content of *Chapter 10 Boiling and Condensation* that can be optional in a first course includes Section 10.5 Forced Convection Boiling, Section 10.9 Film Condensation on Radial Systems, and Section 10.10 Condensation in Horizontal Tubes. However, if time is short, Chapter 10 can be skipped without affecting students' ability to understand the remainder of the text. We recommend that *Chapter 11 Heat Exchangers* be covered in entirety, although Section 11.6 Additional Considerations may be de-emphasized in a first course.

A distinguishing feature of the text, from its inception, is the in-depth coverage of radiation heat transfer in *Chapter 12 Radiation: Processes and Properties*. The content of the chapter is perhaps more relevant today than ever. However, Section 12.9 can be covered in an advanced course. *Chapter 13 Radiation Exchange Between Surfaces* may be covered as time permits, or in an intermediate heat transfer course.

The material in *Chapter 14 Diffusion Mass Transfer* is relevant to many contemporary applications ranging from chemical processing to biotechnology, and should be covered in entirety in an introductory heat and mass transfer course. However, if problems involving stationary media are solely of interest, Section 14.2 may be omitted or covered in a follow-on course.

Heat Transfer Usage of this text for a *first course in heat transfer* might be structured as follows.

The suggested coverage of *Chapters 1 through 5* is identical to that for a course in heat and mass transfer described above. Before beginning *Chapter 6 Introduction to Convection*, it is recommended that the definition of mass transfer, provided in the introductory remarks of *Chapter 14 Diffusion Mass Transfer*, be reviewed with students. With the definition of mass transfer firmly in hand, remaining content that focuses on, for example, Fick's law, Sherwood and Schmidt numbers, and evaporative cooling will be apparent and need not be covered. For example, within Chapter 6, Section 6.1.3 The Concentration Boundary Layer, Section 6.2.2 Mass Transfer, Section 6.7.1 The Heat and Mass Transfer Analogy, and Section 6.7.2. Evaporative Cooling may be skipped in entirety.

Chapter 7 External Flow coverage is the same as recommended for the first course in heat and mass transfer, above. Components of Chapter 7 that can be skipped, such as Example 7.3, will be evident. Section 8.9 Convection Mass Transfer may be skipped in *Chapter 8 Internal Flow* while Section 9.10 Convection Mass Transfer in *Chapter 9 Free Convection* need not be covered.

The recommended coverage in *Chapters 10 through 13* is the same as for a first course in heat and mass transfer, above. Except for its introductory remarks, *Chapter 14 Diffusion Mass Transfer* is not included in a heat transfer course.

End-of-chapter problems involving mass transfer and/or evaporative cooling that should not be assigned in a heat transfer course are clustered toward the end of problem sets, and are identified with appropriate headings.

Acknowledgements

We wish to thank our many colleagues and their students who have offered valuable suggestions through the years. For this edition, we thank Laurent Pilon of the University of California, Los Angeles for his suggestions that have enhanced the presentation of transient conduction in Chapter 5. We also express our appreciation to three practicing engineers, Haifan Liang, Umesh Mather, and Hilbert Li, for their advice that has improved the coverage of thermoelectric power generation and extended surfaces in Chapter 3, and gaseous radiation in Chapter 13.

Appreciation is extended to Matthew Jones of Brigham Young University for improving the table of blackbody radiation functions of Chapter 12. Finally, we are grateful to John Abraham of the University of St. Thomas for his many helpful suggestions regarding the content of Chapter 7.

In closing, we remain deeply grateful to our spouses, Tricia and Greg, for the love they have shared and the patience they have practiced over the past 15 years.

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Supplemental and Web Site Material

The companion web site for the text is www.wiley.com/college/bergman. By clicking on appropriate links, students may access **Answers to Selected Homework Problems** and the **Supplemental Material Handouts** of the text. Supplemental Sections are identified throughout the text with the icon shown in the margin to the left.

Material available *for instructors only* includes that which is available to students and a **Homework Correlation Guide**, the **Solutions Manual**, the **Lecture PowerPoint Slides**, and an **Image Gallery** that includes electronic versions of figures from the text for those wishing to prepare their own materials for classroom presentation. *The* Instructor Solutions Manual *is copyrighted material for use only by instructors who require the text for their course.*[1]

Interactive Heat Transfer 4.0 is available at the companion web site at no cost for both students and instructors. As described by the authors in the *Approach and Organization* section, this simple-to-use software tool provides modeling and computational features useful in solving many problems in the text, and it enables rapid what-if and exploratory analysis of many types of problems.

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Symbols

A	area, m^2
A_b	area of prime (unfinned) surface, m^2
A_c	cross-sectional area, m^2
A_p	fin profile area, m^2
A_r	nozzle area ratio
a	acceleration, m/s^2; speed of sound, m/s
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
Co	Confinement number
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_{AB}	binary mass diffusivity, m^2/s
D_b	bubble diameter, m
D_h	hydraulic diameter, m
d	diameter of gas molecule, nm
E	thermal plus mechanical energy, J; electric potential, V; emissive power, W/m^2
E^{tot}	total energy, J
Ec	Eckert number
$\dot{E}_g$	rate of energy generation, W
$\dot{E}_{\mathrm{in}}$	rate of energy transfer into a control volume, W
$\dot{E}_{\mathrm{out}}$	rate of energy transfer out of control volume, W
$\dot{E}_{\mathrm{st}}$	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; fraction of blackbody radiation in a wavelength band; view factor
Fo	Fourier number
Fr	Froude number
f	friction factor; similarity variable
G	irradiation, W/m^2; mass velocity, kg/s · m^2
Gr	Grashof number
Gz	Graetz number
g	gravitational acceleration, m/s^2
H	nozzle height, m; Henry's constant, bar
h	convection heat transfer coefficient, $W/m^2 \cdot K$; Planck's constant, J · s
h_{fg}	latent heat of vaporization, J/kg
h'_{fg}	modified heat of vaporization, J/kg
h_{sf}	latent heat of fusion, 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 · m^2
j_i	diffusive mass flux of species *i* relative to the mixture mass average velocity, kg/s · m^2
j_H	Colburn *j* factor for heat transfer
j_m	Colburn *j* factor for mass transfer
k	thermal conductivity, W/m · K
k_B	Boltzmann's constant, J/K
k_0	zero-order, homogeneous reaction rate constant, kmol/s · m^3
k_1	first-order, homogeneous reaction rate constant, s^{-1}
k''_1	first-order, surface reaction rate constant, m/s
L	length, m
Le	Lewis number

$\dot{M}_i$	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
$\dot{M}_{\text{in}}$	rate at which mass enters a control volume, kg/s
$\dot{M}_{\text{out}}$	rate at which mass leaves a control volume, kg/s
$\dot{M}_{\text{st}}$	rate of increase of mass stored within a control volume, kg/s
$\mathcal{M}_i$	molecular weight of species *i,* kg/kmol
Ma	Mach number
m	mass, kg
$\dot{m}$	mass flow rate, kg/s
m_i	mass fraction of species *i,* ρ_i/ρ
N	integer number
N_L, N_T	number of tubes in longitudinal and transverse directions
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
$\mathcal{N}$	Avogadro's number
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
P	power, W; perimeter, m
P_L, P_T	dimensionless longitudinal and transverse pitch of a tube bank
Pe	Peclet number
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
q^*	dimensionless conduction heat rate
R	cylinder radius, m; gas constant, J/kg · K
$\mathcal{R}$	universal gas constant, J/kmol · K
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
$R_{t,f}$	fin thermal resistance, K/W
$R_{t,o}$	thermal resistance of fin array, 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; Seebeck coefficient, V/K
S_c	solar constant, W/m^2
S_D, S_L, S_T	diagonal, longitudinal, and transverse pitch of a tube bank, m
Sc	Schmidt number
Sh	Sherwood number
St	Stanton number
T	temperature, K
t	time, s
U	overall heat transfer coefficient, W/m^2 · K; internal energy, J
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	vapor quality
X_{tt}	Martinelli parameter
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
$x_{\text{fd},c}$	concentration entry length, m
$x_{\text{fd},h}$	hydrodynamic entry length, m
$x_{\text{fd},t}$	thermal entry length, m
x_i	mole fraction of species *i,* C_i/C
Z	thermoelectric material property, K^{-1}

Greek Letters

α	thermal diffusivity, m^2/s; accommodation coefficient; absorptivity
β	volumetric thermal expansion coefficient, K^{-1}
Γ	mass flow rate per unit width in film condensation, kg/s · m
γ	ratio of specific heats
δ	hydrodynamic boundary layer thickness, m
δ_c	concentration boundary layer thickness, m
δ_p	thermal penetration depth, m
δ_t	thermal boundary layer thickness, m
ε	emissivity; porosity; heat exchanger effectiveness
ε_f	fin effectiveness
η	thermodynamic efficiency; similarity variable
η_f	fin efficiency
η_o	overall efficiency of fin array
θ	zenith angle, rad; temperature difference, K
κ	absorption coefficient, m^{-1}
λ	wavelength, μm
λ_{mfp}	mean free path length, nm
μ	viscosity, kg/s · m

ν	kinematic viscosity, m^2/s; frequency of radiation, s^{-1}
ρ	mass density, kg/m^3; reflectivity
ρ_e	electric resistivity, Ω/m
σ	Stefan–Boltzmann constant, W/m$^2 \cdot$ K^4; electrical conductivity, 1/$\Omega \cdot$ m; normal viscous stress, N/m^2; surface tension, N/m
Φ	viscous dissipation function, s^{-2}
φ	volume fraction
ϕ	azimuthal angle, rad
ψ	stream function, m^2/s
τ	shear stress, N/m^2; transmissivity
ω	solid angle, sr; perfusion rate, s^{-1}

Subscripts

A, B	species in a binary mixture
abs	absorbed
am	arithmetic mean
atm	atmospheric
b	base of an extended surface; blackbody
C	Carnot
c	cross-sectional; concentration; cold; critical
cr	critical insulation thickness
cond	conduction
conv	convection
CF	counterflow
D	diameter; drag
dif	diffusion
e	excess; emission; electron
evap	evaporation
f	fluid properties; fin conditions; saturated liquid conditions; film
F	forced convection
fd	fully developed conditions
g	saturated vapor conditions
h	hydrodynamic; hot; helical
i	general species designation; inner surface; initial condition; tube inlet condition; incident radiation
L	based on characteristic length
l	saturated liquid conditions
lat	latent energy
lm	log mean condition
m	mean value over a tube cross section
max	maximum
N	natural (free) convection
o	center or midplane condition; tube outlet condition; outer
p	momentum
ph	phonon
R	reradiating surface
r, ref	reflected radiation
rad	radiation
S	solar conditions
s	surface conditions; solid properties; saturated solid conditions
sat	saturated conditions
sens	sensible energy
sky	sky conditions
ss	steady state
sur	surroundings
t	thermal
tr	transmitted
v	saturated vapor conditions
x	local conditions on a surface
λ	spectral
∞	free stream conditions

Superscripts

$*$	molar average; dimensionless quantity
tot	total energy (all forms)

Overbar

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

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 the study of the *modes* of heat transfer and through the 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?* One objective is to develop an appreciation for the fundamental concepts and principles that underlie heat transfer processes. A second objective is to illustrate the manner in which a knowledge of heat transfer may be used with the first law of thermodynamics (*conservation of energy*) to solve problems relevant to technology and society.

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 thermal energy in transit due to a spatial temperature difference.

Whenever a temperature difference exists 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.

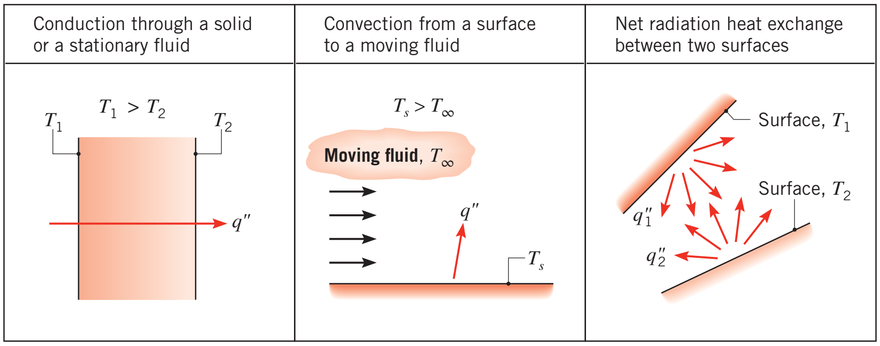


FIGURE 1.1 Conduction, convection, and radiation heat transfer modes.

1.2 *Physical Origins and Rate Equations*

As engineers, it is important that we understand the *physical mechanisms* which underlie the heat transfer modes and that we be able to use the rate equations that quantify the amount of energy being transferred per unit time.

1.2.1 Conduction

At mention of the word *conduction*, we should immediately conjure up concepts of *atomic* and *molecular activity* because processes at these levels sustain this mode of heat transfer. Conduction may be viewed as the transfer of energy from the more energetic to the less energetic particles of a substance due to interactions between the particles.

The physical mechanism of conduction is most easily explained by considering a gas and using ideas familiar from your thermodynamics background. Consider a gas in which a temperature gradient exists, and assume that there is *no bulk*, *or macroscopic, motion.* The gas may occupy the space between two surfaces that are maintained at different temperatures, as shown in Figure 1.2. We associate the temperature at any point with the energy of gas molecules in proximity to the point. This energy is related to the random translational motion, as well as to the internal rotational and vibrational motions, of the molecules.

Higher temperatures are associated with higher molecular energies. When neighboring molecules collide, as they are constantly doing, a transfer of energy from the more energetic to the less energetic molecules must occur. In the presence of a temperature gradient, energy transfer by conduction must then occur in the direction of decreasing temperature. This would be true even in the absence of collisions, as is evident from Figure 1.2. The hypothetical plane at x_o is constantly being crossed by molecules from above and below due to their *random* motion. However, molecules from above are associated with a higher temperature than those from below, in which case there must be a *net* transfer of energy in the positive x-direction. Collisions between molecules enhance this energy transfer. We may speak of the net transfer of energy by random molecular motion as a *diffusion* of energy.

The situation is much the same in liquids, although the molecules are more closely spaced and the molecular interactions are stronger and more frequent. Similarly, in a solid, conduction may be attributed to atomic activity in the form of lattice vibrations. The modern

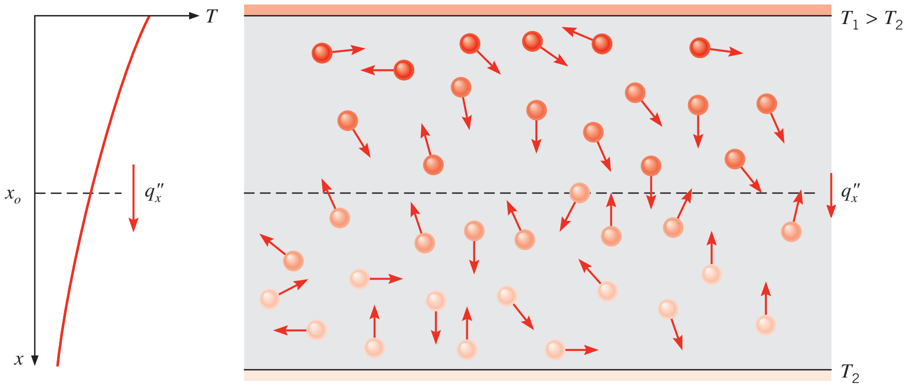


FIGURE 1.2 Association of conduction heat transfer with diffusion of energy due to molecular activity.

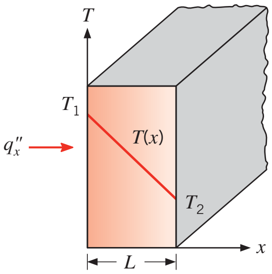


FIGURE 1.3 One-dimensional heat transfer by conduction (diffusion of energy).

view is to ascribe the energy transfer to *lattice waves* induced by atomic motion. In an electrical nonconductor, the energy transfer is exclusively via these lattice waves; in a conductor, it is also due to the translational motion of the free electrons. We treat the important properties associated with conduction phenomena in Chapter 2 and in Appendix A.

Examples of conduction heat transfer are legion. The exposed end of a metal spoon suddenly immersed in a cup of hot coffee is eventually warmed due to the conduction of energy through the spoon. On a winter day, there is significant energy loss from a heated room to the outside air. This loss is principally due to conduction heat transfer through the wall that separates the room air from the outside air.

Heat transfer processes can be quantified in terms of appropriate *rate equations.* These equations may be used to compute the amount of energy being transferred per unit time. For heat conduction, the rate equation is known as *Fourier's law.* For the one-dimensional plane wall shown in Figure 1.3, having a temperature distribution $T(x)$, the rate equation is expressed as

$$q''_x = -k\frac{dT}{dx} \tag{1.1}$$

The *heat flux* q''_x (W/m^2) is the heat transfer rate in the x-direction *per* unit area *perpendicular* to the direction of transfer, and it is proportional to the *temperature gradient*, dT/dx, in this direction. The parameter k is a *transport* property known as the *thermal conductivity* (W/m · K) and is a characteristic of the wall material. The minus sign is a consequence of the fact that heat is transferred in the direction of decreasing temperature. Under the *steady-state conditions* shown in Figure 1.3, where the temperature distribution is *linear*, the temperature gradient may be expressed as

$$\frac{dT}{dx} = \frac{T_2 - T_1}{L}$$

and the heat flux is then

$$q''_x = -k\frac{T_2 - T_1}{L}$$

or

$$q''_x = k\frac{T_1 - T_2}{L} = k\frac{\Delta T}{L} \tag{1.2}$$

Note that this equation provides a *heat flux*, that is, the rate of heat transfer per *unit area.* The *heat rate* by conduction, q_x (W), through a plane wall of area A is then the product of the flux and the area, $q_x = q''_x \cdot A$.

IHT* EXAMPLE 1.1

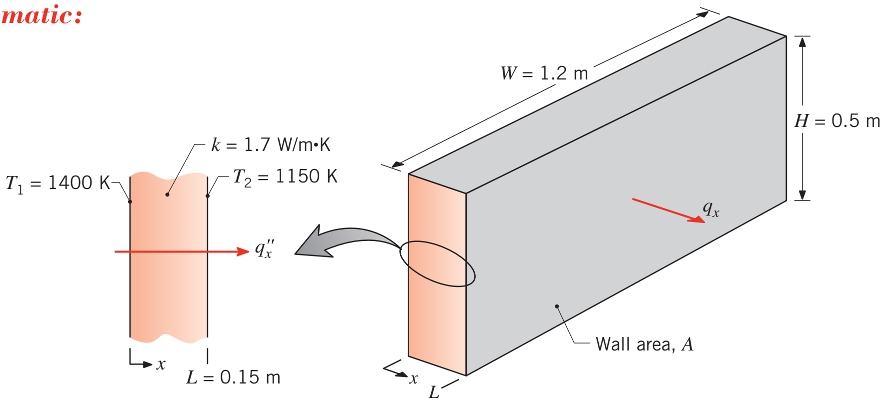
The wall of an industrial furnace is constructed from 0.15-m-thick fireclay brick having a thermal conductivity of 1.7 W/m · K. Measurements made during steady-state operation reveal temperatures of 1400 and 1150 K at the inner and outer surfaces, respectively. What is the rate of heat loss through a wall that is 0.5 m × 1.2 m on a side?

SOLUTION

Known: Steady-state conditions with prescribed wall thickness, area, thermal conductivity, and surface temperatures.

Find: Rate of heat loss through wall.

Schematic:



Assumptions:

1. Steady-state conditions.
2. One-dimensional conduction through the wall.
3. Constant thermal conductivity.

Analysis: Since heat transfer through the wall is by conduction, the heat flux may be determined from Fourier's law. Using Equation 1.2, we have

$$q''_x = k\frac{\Delta T}{L} = 1.7 \text{ W/m} \cdot \text{K} \times \frac{250 \text{ K}}{0.15 \text{ m}} = 2833 \text{ W/m}^2$$

The heat flux represents the rate of heat transfer through a section of unit area, and it is uniform (invariant) across the surface of the wall. The rate of heat loss through the wall of area $A = H \times W$ is then

$$q_x = (HW)q''_x = (0.5 \text{ m} \times 1.2 \text{ m})2833 \text{ W/m}^2 = 1700 \text{ W} \qquad \triangleleft$$

Comments: Note the direction of heat flow and the distinction between heat flux and heat rate.

*This icon identifies examples that are available in tutorial form in the *Interactive Heat Transfer (IHT)* software that accompanies the text. Each tutorial is brief and illustrates a basic function of the software. *IHT* can be used to solve simultaneous equations, perform parameter sensitivity studies, and graph the results. Use of *IHT* will reduce the time spent solving more complex end-of-chapter problems.

1.2.2 Convection

The convection heat transfer *mode* is comprised of *two mechanisms.* In addition to energy transfer due to *random molecular motion* (*diffusion*), energy is also transferred by the *bulk*, or *macroscopic, motion* of the fluid. This fluid motion is associated with the fact that, at any instant, large numbers of molecules are moving collectively or as aggregates. Such motion, in the presence of a temperature gradient, contributes to heat transfer. Because the molecules in the aggregate retain their random motion, the total heat transfer is then due to a superposition of energy transport by the random motion of the molecules and by the bulk motion of the fluid. The term *convection* is customarily used when referring to this cumulative transport, and the term *advection* refers to transport due to bulk fluid motion alone.

We are especially interested in convection heat transfer between a fluid in motion and a bounding surface when the two are at different temperatures. Consider fluid flow over the hot surface of Figure 1.4. A consequence of the fluid–surface interaction is the development of a region in the fluid through which the velocity varies from zero at the surface to a finite value u_∞ associated with the flow. This region of the fluid is known as the *hydrodynamic*, or *velocity, boundary layer.* Moreover, if the surface and flow temperatures differ, there will be a region of the fluid through which the temperature varies from T_s at $y = 0$ to T_∞ in the outer flow. This region, called the *thermal boundary layer*, may be smaller, larger, or the same size as that through which the velocity varies. In any case, if $T_s > T_\infty$, convection heat transfer will occur from the surface to the outer flow.

The convection heat transfer mode is sustained both by random molecular motion and by the bulk motion of the fluid within the boundary layer. The contribution due to random molecular motion (diffusion) dominates near the surface where the fluid velocity is low. In fact, at the interface between the surface and the fluid ($y = 0$), the fluid velocity is zero, and heat is transferred by this mechanism only. The contribution due to bulk fluid motion originates from the fact that the boundary layer *grows* as the flow progresses in the x-direction. In effect, the heat that is conducted into this layer is swept downstream and is eventually transferred to the fluid outside the boundary layer. Appreciation of boundary layer phenomena is essential to understanding convection heat transfer. For this reason, the discipline of fluid mechanics will play a vital role in our later analysis of convection.

Convection heat transfer may be classified according to the nature of the flow. We speak of *forced convection* when the flow is caused by external means, such as by a fan, a pump, or atmospheric winds. As an example, consider the use of a fan to provide forced convection air cooling of hot electrical components on a stack of printed circuit boards (Figure 1.5*a*). In contrast, for *free* (or *natural*) *convection*, the flow is induced by buoyancy forces, which are due to density differences caused by temperature variations in the fluid. An example is the free convection heat transfer that occurs from hot components on

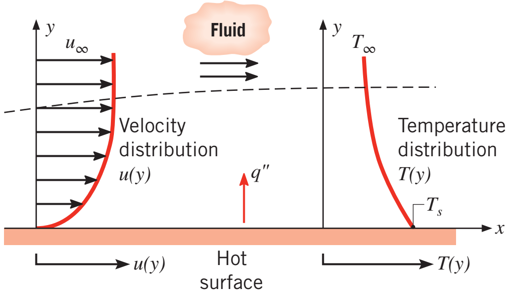


FIGURE 1.4 Boundary layer development in convection heat transfer.

a vertical array of circuit boards in air (Figure 1.5*b*). Air that makes contact with the components experiences an increase in temperature and hence a reduction in density. Since it is now lighter than the surrounding air, buoyancy forces induce a vertical motion for which warm air ascending from the boards is replaced by an inflow of cooler ambient air.

While we have presumed *pure* forced convection in Figure 1.5*a* and *pure* natural convection in Figure 1.5*b*, conditions corresponding to *mixed* (*combined*) *forced* and *natural convection* may exist. For example, if velocities associated with the flow of Figure 1.5*a* are small and/or buoyancy forces are large, a secondary flow that is comparable to the imposed forced flow could be induced. In this case, the buoyancy-induced flow would be normal to the forced flow and could have a significant effect on convection heat transfer from the components. In Figure 1.5*b*, mixed convection would result if a fan were used to force air upward between the circuit boards, thereby assisting the buoyancy flow, or downward, thereby opposing the buoyancy flow.

We have described the convection heat transfer mode as energy transfer occurring within a fluid due to the combined effects of conduction and bulk fluid motion. Typically, the energy that is being transferred is the *sensible*, or internal thermal, energy of the fluid. However, for some convection processes, there is, in addition, *latent* heat exchange. This latent heat exchange is generally associated with a phase change between the liquid and vapor states of the fluid. Two special cases of interest in this text are *boiling* and *condensation*. For example, convection heat transfer results from fluid motion induced by vapor bubbles generated at the bottom of a pan of boiling water (Figure 1.5*c*) or by the condensation of water vapor on the outer surface of a cold water pipe (Figure 1.5*d*).

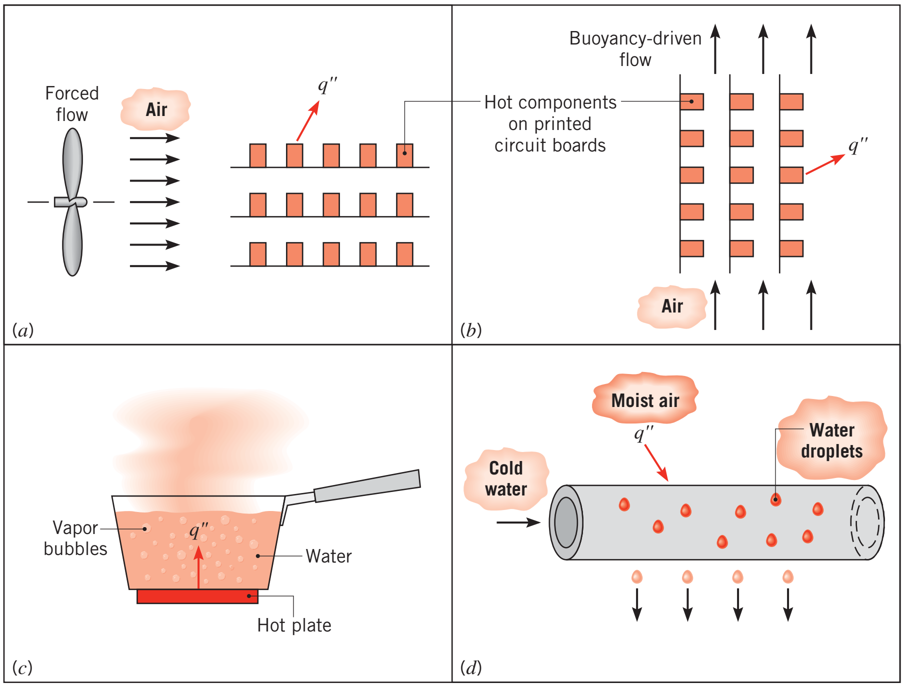


FIGURE 1.5 Convection heat transfer processes. (a) Forced convection. (b) Natural convection. (c) Boiling. (d) Condensation.

TABLE 1.1 Typical values of the convection heat transfer coefficient

Process	h (W/m$^2 \cdot$ K)
Free convection	
Gases	2–25
Liquids	50–1000
Forced convection	
Gases	25–250
Liquids	100–20,000
Convection with phase change	
Boiling or condensation	2500–100,000

Regardless of the nature of the convection heat transfer process, the appropriate rate equation is of the form

$$q'' = h(T_s - T_\infty) \tag{1.3a}$$

where q'', the convective *heat flux* (W/m^2), is proportional to the difference between the surface and fluid temperatures, T_s and T_∞, respectively. This expression is known as *Newton's law of cooling*, and the parameter h (W/m$^2 \cdot$ K) is termed the *convection heat transfer coefficient.* This coefficient depends on conditions in the boundary layer, which are influenced by surface geometry, the nature of the fluid motion, and an assortment of fluid thermodynamic and transport properties.

Any study of convection ultimately reduces to a study of the means by which h may be determined. Although consideration of these means is deferred to Chapter 6, convection heat transfer will frequently appear as a boundary condition in the solution of conduction problems (Chapters 2 through 5). In the solution of such problems we presume h to be known, using typical values given in Table 1.1.

When Equation 1.3a is used, the convection heat flux is presumed to be *positive* if heat is transferred *from* the surface ($T_s > T_\infty$) and *negative* if heat is transferred *to* the surface ($T_\infty > T_s$). However, nothing precludes us from expressing Newton's law of cooling as

$$q'' = h(T_\infty - T_s) \tag{1.3b}$$

in which case heat transfer is positive if it is to the surface.

1.2.3 Radiation

Thermal radiation is energy *emitted* by matter that is at a nonzero temperature. Although we will focus on radiation from solid surfaces, emission may also occur from liquids and gases. Regardless of the form of matter, the emission may be attributed to changes in the electron configurations of the constituent atoms or molecules. The energy of the radiation field is transported by electromagnetic waves (or alternatively, photons). While the transfer of energy by conduction or convection requires the presence of a material medium, radiation does not. In fact, radiation transfer occurs most efficiently in a vacuum.

Consider radiation transfer processes for the surface of Figure 1.6*a*. Radiation that is *emitted* by the surface originates from the thermal energy of matter bounded by the surface, and the rate at which energy is released per unit area (W/m^2) is termed the surface *emissive power, E.* There is an upper limit to the emissive power, which is prescribed by the *Stefan–Boltzmann law*

$$E_b = \sigma T_s^4 \tag{1.4}$$

where T_s is the *absolute temperature* (K) of the surface and σ is the *Stefan–Boltzmann constant* ($\sigma = 5.67 \times 10^{-8}\ \mathrm{W/m^2 \cdot K^4}$). Such a surface is called an ideal radiator or *blackbody.*

The heat flux emitted by a real surface is less than that of a blackbody at the same temperature and is given by

$$E = \varepsilon \sigma T_s^4 \tag{1.5}$$

where ε is a radiative property of the surface termed the *emissivity.* With values in the range $0 \le \varepsilon \le 1$, this property provides a measure of how efficiently a surface emits energy relative to a blackbody. It depends strongly on the surface material and finish, and representative values are provided in Appendix A.

Radiation may also be *incident* on a surface from its surroundings. The radiation may originate from a special source, such as the sun, or from other surfaces to which the surface of interest is exposed. Irrespective of the source(s), we designate the rate at which all such radiation is incident on a unit area of the surface as the *irradiation G* (Figure 1.6*a*).

A portion, or all, of the irradiation may be *absorbed* by the surface, thereby increasing the thermal energy of the material. The rate at which radiant energy is absorbed per unit surface area may be evaluated from knowledge of a surface radiative property termed the *absorptivity* α. That is,

$$G_{\mathrm{abs}} = \alpha G \tag{1.6}$$

where $0 \le \alpha \le 1$. If $\alpha < 1$ and the surface is *opaque*, portions of the irradiation are *reflected.* If the surface is *semitransparent*, portions of the irradiation may also be *transmitted.* However, whereas absorbed and emitted radiation increase and reduce, respectively, the thermal energy of matter, reflected and transmitted radiation have no effect on this

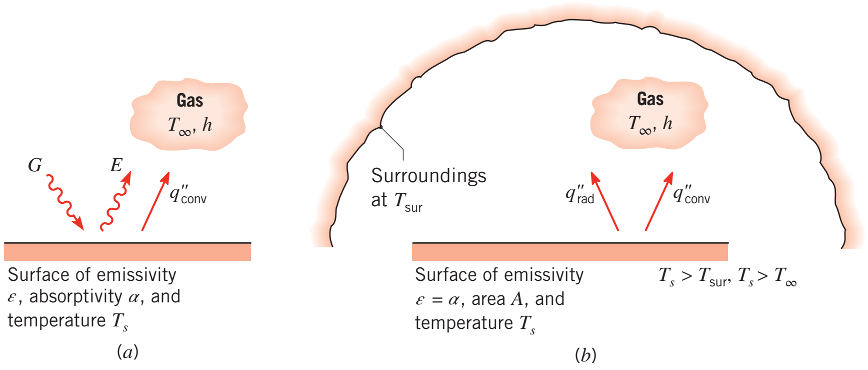


FIGURE 1.6 Radiation exchange: (a) at a surface and (b) between a surface and large surroundings.