HEAT TRANSFER

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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 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 for the analysis of radiation systems.

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. Chapter 13 on environmental heat transfer is also rather specialized but contains material which is of increasing interest.

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 the student to apply the basic principles to new situations and develop his own equations. Both types of problems are important.

The subject of heat transfer is not a static one. 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 before him. 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.

The author has enjoyed the pleasure of teaching the material in this text to students at Southern Methodist University for more than ten years. Their patience, suggestions, and comments have contributed in a large way to the particular subject matter and presentation in the text. I hope that this new edition will reflect their interests and stimulate further lively discussions in the future.

Mention should be made of the modifications which appear in this third edition. A set of review questions has been added at the end of each chapter as well as additional problems. Some emphasis is given to SI units throughout the book by expressing answers to examples in this system in addition to the English units.

More emphasis has been given to numerical methods in the chapters on conduction with discussion of techniques most applicable to computer solution. Empirical relations for flow over bluff bodies has been expressed in a more compact form. Several new correlations for free convection systems are presented in Chapter 7 and the old conventional correlations are grouped together in a more compact and usable display. Minor modifications have been made to the radiation chapter. New information on peak heat flux in boiling has been added to Chapter 9 as well as some recent references. A discussion of the heat pipe and its applications has been added to the special topics chapter. A new chapter on environmental problems has been added to stress the variety of applications of the subject of heat transfer. It is hoped that these additions throughout the book will provide a flavor which increases the general appeal of the subject.

Many people have been generous with their comments and suggestions for improvement of the book. S. J. Kline, R. J. Schoenhals, J. V. Beck, Erich Soehngen, K. V. Prasanna, M. Fleischman, J. E. Sunderland, W. G. Wyatt, and others, have been most helpful and I am grateful for their interest. Finally, I particularly appreciate the continuing support of the editorial staff at the McGraw-Hill Book Company.

J. P. HOLMAN

LIST OF SYMBOLS

a	Local velocity of sound
a	Attenuation coefficient (Chap. 13)
A	Area
A	Albedo (Chap. 13)
A_m	Fin profile area (Chap. 2)
$\mathbf{B}$	Magnetic field strength
c	Specific heat, usually Btu/lb_m-°F
C	Concentration (Chap. 11)
C_D	Drag coefficient, defined by Eq. (6-10)
C_f	Friction coefficient, defined by Eq. (5-44)
c_p	Specific heat at constant pressure, usually Btu/lb_m-°F
c_v	Specific heat at constant volume, usually Btu/lb_m-°F
d	Diameter
D	Depth or diameter
D	Diffusion coefficient (Chap. 11)
D_H	Hydraulic diameter, defined by Eq. (6-9)
e	Internal energy per unit mass, usually Btu/lb_m
E	Internal energy, usually Btu
E	Emissive power, usually Btu/hr-ft^2 (Chap. 8)
E_{b_0}	Solar constant (Chaps. 8, 13)
$E_{b\lambda}$	Blackbody emissive power per unit wavelength, defined by Eq. (8-10)
$\mathbf{E}$	Electric field vector
f	Friction factor, defined by Eq. (5-70)
F	Force, usually lb_f
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. (1-12)
$G = \frac{\dot{m}}{A}$	Mass velocity
G	Irradiation (Chap. 8)
h	Heat-transfer coefficient, usually Btu/hr-ft^2-°F
$\bar{h}$	Average heat-transfer coefficient
h_D	Mass-transfer coefficient, usually ft/hr
h_{fg}	Enthalpy of vaporization, Btu/lb_m
h_r	Radiation heat-transfer coefficient (Chap. 8)
$\mathbf{H}$	Magnetic field intensity
i	Enthalpy, usually Btu/lb_m
I	Intensity of radiation
I	Solar insolation (Chap. 13)
I_0	Solar insolation at outer edge of atmosphere [Eq. (13-4b)]
J	Radiosity (Chap. 8)
$\mathbf{J}$	Current density
k	Thermal conductivity, usually Btu/hr-ft-°F
k_e	Effective thermal conductivity of enclosed spaces (Chap. 7). Defined by Eq. (7-35)
k_λ	Scattering coefficient (Chap. 13)
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. (13-4)
N	Molal diffusion rate, moles per unit time (Chap. 11)
p	Pressure, usually lb_f/ft^2
P	Perimeter
q	Heat-transfer rate, Btu per unit time
q''	Heat flux, Btu 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 and 4)
Q	Heat, Btu
r	Radius or radial distance
r	Recovery factor, defined by Eq. (5-78)
R	Fixed radius
R	Gas constant
R_{th}	Thermal resistance, usually hr-°F/Btu
s	A characteristic dimension (Chap. 4)
S	Molecular speed ratio (Chap. 12)
S	Conduction shape factor, usually ft
t	Thickness, applied to fin problems (Chap. 2)
t, T	Temperature
u	Velocity
v	Velocity
v	Specific volume, usually ft^3/lb_m
V	Velocity
V	Molecular volume (Chap. 11)
W	Weight, usually lb_f
x, y, z	Space coordinates in cartesian system
$\alpha = \frac{k}{\rho c}$	Thermal diffusivity, usually ft^2/hr
α	Absorptivity (Chap. 8)
α	Accommodation coefficient (Chap. 12)
α	Solar altitude angle, degrees, (Chap. 13)
α	Ambient atmospheric lapse rate (LR)
β	Volume coefficient of expansion, 1/°R
β	Temperature coefficient of thermal conductivity, 1/°F
$\gamma = \frac{c_p}{c_v}$	Isentropic exponent, dimensionless
Γ	Condensate mass flow per unit depth of plate (Chap. 9)
Γ	Dry adiabatic lapse rate (DALR) (Chap. 13)
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
λ	Mean-free path (Chap. 12)
μ	Dynamic viscosity
μ	Denotes micron unit of wavelength, $1\mu = 10^{-6}$ m (Chap. 8)
ν	Kinematic viscosity
ν	Frequency of radiation (Chap. 8)
ρ	Density, usually lb_m/ft^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

$\text{Bi} = \dfrac{hs}{k}$ Biot modulus

$\text{Ec} = \dfrac{u_\infty^2}{c_p(T_\infty - T_w)}$ Eckert number

$\text{Fo} = \dfrac{\alpha\tau}{s^2}$ Fourier modulus

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

$\text{Gr}^* = \text{GrNu}$ Modified Grashof number for constant heat flux

$\text{Gz} = \text{Re}\,\text{Pr}\,\dfrac{d}{L}$ Graetz number

$\text{Kn} = \dfrac{\lambda}{L}$ Knudsen number

$\text{Le} = \dfrac{\alpha}{D}$ Lewis number (Chap. 11)

$\text{M} = \dfrac{u}{a}$ Mach number

$\text{N} = \dfrac{\sigma B_y^2 x}{\rho u_\infty}$ Magnetic influence number

$\text{Nu} = \dfrac{hx}{k}$ Nusselt number

$\overline{\text{Nu}} = \dfrac{\bar{h}x}{k}$ Average Nusselt number

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

$\text{Pr} = \dfrac{c_p\mu}{k}$ Prandtl number

$\text{Re} = \dfrac{\rho ux}{\mu}$ Reynolds number

$\text{Sc} = \dfrac{\nu}{D}$ Schmidt number (Chap. 11)

$\text{Sh} = \dfrac{h_D x}{D}$ Sherwood number (Chap. 11)

$\text{St} = \dfrac{h}{\rho c_p u}$ Stanton number

$\overline{\text{St}} = \dfrac{\bar{h}}{\rho c_p u}$ Average Stanton number

Subscripts

aw	Adiabatic wall conditions
b	Refers to blackbody conditions (Chap. 8)
b	Evaluated at bulk conditions [see Eq. (5-61)]
d	Based on diameter
f	Evaluated at film conditions [see Eq. (5-43)]
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 and 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. (5-82)
∞	Evaluated at free-stream conditions

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CHAPTER 1

INTRODUCTION

Heat transfer is that science which seeks to predict the energy transfer which may take place between material bodies as a result of a temperature difference. Thermodynamics teaches that this energy transfer is defined as heat. The science of heat transfer seeks not merely to explain how heat energy may be transferred, but also to predict the rate at which the exchange will take place under certain specified conditions. The fact that a heat-transfer *rate* is the desired objective of an analysis points out the difference between heat transfer and thermodynamics. Thermodynamics deals with systems in equilibrium; it may be used to predict the amount of energy required to change a system from one equilibrium state to another; it may not be used to predict how fast a change will take place since the system is not in equilibrium during the process. Heat transfer supplements the first and second principles of thermodynamics by providing additional experimental rules which may be used to establish energy-transfer rates. As in the science of thermodynamics, the experimental rules used as a basis of the subject of heat transfer are rather simple and easily expanded to encompass a variety of practical situations.

As an example of the different kinds of problems which are treated by thermodynamics and heat transfer, consider the cooling of a hot steel bar which is placed in a pail of water. Thermodynamics may be used to predict the final equilibrium temperature of the steel bar–water combination. Thermodynamics will not tell us how long it takes to reach this equilibrium condition or what the temperature of the bar will be after a certain length of time before the equilibrium condition is attained. Heat transfer may be used to predict the temperature of both the bar and the water as a function of time.

Most readers will be familiar with the terms used to denote the three modes of heat transfer: conduction, convection, and radiation. In this chapter we seek to explain the mechanism of these modes qualitatively so that each may be considered in its proper perspective. Subsequent chapters will treat the three types of heat transfer in detail.