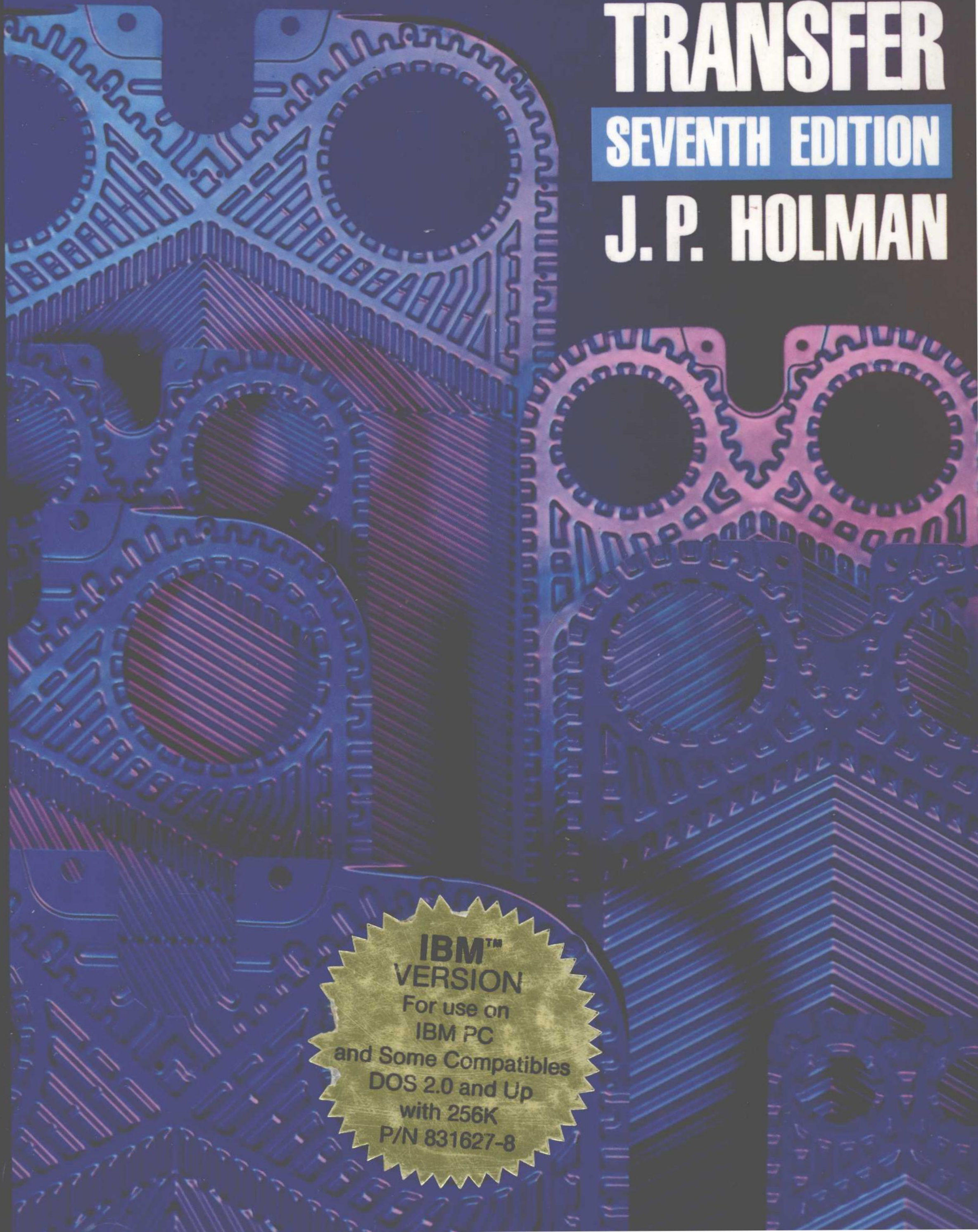
HEAT TRANSFER

SEVENTH EDITION

J. P. HOLMAN



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Seventh Edition

J. P. HOLMAN

Professor of Mechanical Engineering
Southern Methodist University

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Basic heat transfer relations

Fourier's law of heat conduction:

$$q_x = -kA \frac{\partial T}{\partial x}$$

Convection heat transfer from a surface:

$$q = hA(T_{\text{surface}} - T_{\text{free stream}}) \qquad \text{for exterior flows}$$

$$q = hA(T_{\text{surface}} - T_{\text{fluid bulk}}) \qquad \text{for flow in channels}$$

Forced convection: Nu = f(Re, Pr) (Chapters 5 and 6, Tables 5-2 and 6-8)

Free convection: Nu = f(Gr, Pr) (Chapter 7, Table 7-4)

$$\text{Re} = \frac{\rho u x}{\mu} \qquad \text{Gr} = \frac{\rho^2 g \beta \, \Delta T x^3}{\mu^2} \qquad \text{Pr} = \frac{c_p \mu}{k}$$

x = characteristic dimension

Radiation heat transfer (Chapter 8)

Black body emissive power, $\dfrac{\text{energy emitted by black body}}{\text{area}\cdot\text{time}} = \sigma T^4$

Radiosity $= \dfrac{\text{energy leaving surface}}{\text{area}\cdot\text{time}}$

Irradiation $= \dfrac{\text{energy incident on surface}}{\text{area}\cdot\text{time}}$

Radiation shape factor F_{mn} = fraction of energy leaving surface m and arriving at surface n

Reciprocity relation: $A_m F_{mn} = A_n F_{nm}$

Radiation heat transfer from surface with area A_1, emissivity ϵ_1, and temperature $T_1(K)$ to large enclosure at temperature T_2:

$$q = \sigma A_1 \epsilon_1 (T_1^4 - T_2^4)$$

LMTD method for heat exchangers (Section 10-5):

$$q = UAF \, \Delta T_m$$

where F = factor for specific heat exchanger; ΔT_m = LMTD for counterflow double-pipe heat exchanger with same inlet temperatures

Effectiveness-NTU method for heat exchangers (Section 10-6, Table 10-3):

$$\epsilon = \frac{\text{Temperature difference for fluid with minimum value of } \dot{m}c}{\text{Largest temperature difference in heat exchanger}}$$

$$\text{NTU} = \frac{UA}{C_{\min}} \qquad \epsilon = f(\text{NTU}, C_{\min}/C_{\max})$$

See List of Symbols on page xvii for definitions of terms.

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ABOUT THE AUTHOR

JACK P. HOLMAN received his Ph.D. in mechanical engineering from Oklahoma State University in 1958. After two years active duty as a research scientist in the Air Force Aerospace Research Laboratory he joined the faculty of Southern Methodist University, where he is presently Brown Foundation Professor of Mechanical Engineering.

During his tenure at Southern Methodist University he has nine times been voted the Outstanding Engineering Faculty Member by the student body in a poll conducted annually. He has been active on many committees and has held administrative positions as Director of the Thermal and Fluid Sciences Center, Head of Civil and Mechanical Engineering Department, and Assistant Provost for Instructional Media.

As a principal investigator for research sponsored by the Atomic Energy Commission, National Science Foundation, NASA, and the Environmental Protection Agency, he has published extensively in such journals as *Industrial and Engineering Chemistry, International Journal of Heat and Mass Transfer, Journal of the Aerospace Sciences,* and others.

His three widely used textbooks, *Heat Transfer,* 1963 (7th ed. 1990), *Experimental Methods for Engineers,* 1966 (5th ed. 1989), and *Thermodynamics,* 1969 (4th ed. 1988), all published by the McGraw-Hill Publishing Company, have been translated into Spanish, Chinese, Japanese, Korean, and Portuguese and are distributed world wide. Dr. Holman is the consulting editor for the McGraw-Hill Series in Mechanical Engineering and also consults for industry in the fields of energy conservation and energy systems.

A member of the American Society of Engineering Education, he is past Chairman of the National Mechanical Engineering Division and past Chairman of the ASME Region X Mechanical Engineering Department Heads. Dr. Holman is a registered professional engineer in the state of Texas and received the *Mechanical Engineer of the Year* award by the North Texas Section of the American Society of Mechanical Engineers in 1971.

Dr. Holman is also the recipient of the *George Westinghouse Award* from the American Society of Engineering Education for distinguished contributions to Engineering Education (1972), the *James Harry Potter Gold Medal* for contributions to thermodynamics from ASME (1986), and the *Worcester Reed Warner Gold Medal* for outstanding contributions to the permanent literature of engineering from ASME (1987). He is a Fellow of ASME.

PREFACE

This book presents an elementary treatment of the principles of heat transfer. As a text it contains sufficient material for a one-semester course which may be presented at the junior level, or higher, depending on individual course objectives. A background in ordinary differential equations is helpful for proper understanding of the material. Although some familiarity with fluid mechanics will aid in the convection discussions, it is not essential. The concepts of thermodynamic energy balances are also useful in the various analytical developments.

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 which 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 which is gained from analytical solutions as well as the important tools of numerical analysis which must often be used in practice. 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 which 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.

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 number of special topics are discussed in Chapter 12 which give added flavor to the basic material of the preceding chapters.

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 which 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.

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 which 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 which 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 greater depth which 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 which can pyramid upon further investigation.

A textbook in its seventh edition obviously reflects many compromises and evolutionary processes over the years. This book is no exception. While the basic physical mechanisms of heat transfer have not changed, analytical techniques and experimental data are constantly being revised and improved. One objective of this new edition is to keep the exposition up to date with recent information while still retaining a simple approach which can be understood by the beginning student.

The computer is now the preferred vehicle for solution of many heat-transfer problems. Personal computers with either local software or communication links offer the engineer ample power for the solution of most problems. Despite the ready availability of this computing power I have resisted the temptation to include specific computer programs for two reasons: (1) each computer installation is somewhat different in its input-output capability and (2) a number of programs for microcomputers in a menu-driven format are already on the scene. The central issue here has been directed toward problem setup which can be adapted to any computational facility.

For those persons wishing to exploit the convenience of the microcomputer, a software package developed by Professor Allan D. Kraus, of the Naval Postgraduate School, has been included as Appendix D. A disk containing the programs will be found on the inside back cover. Appendix D contains the necessary documentation, examples, and problems for use of the programs. Some open-ended design problems are included to take advantage of the power of the computer. Note that the body of the text *does not require use of these computer programs*. On the other hand, intelligent use of the programs requires an understanding of the subject of heat transfer. References to appropriate sections of the text are therefore given in Appendix D.

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 completely in English units. Some figures have dual coordinates that show both systems of units. These displays will enable the student to develop a "bilingual" capability during the period before full metric conversion is achieved.

In this edition minor modifications and adjustments have been made along with the inclusion of the heat-transfer software package. Many new problems have been added so that the instructor and student may now choose from over 1000 problems of varying complexity. The open-ended design problems associated with the heat-transfer software are an important part of these additions.

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.

McGraw-Hill and I would like to thank the following reviewers for their many helpful comments and suggestions: J. Benjamin Austin, Bucknell University; Roger Carlson, Auburn University; Young Cho, Drexel University; Ronald Mussulman, Cal Poly—San Luis Obispo; Douglas J. Nelson, Virginia Polytechnic Institute and State University; Eugene E. Niemi, Jr., University of Lowell; Brian Vick, Virginia Polytechnic Institute and State University; and Paul H. Zang, GMI Engineering and Management Institute.

With a book at this stage of revision the list of other people who have been generous with their comments and suggestions has grown very long indeed. Rather than risk omission of a single name, I hope that a grateful general acknowledgment will express my sincere gratitude for these persons' help and encouragement.

J. P. Holman

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)
B	Magnetic field strength
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/m² (Chap. 8)
E_{b0}	Solar constant (Chap. 8)
$E_{b\lambda}$	Blackbody emmissive power per unit wavelength, defined by Eq. (8-12)
$\mathbf{E}$	Electric field vector
f	Friction factor, defined by Eq. (5-107) or Eq. (10-29)
F	Force, usually N
F_{m-n} or F_{mn}	Radiation shape factor for radiation from surface m to surface n
g	Acceleration of gravity
g_c	Conversion factor, defined by Eq. (1-14)
$G = \frac{\dot{m}}{A}$	Mass velocity
G	Irradiation (Chap. 8)
h	Heat-transfer coefficient, usually W/m² · °C
$\bar{h}$	Average heat-transfer coefficient
h_D	Mass-transfer coefficient, usually m/h
h_{fg}	Enthalpy of vaporization, kJ/kg
h_r	Radiation heat-transfer coefficient (Chap. 8)

H	Magnetic field intensity
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)
J	Current density
k	Thermal conductivity, usually W/m · °C
k_e	Effective thermal conductivity of enclosed spaces (Chap. 7)
k_λ	Scattering coefficient (Chap. 8)
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	Turbidity factor, defined by Eq. (8-120)
N	Molal diffusion rate, moles per unit time (Chap. 11)
p	Pressure, usually N/m², 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
$\bar{q}_{m,n}$	Residual of a node, used in relaxation method (Chaps. 3,4)
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	Molecular speed ratio (Chap. 12)
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 m³/kg
V	Velocity
V	Molecular volume (Chap. 11)
W	Weight, usually N
x, y, z	Space coordinates in cartesian system
$\alpha = \dfrac{k}{\rho c}$	Thermal diffusivity, usually m²/s
α	Absorptivity (Chap. 8)
α	Accommodation coefficient (Chap. 12)
α	Solar altitude angle, deg (Chap. 8)
β	Volume coefficient of expansion, 1/K
β	Temperature coefficient of thermal conductivity, 1/°C
$\gamma = \dfrac{c_p}{c_v}$	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)
$\zeta = \dfrac{\delta_t}{\delta}$	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
λ	Mean free path (Chap. 12)
μ	Dynamic viscosity
ν	Kinematic viscosity
ν	Frequency of radiation (Chap. 8)
ρ	Density, usually kg/m^3
ρ	Reflectivity (Chap. 8)
ρ_e	Charge density
σ	Electrical conductivity
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

$\mathrm{Bi} = \dfrac{hs}{k}$	Biot number
$\mathrm{Ec} = \dfrac{u_\infty^2}{c_p(T_\infty - T_w)}$	Eckert number
$\mathrm{Fo} = \dfrac{\alpha\tau}{s^2}$	Fourier number
$\mathrm{Gr} = \dfrac{g\beta(T_w - T_\infty)x^3}{\nu^2}$	Grashof number
$\mathrm{Gr}^* = \mathrm{Gr\ Nu}$	Modified Grashof number for constant heat flux
$\mathrm{Gz} = \mathrm{Re\ Pr}\,\dfrac{d}{L}$	Graetz number
$\mathrm{Kn} = \dfrac{\lambda}{L}$	Knudsen number
$\mathrm{Le} = \dfrac{\alpha}{D}$	Lewis number (Chap. 11)
$\mathrm{M} = \dfrac{u}{a}$	Mach number
$\mathrm{N} = \dfrac{\sigma B_y^2 x}{\rho u_\infty}$	Magnetic-influence number
$\mathrm{Nu} = \dfrac{hx}{k}$	Nusselt number
$\overline{\mathrm{Nu}} = \dfrac{\bar{h}x}{k}$	Average Nusselt number
$\mathrm{Pe} = \mathrm{Re\ Pr}$	Peclet number
$\mathrm{Pr} = \dfrac{c_p\mu}{k}$	Prandtl number
$\mathrm{Ra} = \mathrm{Gr\ Pr}$	Rayleigh number
$\mathrm{Re} = \dfrac{\rho u x}{\mu}$	Reynolds number
$\mathrm{Sc} = \dfrac{\nu}{D}$	Schmidt number (Chap. 11)
$\mathrm{Sh} = \dfrac{h_D x}{D}$	Sherwood number (Chap. 11)
$\mathrm{St} = \dfrac{h}{\rho c_p u}$	Stanton number
$\overline{\mathrm{St}} = \dfrac{\bar{h}}{\rho c_p u}$	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 Chaps. 3, 4)
0	Denotes stagnation flow conditions (Chap. 5) or some initial condition at time zero
r	At specified radial position
s	Evaluated at condition of surroundings
x	Denotes some local position with respect to x coordinate
w	Evaluated at wall conditions
$*$	(Superscript) Properties evaluated at reference temperature, given by Eq. (5-124)
∞	Evaluation at free-stream conditions

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CONTENTS