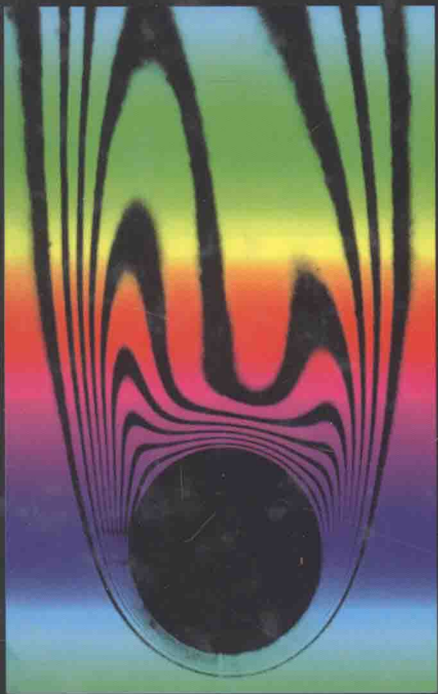
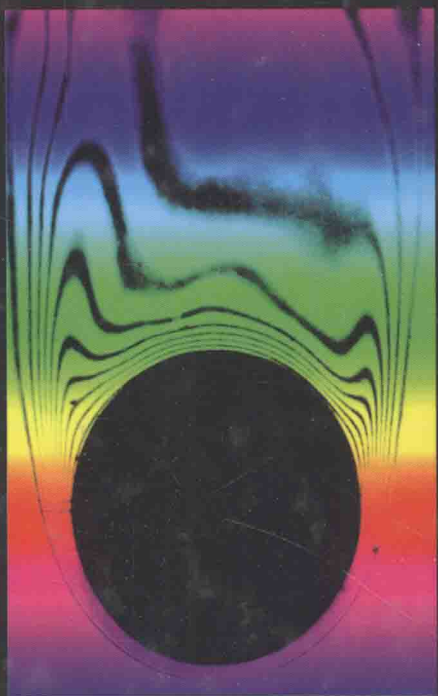
Heat Transfer

Tenth Edition





J.P. Holman

Heat Transfer

Tenth Edition

J. P. Holman
Department of Mechanical Engineering
Southern Methodist University

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HEAT TRANSFER, TENTH EDITION

Published by McGraw-Hill, a business unit of The McGraw-Hill Companies, Inc., 1221 Avenue of the Americas, New York, NY 10020.

This book is printed on acid-free paper.

1 2 3 4 5 6 7 8 9 0 VNH/VNH 0 9

ISBN 978–0–07–352936–3
MHID 0–07–352936–2

Global Publisher: *Raghothaman Srinivasan*
Senior Sponsoring Editor: *Bill Stenquist*
Director of Development: *Kristine Tibbetts*
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Associate Design Coordinator: *Brenda A. Rolwes*
Cover Designer: *Studio Montage, St. Louis, Missouri*
Cover Image: *Interferometer photo of air flow across a heated cylinder, digitally enhanced by the author.*
Compositor: *S4Carlisle Publishing Services*
Typeface: *10.5/12 Times Roman*
Printer: *R. R. Donnelley, Jefferson City, MO*

Library of Congress Cataloging-in-Publication Data

Holman, J. P. (Jack Philip)
Heat transfer / Jack P. Holman.—10th ed.
p. cm.—(Mcgraw-Hill series in mechanical engineering)
Includes index.
ISBN 978–0–07–352936–3—ISBN 0–07–352936–2 (hard copy : alk. paper)
1. Heat-Transmission. I. Title.

QC320.H64 2010
621.402′2—dc22 2008033196

www.mhhe.com

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McGraw-Hill Series in Mechanical Engineering

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PREFACE

This book presents an elementary treatment of the principles of heat transfer. As a text it contains more than enough material for a one-semester course that may be presented at the junior level, or higher, depending on individual course objectives. The course is normally required in chemical and mechanical engineering curricula but is recommended for electrical engineering students as well, because of the significance of cooling problems in various electronics applications. In the author's experience, electrical engineering students do quite well in a heat-transfer course, even with no formal coursework background in thermodynamics or fluid mechanics. A background in ordinary differential equations is helpful for proper understanding of the material.

Presentation of the subject follows classical lines of separate discussions for conduction, convection, and radiation, although it is emphasized that the physical mechanism of convection heat transfer is one of conduction through the stationary fluid layer near the heat-transfer surface. Throughout the book emphasis has been placed on physical understanding while, at the same time, relying on meaningful experimental data in those circumstances that do not permit a simple analytical solution.

Conduction is treated from both the analytical and the numerical viewpoint, so that the reader is afforded the insight that is gained from analytical solutions as well as the important tools of numerical analysis that must often be used in practice. A liberal number of numerical examples are given that include heat sources and radiation boundary conditions, non-uniform mesh size, and one example of a three-dimensional nodal system. A similar procedure is followed in the presentation of convection heat transfer. An integral analysis of both free- and forced-convection boundary layers is used to present a physical picture of the convection process. From this physical description, inferences may be drawn that naturally lead to the presentation of empirical and practical relations for calculating convection heat-transfer coefficients. Because it provides an easier instruction vehicle than other methods, the radiation-network method is used extensively in the introduction of analysis of radiation systems, while a more generalized formulation is given later. Systems of nonlinear equations requiring iterative solutions are also discussed in the conduction and radiation chapters but the details of solution are relegated to cited software references. The assumption is made that the well-disposed reader should select his or her own preferred vehicle for solution of systems of nonlinear equations.

The log-mean-temperature-difference and effectiveness approaches are presented in heat-exchanger analysis since both are in wide use and each offers its own advantages to the designer. A brief introduction to diffusion and mass transfer is presented in order to acquaint the reader with these processes and to establish more firmly the important analogies between heat, mass, and momentum transfer. A new Chapter 12 has been added on summary and design information. Numerous calculation charts are offered in this chapter as an aid in preliminary design work where speed and utility may be more important than the accuracy that may be required in final design stages. Eleven new examples are presented in this chapter illustrating use of the charts.

Problems are included at the end of each chapter. Some of these problems are of a routine nature to familiarize the student with the numerical manipulations and orders of magnitude of various parameters that occur in the subject of heat transfer. Other problems extend the subject matter by requiring students to apply the basic principles to new situations and develop their own equations. Both types of problems are important.

There is also a section at the end of each problem set designated as "Design-Oriented Problems." The problems in these sections typically are open-ended and do not result in a unique answer. In some cases they are rather extended in length and require judgment decisions during the solution process. Over 100 such problems are included in the text.

The subject of heat transfer is not static. New developments occur quite regularly, and better analytical solutions and empirical data are continuously made available to the professional in the field. Because of the huge amount of information that is available in the research literature, the beginning student could easily be overwhelmed if too many of the nuances of the subject were displayed and expanded. The book is designed to serve as an elementary text, so the author has assumed a role of interpreter of the literature with those findings and equations being presented that can be of immediate utility to the reader. It is hoped that the student's attention is called to more extensive works in a sufficient number of instances to emphasize the depth that is available on most of the subjects of heat transfer. For the serious student, then, the end-of-chapter references offer an open door to the literature of heat transfer that can pyramid upon further investigation. In several chapters the number of references offered is much larger than necessary, and older citations of historical interest have been retained freely. The author feels this is a luxury that will not be intrusive on the reader or detract from the utility of the text.

A book in its tenth edition obviously reflects many compromises and evolutionary processes over the years. While the basic physical mechanisms of heat transfer have not changed, analytical techniques and experimental data have been revised and improved. In this edition some trimming of out-of-date material has been effected, new problems added, and old problems refreshed. Sixteen new worked examples have been added. All worked examples are now referenced by page number at the front of the book, just following the Table of Contents. The listing of such examples is still retained at the end of each chapter.

A feature is the use of Microsoft Excel for solution of both steady-state and transient conduction heat-transfer problems. Excel is given a rather full discussion in a new Appendix D, which includes treatment of heat source and radiation boundary conditions, steady-state and transient conditions, and interfaces between composite materials. A special template is provided that automatically writes nodal equations for most common boundary conditions. Ten examples of the use of Excel for solution of problems are provided, including some modifications and expansions of examples that appear in Chapters 3 and 4. One example illustrates the progression of transient solution to yield the steady-state solution for sufficiently long-time duration.

In addition to the summary tables of convection formulas provided at the conclusion of each of the main convection chapters (Chapters 5, 6, 7), an overall procedure is now offered for analysis of all convection problems, and is included in the inside book cover as well as in the body of the text. While one might interpret this as a cookbook approach, the true intent is to help heat-transfer practitioners avoid common and disarmingly simple pitfalls in the analysis and solution of convection problems.

The SI (metric) system of units is the primary one for the text. Because the Btu-ft-pound system is still in wide use, answers and intermediate steps to examples are occasionally stated in these units. A few examples and problems are in English units.

It is not possible to cover all the topics in this book in either a quarter- or semester-term course, but it is hoped that the variety of topics and problems will provide the necessary flexibility for many applications.

ACKNOWLEDGMENTS

With a book at this stage of revision, the list of persons who have been generous with their comments and suggestions has grown very long indeed. The author hopes that a blanket note of thanks for all these individuals contributions will suffice. As in the past, all comments from users will be appreciated and acknowledged. The author and McGraw-Hill editorial staff would like to acknowledge the following people for their helpful comments and suggestions while developing the plan for the new edition:

Neil L. Book, *University of Missouri–Rolla*
Rodney D.W. Bowersox, *Texas A & M University*
Kyle V. Camarda, *University of Kansas*
Richard Davis, *University of Minnesota–Duluth*
Roy W. Knight, *Auburn University*
Frank A. Kulacki, *University of Minnesota*
Ian H. Leslie, *New Mexico State University*
Daniela S. Mainardi, *Louisiana Tech University*
Randall D. Manteufel, *University of Texas at San Antonio*
M. Pinar Menguc, *University of Kentucky*
Samuel Paolucci, *University of Notre Dame*
Paul D. Ronney, *University of Southern California*
Harris Wong, *Louisiana State University*

J. P. Holman

ABOUT THE AUTHOR

J. P. Holman received the Ph.D. in mechanical engineering from Oklahoma State University. After two years as a research scientist at the Wright Aerospace Research Laboratory, he joined the faculty of Southern Methodist University, where he is presently Professor Emeritus of Mechanical Engineering. He has also held administrative positions as Director of the Thermal and Fluid Sciences Center, Head of the Civil and Mechanical Engineering Department, and Assistant Provost for Instructional Media. During his tenure at SMU he has been voted the outstanding faculty member by the student body 13 times.

Dr. Holman has published over 30 papers in several areas of heat transfer and his three widely used textbooks, *Heat Transfer* (9th edition, 2002), *Experimental Methods for Engineers* (7th edition, 2001), and *Thermodynamics* (4th edition, 1988), all published by McGraw-Hill, have been translated into Spanish, Portuguese, Japanese, Chinese, Korean, and Indonesian, and are distributed worldwide. He is also the author of the utilitarian monograph *What Every Engineer Should Know About EXCEL* (2006), published by CRC Press. Dr. Holman also consults for industry in the fields of heat transfer and energy systems.

A member of ASEE, he is past Chairman of the National Mechanical Engineering Division and past chairman of the Region X Mechanical Engineering Department Heads. Dr. Holman is a Fellow of ASME and recipient of several national awards: the George Westinghouse Award from ASEE for distinguished contributions to engineering education (1972), the James Harry Potter Gold Medal from ASME for contributions to thermodynamics (1986), the Worcester Reed Warner Gold Medal from ASME for outstanding contributions to the permanent literature of engineering (1987), and the Ralph Coats Roe Award from ASEE as the outstanding mechanical engineering educator of the year (1995). In 1993 he was the recipient of the Lohmann Medal from Oklahoma State University, awarded annually to a distinguished engineering alumnus of that institution.

LIST OF SYMBOLS

a Local velocity of sound

a Attenuation coefficient (Chap. 8)

A Area

A Albedo (Chap. 8)

A_m Fin profile area (Chap. 2)

c Specific heat, usually kJ/kg · °C

C Concentration (Chap. 11)

C_D Drag coefficient, defined by Eq. (6-13)

C_f Friction coefficient, defined by Eq. (5-52)

c_p Specific heat at constant pressure, usually kJ/kg · °C

c_v Specific heat at constant volume, usually kJ/kg · °C

d Diameter

D Depth or diameter

D Diffusion coefficient (Chap. 11)

D_H Hydraulic diameter, defined by Eq. (6-14)

e Internal energy per unit mass, usually kJ/kg

E Internal energy, usually kJ

E Emissive power, usually W/m^2 (Chap. 8)

E_{b0} Solar constant (Chap. 8)

$E_{b\lambda}$ Blackbody emmissive power per unit wave-length, defined by Eq. (8-12)

f Friction factor

F Force, usually N

F_{m-n} or F_{ij} Radiation shape factor for radiation from surface i to surface j

g Acceleration of gravity

g_c Conversion factor, defined by Eq. (1-14)

G Irradiation (Chap. 8)

$G = \frac{\dot{m}}{A}$ Mass velocity

h Heat-transfer coefficient, usually W/m^2 · °C

$\bar{h}$ Average heat-transfer coefficient

h_{fg} Enthalpy of vaporization, kJ/kg

h_r Radiation heat-transfer coefficient (Chap. 8)

i Enthalpy, usually kJ/kg

I Intensity of radiation

I Solar insolation (Chap. 8)

I_0 Solar insolation at outer edge of atmosphere

J Radiosity (Chap. 8)

k Thermal conductivity, usually W/m · °C

k_e Effective thermal conductivity of enclosed spaces (Chap. 7)

k_λ Scattering coefficient (Chap. 8)

K Mass-transfer coefficient, m/h

L	Length
L_c	Corrected fin length (Chap. 2)
m	Mass
$\dot{m}$	Mass rate of flow
M	Molecular weight (Chap. 11)
n	Molecular density
N	Molal diffusion rate, moles per unit time (Chap. 11)
p	Pressure, usually N/m^2, Pa
P	Perimeter
q	Heat-transfer rate, kJ per unit time
q''	Heat flux, kJ per unit time per unit area
$\dot{q}$	Heat generated per unit volume
Q	Heat, kJ
r	Radius or radial distance
r	Recovery factor, defined by Eq. (5-120)
R	Fixed radius
R	Gas constant
R_{th}	Thermal resistance, usually °C/W
s	A characteristic dimension (Chap. 4)
S	Conduction shape factor, usually m
t	Thickness, applied to fin problems (Chap. 2)
t, T	Temperature
u	Velocity
v	Velocity
v	Specific volume, usually m^3/kg
V	Velocity
V	Molecular volume (Chap. 11)
W	Weight, usually N
x, y, z	Space coordinates in cartesian system
$\alpha = \frac{k}{pc}$	Thermal diffusivity, usually m^2/s
α	Absorptivity (Chap. 8)
α	Accommodation coefficient (Chap. 7)
α	Solar altitude angle, deg (Chap. 8)
β	Volume coefficient of expansion, 1/K
β	Temperature coefficient of thermal conductivity, 1/°C
$\gamma = \frac{c_p}{c_v}$	Isentropic exponent, dimensionless
Γ	Condensate mass flow per unit depth of plate (Chap. 9)
δ	Hydrodynamic-boundary-layer thickness
δ_t	Thermal-boundary-layer thickness
ϵ	Heat-exchanger effectiveness
ϵ	Emissivity
ϵ_H, ϵ_M	Eddy diffusivity of heat and momentum (Chap. 5)
$\zeta = \frac{\delta_t}{\delta}$	Ratio of thermal-boundary-layer thickness to hydrodynamic-boundary-layer thickness
η	Similarity variable, defined by Eq. (B-6)
η_f	Fin efficiency, dimensionless
θ	Angle in spherical or cylindrical coordinate system
θ	Temperature difference, $T - T_{\text{reference}}$
	The reference temperature is chosen differently for different systems (see Chaps. 2 to 4)

λ Wavelength (Chap. 8)

λ Mean free path (Chap. 7)

μ Dynamic viscosity

ν Kinematic viscosity, m^2/s

ν Frequency of radiation (Chap. 8)

ρ Density, usually kg/m^3

ρ Reflectivity (Chap. 8)

σ Stefan-Boltzmann constant

σ Surface tension of liquid-vapor interface (Chap. 9)

τ Time

τ Shear stress between fluid layers

τ Transmissivity (Chap. 8)

ϕ Angle in spherical or cylindrical coordinate system

ψ Stream function

Dimensionless Groups

$\mathrm{Bi} = \frac{hs}{k}$ Biot number

$\mathrm{Fo} = \frac{\alpha\tau}{s^2}$ Fourier number

$\mathrm{Gr} = \frac{g\beta(T_w - T_\infty)x^3}{\nu^2}$ Grashof number

$\mathrm{Gr}^* = \mathrm{Gr}\,\mathrm{Nu}$ Modified Grashof number for constant heat flux

$\mathrm{Gz} = \mathrm{Re}\,\mathrm{Pr}\,\frac{d}{L}$ Graetz number

$\mathrm{Kn} = \frac{\lambda}{L}$ Knudsen number

$\mathrm{Le} = \frac{\alpha}{D}$ Lewis number (Chap. 11)

$\mathrm{M} = \frac{u}{a}$ Mach number

$\mathrm{Nu} = \frac{hx}{k}$ Local Nusselt number

$\overline{\mathrm{Nu}} = \frac{\bar{h}x}{k}$ Average Nusselt number

$\mathrm{Pe} = \mathrm{Re}\,\mathrm{Pr}$ Peclet number

$\mathrm{Pr} = \frac{c_p\mu}{k}$ Prandtl number

$\mathrm{Ra} = \mathrm{Gr}\,\mathrm{Pr}$ Rayleigh number

$\mathrm{Re} = \frac{\rho u x}{\mu}$ Reynolds number

$\mathrm{Sc} = \frac{\nu}{D}$ Schmidt number (Chap. 11)

$\mathrm{Sh} = \frac{Kx}{D}$ Sherwood number (Chap. 11)

$\mathrm{St} = \frac{h}{\rho c_p u}$ Stanton number

$\overline{\mathrm{St}} = \frac{\bar{h}}{\rho c_p u}$ Average Stanton number

Subscripts

aw Adiabatic wall conditions

b Refers to blackbody conditions (Chap. 8)

b	Evaluated at bulk conditions
d	Based on diameter
f	Evaluated at film conditions
g	Saturated vapor conditions (Chap. 9)
i	Initial or inlet conditions
L	Based on length of plate
m	Mean flow conditions
m, n	Denotes nodal positions in numerical solution (see Chap. 3, 4)
r	At specified radial position
s	Evaluated at condition of surroundings
w	Evaluated at wall conditions
x	Denotes some local position with respect to x coordinate
0	Denotes stagnation flow conditions (Chap. 5) or some initial condition at time zero
*	(Superscript) Properties evaluated at reference temperature, given by Eq. (5-124)
∞	Evaluation at free-stream conditions

CONTENTS