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（英文版·原书第9版）

传热学

Heat Transfer

(美)J. P.霍尔曼(J. P.Holman) 著

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Useful conversion factors

Physical quantity	Symbol	SI to English conversion	English to SI conversion
Length	L	1 m = 3.2808 ft	1 ft = 0.3048 m
Area	A	1 m^2 = 10.7639 ft^2	1 ft^2 = 0.092903 m^2
Volume	V	1 m^3 = 35.3134 ft^3	1 ft^3 = 0.028317 m^3
Velocity	v	1 m/s = 3.2808 ft/s	1 ft/s = 0.3048 m/s
Density	ρ	1 kg/m^3 = 0.06243 lb_m/ft^3	1 lb_m/ft^3 = 16.018 kg/m^3
Force	F	1 N = 0.2248 lb_f	1 lb_f = 4.4482 N
Mass	m	1 kg = 2.20462 lb_m	1 lb_m = 0.45359237 kg
Pressure	p	1 N/m^2 = 1.45038×10^{-4} lb_f/in^2	1 lb_f/in^2 = 6894.76 N/m^2
Energy, heat	q	1 kJ = 0.94783 Btu	1 Btu = 1.05504 kJ
Heat flow	q	1 W = 3.4121 Btu/h	1 Btu/h = 0.29307 W
Heat flux per unit area	q/A	1 W/m^2 = 0.317 Btu/h·ft^2	1 Btu/h · ft^2 = 3.154 W/m^2
Heat flux per unit length	q/L	1 W/m = 1.0403 Btu/h·ft	1 Btu/h · ft = 0.9613 W/m
Heat generation per unit volume	$\dot{q}$	1 W/m^3 = 0.096623 Btu/h·ft^3	1 Btu/h · ft^3 = 10.35 W/m^3
Energy per unit mass	q/m	1 kJ/kg = 0.4299 Btu/lb_m	1 Btu/lb_m = 2.326 kJ/kg
Specific heat	c	1 kJ/kg·°C = 0.23884 Btu/lb_m·°F	1 Btu/lb_m·°F = 4.1869 kJ/kg·°C
Thermal conductivity	k	1 W/m·°C = 0.5778 Btu/h·ft·°F	1 Btu/h·ft·°F = 1.7307 W/m·°C
Convection heat transfer coefficient	h	1 W/m^2·°C = 0.1761 Btu/h·ft^2·°F	1 Btu/h·ft^2·°F = 5.6782 W/m^2·°C
Dynamic		1 kg/m·s = 0.672 lb_m/ft·s	
viscosity	μ	= 2419.2 lb_m/ft·h	1 lb_m/ft·s = 1.4881 kg/m·s
Kinematic viscosity and thermal diffusivity	ν, α	1 m^2/s = 10.7639 ft^2/s	1 ft^2/s = 0.092903 m^2/s

Important physical constants

Avogadro's number	$N_0 = 6.022045 \times 10^{26}$ molecules/kg mol
Universal gas constant	$\mathcal{R}$ = 1545.35 ft·lbf/lbm·mol·°R = 8314.41 J/kg mol·K = 1.986 Btu/lbm·mol·°R = 1.986 kcal/kg mol·K
Planck's constant	$h = 6.626176 \times 10^{-34}$ J-sec
Boltzmann's constant	$k = 1.380662 \times 10^{-23}$ J/molecule·K $= 8.6173 \times 10^{-5}$ eV/molecule·K
Speed of light in vacuum	$c = 2.997925 \times 10^{8}$ m/s
Standard gravitational acceleration	g = 32.174 ft/s^2 = 9.80665 m/s^2
Electron mass	$m_e = 9.1095 \times 10^{-31}$ kg
Charge on the electron	$e = 1.602189 \times 10^{-19}$ C
Stefan-Boltzmann constant	$\sigma = 0.1714 \times 10^{-8}$ Btu/hr· ft^2·R^4 $= 5.669 \times 10^{-8}$ W/m^2·K^4
1 atm	= 14.69595 lbf/in^2 = 760 mmHg at 32°F = 29.92 inHg at 32°F = 2116.21 lbf/ft^2 $= 1.01325 \times 10^{5}$ N/m^2

Basic Heat-Transfer Relations

Fourier's law of heat conduction:

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

Characteristic thermal resistance for conduction $= \Delta x/kA$

Characteristic thermal resistance for convection $= 1/hA$

Overall heat transfer $= \Delta T_{\text{overall}}/\Sigma R_{\text{thermal}}$

Convection heat transfer from a surface:

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

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

Forced convection: $\text{Nu} = f(\text{Re}, \text{Pr})$ (Chapters 5 and 6, Tables 5-2 and 6-8)
Free convection: $\text{Nu} = f(\text{Gr}, \text{Pr})$ (Chapter 7, Table 7-5)

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

$x =$ characteristic dimension

General procedure for analysis of convection problems: Section 7-14, Figure 7-15, Inside back cover.

Radiation heat transfer (Chapter 8)

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

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

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

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 $T_2(K)$:

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

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

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

where $F =$ factor for specific heat exchanger; $\Delta T_m =$ LMTD for counterflow double-pipe heat exchanger with same inlet and exit temperatures

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

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

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

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

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出版说明

随着我国加入WTO，国际间的竞争越来越激烈，而国际间的竞争实际上也就是人才的竞争、教育的竞争。为了加快培养具有国际竞争力的高水平技术人才，加快我国教育改革的步伐，国家教育部近来出台了一系列倡导高校开展双语教学、引进原版教材的政策。以此为契机，机械工业出版社近期推出了一系列国外影印版教材，其内容涉及高等学校公共基础课，以及机、电、信息领域的专业基础课和专业课。

引进国外优秀原版教材，在有条件的学校推动开展英语授课或双语教学，自然也引进了先进的教学思想和教学方法，这对提高我国自编教材的水平，加强学生的英语实际应用能力，使我国的高等教育尽快与国际接轨，必将起到积极的推动作用。

为了做好教材的引进工作，机械工业出版社特别成立了由著名专家组成的国外优秀教材审定委员会。这些专家对实施双语教学做了深入细致的调查研究，对引进原版教材提出许多建设性意见，并慎重地对每一本将要引进的原版教材一审再审，精选再精选，确认教材本身的质量水平，以及权威性和先进性，以期所引进的原版教材能适应我国学生的外语水平和学习特点。在引进工作中，审定委员会还结合我国高校教学课程体系的设置和要求，对原版教材的教学思想和方法的先进性、科学性严格把关，同时尽量考虑原版教材的系统性和经济性。

这套教材出版后，我们将根据各高校的双语教学计划，举办原版教材的教师培训，及时地将其推荐给各高校选用。希望高校师生在使用教材后及时反馈意见和建议，使我们更好地为教学改革服务。

机械工业出版社
高等教育分社

序 1

近十年来，我国高等学校的广大教师纷纷在本科教学过程中尝试使用不同程度的汉语加英语的教学方式（通称双语教学）。2001年教育部在《关于加强高等学校本科教学工作提高教学质量的若干意见》中明确指出：按照“教育面向现代化、面向世界、面向未来”的要求，为适应经济全球化和科技革命的挑战，本科教育要创造条件使用英语等外语进行公共课和专业课教学。这一文件精神的传达更加激发了我国高等学校广大教师采用双语教学的积极性。

根据笔者自己的经历，在工程类专业教学中，首先应当在技术基础课程的教学中推行双语教学。笔者和同事 1995 年曾经在西安交通大学能源与动力学院三年级的传热学课程教学中对一个小班尝试过用英语授课（汉语教材、英语讲授）。尽管有部分学生因为课程负担问题未能从头听到底，能坚持到底的学生到课程结束时确实感到很有收获。但同时又深切地感受到，如果能有一本合适的英文教材相配合效果会更好。近年来，为配合双语教学，国内一些出版社引进了不少国际上知名的教材。但常常由于目前教材的价格与学生的承受能力相差太大而使其应用受到限制。

对于传热学课程的双语教学，现在这一问题有了较好的解决方案：机械工业出版社与世界著名的 McGraw-Hill 公司经过协商，决定在国内由机械工业出版社影印 J.P.Holman 的《Heat Transfer》第 9 版；并且为了减轻读者的负担，机械工业出版社预先约请了有关专家对原著中的某些内容在不影响教材使用的前提下作了删节。现在展现在读者面前的就是这样一本教材。

Holman 教授在美国乃至全世界的传热学教学中具有特殊的地位：他的《Heat Transfer》自 1963 年出版第 1 版以来，已经经历 40 余个年头，平均每隔 5 年再版一次，其销量在美国一直常兴不衰。究其原因除了该教材说理清楚、语言流畅、深入浅出、注重应用等特点外，能及时反映传热学的最新研究进展也是一个重要原因。笔者对比了第 9 版与第 8 版的内容，就发现了不少区别：第 9 版将专题中的热管内容移到相变换热这一章，而删去了某些过分专门的内容（如电磁流体发电中的传热问题等）；每章后面增加了例题清单，便于读者查阅；计算机辅助计算的程序也改为功能更广的 Microsoft Excel 等。

感谢机械工业出版社做了一件很有意义的事，相信本书在国内的影印一定会对促进我国传热学乃至热工课程的双语教学和课程改革起到积极作用。

陶文铨
教育部热工基础课程教学
指导分委员会主任委员
于西安

序 2

知道并使用 J.P.Holman 教授编著的《Heat Transfer》始于 20 世纪 70 年代末 80 年代初。那时笔者正上大学，该书由此成为我从事传热学教学和科研工作生涯中影响最深远的专业书籍之一。该书语言简洁，说理明晰，深入浅出，尤其趣味横生、精细巧妙的数理描述更是引人入胜，把我带进了一个全新的未知世界，并使我与传热学结下不解之缘。

自 1963 年该书第 1 版面世以来，在美国和世界各国高校十分流行，多用做本科传热学教材或主要参考书；在中国也有很高的知名度，为相关专业教学、科研和工程技术人员所熟知，受到学生的广泛欢迎。本书是 Holman 教授经 8 次修订和增补充实内容后的第 9 版，作者在前言中已对全书内容、结构框架、特点、修订演变等作了详尽介绍，这里不再重复。笔者认为，除保持原有风格和特色外，这一版又有许多新意，尤其对中国读者更值得提及。

1．进一步浓缩和精炼了基础知识、理论和基本技能训练等内容。

2．补充了集中反映当今传热学新进展的内容，包括导热、对流（单相和相变）、辐射、传质、换热器（设备）等方面的新的基本认识、研究思维和方法、新的应用领域等。

3．更加紧密地把传热学基础理论和现代高新科技的发展结合在一起，从应用对象上给人以新的视野，同时也给读者发展创新技术应用提供新的想像空间，这些主要体现在书中的例题、思考题和习题中，所附创新设计性专题尤其结合了现代发展的前沿。

4．本书的9个版本演绎了近50年传热学教学与研究的发展历史，而这一版更是集中其中的精髓，这种演变线索的提供，为读者营造了一个认识、学习和掌握传热学知识的良好氛围。

尽管这次影印出版者作了一些删节，但仍很好地保持着原著的内容和框架体系，尤其保留了所有重要的修订和适应创新需求的新内容，基本可达到原著期望的目标。相信除本书精彩的编写论述所带来的科学技术魅力外，优雅的英文文字也同样会给读者以美的享受。

彭晓峰
清华大学教授
于清华园

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 which 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 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.

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 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 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 ninth 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 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. Seventeen new worked examples have been added; many in the computer-numerical solution area. 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. The computer software developed by Professor Allan D. Kraus and previously included as an Appendix is now offered via the web or from the author at no charge.

A new feature is the use of Microsoft Excel for solution of both steady state and transient 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 which 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. Examples are also given for lumped-capacity analyses incorporating variable convection and radiation boundary conditions.

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 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.

In response to user requests, answers to selected problems have been provided in a section at the back of the book.

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.

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 people's 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:

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J. P. Holman

ABOUT THE AUTHOR

J. P. Holman received his 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 Brown Foundation Professor of Mechanical Engineering. He has also 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. 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. Dr. Holman is also a consulting editor for the McGraw-Hill Series in Mechanical Engineering and 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_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_H Hydraulic diameter, defined by Eq. (6-14)

e Internal energy per unit mass, usually kJ/kg

E Internal energy, usually kJ

E Emlssive 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)

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

G Irradiation (Chap. 8)

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)

K Mass-transfer coefficient, m/h

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/mC · °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

n Molecular density

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

W Weight, usually N

x, y, z Space coordinates in cartesian system

$\alpha = \frac{k}{\rho c}$ 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_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

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

$\mathrm{Nu} = \frac{hx}{k}$ 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

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

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
w	Evaluated at wall conditions
x	Denotes some local position with respect to x coordinate
*	(Superscript) Properties evaluated at reference temperature, given by Eq. (5-124)
∞	Evaluation at free-stream conditions

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我们的联系方式：

北京百万庄大街22号　100037
机械工业出版社　高等教育分社
联系人　蔡开颖
Tel　010－88379713
Fax　010－68994030
E－mail　cky@ mail. machineinfo. gov. cn

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麦格劳－希尔北京代表处
清华科技园创新大厦907　北京100084
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