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Heat Transfer

Tenth Edition

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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.

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	f	Friction factor
a	Attenuation coefficient (Chap. 8)	F	Force, usually N
A	Area	F_{m-n} or F_{ij}	Radiation shape factor for radiation from surface i to surface j
A	Albedo (Chap. 8)	g	Acceleration of gravity
A_m	Fin profile area (Chap. 2)	gc	Conversion factor, defined by Eq. (1-14)
c	Specific heat, usually kJ/kg · °C	G	Irradiation (Chap. 8)
C	Concentration (Chap. 11)	$G = \frac{\dot{m}}{A}$	Mass velocity
C_D	Drag coefficient, defined by Eq. (6-13)	h	Heat-transfer coefficient, usually W/m ² · °C
C_f	Friction coefficient, defined by Eq. (5-52)	$\bar{h}$	Average heat-transfer coefficient
c_p	Specific heat at constant pressure, usually kJ/kg · °C	h_{fg}	Enthalpy of vaporization, kJ/kg
c_v	Specific heat at constant volume, usually kJ/kg · °C	h_r	Radiation heat-transfer coefficient (Chap. 8)
d	Diameter	i	Enthalpy, usually kJ/kg
D	Depth or diameter	I	Intensity of radiation
D	Diffusion coefficient (Chap. 11)	I	Solar insolation (Chap. 8)
D_H	Hydraulic diameter, defined by Eq. (6-14)	I_0	Solar insolation at outer edge of atmosphere
e	Internal energy per unit mass, usually kJ/kg	J	Radiosity (Chap. 8)
E	Internal energy, usually kJ	k	Thermal conductivity, usually W/m · °C
E	Emissive power, usually W/m ² (Chap. 8)	k_e	Effective thermal conductivity of enclosed spaces (Chap. 7)
E_{b0}	Solar constant (Chap. 8)	k_λ	Scattering coefficient (Chap. 8)
$E_{b\lambda}$	Blackbody emissive power per unit wave-length, defined by Eq. (8-12)	K	Mass-transfer coefficient, m/h

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

λ	Wavelength (Chap. 8)	$Gr = \frac{g\beta(T_w - T_\infty)x^3}{\nu^2}$	Grashof number
λ	Mean free path (Chap. 7)	$Gr^* = Gr Nu$	Modified Grashof number for constant heat flux
μ	Dynamic viscosity	$Gz = Re Pr \frac{d}{L}$	Graetz number
ν	Kinematic viscosity, m^2/s	$Kn = \frac{\lambda}{L}$	Knudsen number
ν	Frequency of radiation (Chap. 8)	$Le = \frac{\alpha}{D}$	Lewis number (Chap. 11)
ρ	Density, usually kg/m^3	$M = \frac{u}{a}$	Mach number
ρ	Reflectivity (Chap. 8)	$Nu = \frac{hx}{k}$	Local Nusselt number
σ	Stefan- Boltzmann constant	$Nu = \frac{\bar{h}x}{k}$	Average Nusselt number
σ	Surface tension of liquid-vapor interface (Chap. 9)	$Pe = Re Pr$	Peclet number
		$Pr = \frac{c_p \mu}{k}$	Prandtl number
		$Ra = Gr Pr$	Rayleigh number
		$Re = \frac{\rho u x}{\mu}$	Reynolds number
τ	Time	$Sc = \frac{\nu}{D}$	Schmidt number (Chap. 11)
τ	Shear stress between fluid layers	$Sh = \frac{Kx}{D}$	Sherwood number (Chap. 11)
τ	Transmissivity (Chap. 8)	$St = \frac{h}{\rho c_p u}$	Stanton number
ϕ	Angle in spherical or cylindrical coordinate system	$\bar{St} = \frac{\bar{h}}{\rho c_p u}$	Average Stanton number
ψ	Stream function	Subscripts	

Dimensionless Groups

$Bi = \frac{hs}{k}$	Biot number	aw	Adiabatic wall conditions
$Fo = \frac{\alpha \tau}{s^2}$	Fourier number	b	Refers to blackbody conditions (Chap. 8)

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

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