Heat and Mass Transfer

Rajendra Karwa

Heat and Mass Transfer

Springer

Rajendra Karwa
Jodhpur Institute of Engineering & Technology
Jodhpur, Rajasthan
India

ISBN 978-981-10-1556-4 ISBN 978-981-10-1557-1 (eBook)
DOI 10.1007/978-981-10-1557-1

Library of Congress Control Number: 2016940348

© Springer Science+Business Media Singapore 2017
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made.

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer Science+Business Media Singapore Pte Ltd.

Preface

This textbook caters to heat and mass transfer courses taught at the undergraduate and graduate levels to students of mechanical, automobile, aerospace, and production & industrial engineering. The heat transfer part of the book will also be useful for students of chemical engineering.

The book presents a classical treatment of the fundamentals of heat transfer. It takes the basic approach of separate discussions of conduction, convection, and radiation. The book comprises 16 chapters and two appendices. Each chapter includes a number of solved problems and end-of-chapter exercises, supplemented with step-wise answers.

Chapter 1 presents an overview of different modes of heat transfer.

Chapters 2, 3, and 4 present the conventional treatment of one-dimensional heat conduction through plane wall, cylindrical and spherical systems, fins, and simple systems with volumetric heat generation.

Chapter 5 presents an analytical treatment of some cases of two-dimensional steady-state heat conduction, followed by a discussion of finite-difference numerical methods which are often used in practice for solving complex problems.

Chapter 6 is devoted to transient heat conduction. It includes lumped heat capacity analysis and solution of problems based on Heisler charts. The chapter presents numerical methods of solving transient conduction problems with a number of illustrative examples.

Chapter 7 presents analytical solutions of some simple convection heat transfer problems, especially the convection with laminar flow.

Chapters 8 and 9 cover empirical relations for forced and natural or free convection heat transfer, respectively.

Chapters 10 and 11 deal with fundamentals of radiation heat transfer and the exchange of thermal radiation between surfaces separated by transparent medium, respectively. The method of radiation-network has been used extensively in the analysis of radiation problems. Gaseous radiation problems have been dealt with using the conventional Hottel charts in Chap. 12.

Chapter 13 is divided into two parts. In the first part, the basic modes of condensation are presented, followed by the presentation of the analytical solution due to Nusselt for laminar film condensation on a vertical surface. The second part discusses the phenomenon of pool boiling followed by discussion on forced boiling in vertical and horizontal pipes.

The conventional thermal analysis of heat exchangers (the log-mean-temperature-difference and NTU-effectiveness approaches) is presented in Chap. 14, followed by introduction to design methodology of heat exchangers considering design of double-pipe heat exchanger.

Chapter 15 presents a brief introduction to mass diffusion in a quiescent medium and convective mass transfer. Analogies between heat, mass, and momentum transfer are established.

Chapter 16 covers thermal analysis and discussion of conventional and enhanced performance solar air heaters.

Readers are advised to refer to the reference books, handbooks, and journals, some of which are listed at the end of book, for details beyond the coverage of this textbook and also for the new developments in the field of heat transfer. Computers have made possible the numerical solution of quite complex problems. Readers are advised to refer to advanced works for computer-aided solutions of heat transfer problems.

The author sincerely expresses deep sense of gratitude and indebtedness to the authors and publishers of various advanced books, handbooks, journals, and other references which have been consulted and whose material has been used in the preparation of this book.

In spite of the care taken in preparing the manuscript of this book and reading the proofs, there is always a scope for improvement and some errors might have crept in. I will be grateful to the readers if they can suggest ways to improve the contents and bring to my attention the errors, if any, noticed by them.

Jodhpur Dr. Rajendra Karwa

Contents

1 Introduction 1
- 1.1 Introduction 1
- 1.2 Heat Transfer by Conduction 1
- 1.3 Heat Transfer by Convection 3
- 1.4 Heat Transfer by Radiation 4

2 One-Dimensional Steady State Heat Conduction 7
- 2.1 Introduction 7
- 2.2 Temperature Field and Temperature Gradient 7
- 2.3 Thermal Conductivity 9
  - 2.3.1 Thermal Conductivity of Solids 10
  - 2.3.2 Thermal Conductivity of Metals and Alloys 10
  - 2.3.3 Thermal Conductivity of Construction and Heat-Insulating Materials 10
  - 2.3.4 Thermal Conductivity of Gases 11
  - 2.3.5 Thermal Conductivity of Liquids 12
- 2.4 General Heat Conduction Equations 13
  - 2.4.1 General Heat Conduction Equation in Cartesian Coordinates 13
  - 2.4.2 General Heat Conduction Equation in Cylindrical Coordinates 18
  - 2.4.3 General Heat Conduction Equation in Spherical Coordinates 23
- 2.5 One-Dimensional Steady-State Heat Conduction 27
  - 2.5.1 Composite Plane Wall 29
  - 2.5.2 One-Dimensional Steady-State Heat Conduction Through a Plane Homogeneous Wall Considering Film Coefficients 30

2.5.3 One-Dimensional Steady-State Conduction Heat Transfer Through a Plane Homogeneous Wall Considering Heat Transfer by Convection and Radiation from the Wall Surface. 32
2.6 One-Dimensional Steady-State Heat Conduction Through a Cylindrical Shell 45
2.6.1 One Dimensional Steady-State Heat Conduction Through a Cylindrical Shell Considering Film Coefficients 50
2.6.2 Composite Cylindrical Wall. 53
2.7 One-Dimensional Steady-State Heat Conduction Through a Spherical Shell 61
2.7.1 One-Dimensional Steady-State Heat Conduction Through a Spherical Shell Considering the Film Coefficients. 66
2.7.2 Composite Spherical Shell 67
2.8 Measurement of Thermal Conductivity 71
2.8.1 Thermal Conductivity Measurement of Solids 71
2.8.2 Thermal Conductivity Measurements of Liquids and Gases 73
2.9 Effect of Variable Thermal Conductivity 75
2.9.1 Plane Wall. 76
2.9.2 Cylindrical Shell. 78
2.9.3 Spherical Shell. 79
2.10 Critical Thickness of Insulation 95
2.10.1 Critical Thickness of Insulation for Cylinders. 95
2.10.2 Critical Thickness of Insulation for Spherical Vessel. 98
2.11 Thermal Contact Resistance. 109
References 116

3 Extended Surfaces (Fins) 117
3.1 Introduction. 117
3.2 Heat Transfer from a Fin of Uniform Cross-Section 119
3.2.1 A Very Long Fin 121
3.2.2 Negligible Heat Transfer from the Fin End as Compared to the Heat Transferred from the Fin Surface ($A_c \ll PL$). 123
3.2.3 Short Fins (Fin with Heat Loss from the Fin End). 126
3.3 Hollow Fins 129
3.4 Composite Fins 130
3.5 Effectiveness and Efficiency of Fins 138
3.6 Heat Transfer from a Finned Wall 142
3.7 Intensification of Heat Transfer by Finning 143

3.8 Error in Temperature Measurement with Thermometer Well 151
3.9 When Fins Are to Be Used? 153
3.10 Heat Transfer from a Bar Connected to Two Heat Sources at Different Temperatures 160
3.11 Generalized Equation of Fin 176
3.12 Fin of Minimum Weight (Isachenko et al. 1977) 178
3.13 Straight Fin of Triangular Section. 179
3.14 Straight Fin of Trapezoidal Section. 183
3.15 Annular Fin. 185
3.16 Fin Efficiency Plots 188
References 196

4 Conduction with Heat Generation. 197
4.1 Plane Wall with Uniform Heat Generation. 197
  4.1.1 Case (A) Surfaces at Different Temperatures 199
  4.1.2 Case (B) Surfaces at the Same Temperature. 205
4.2 Cylinder with Uniform Heat Generation 209
4.3 Solid Sphere with Uniform Heat Generation 224
4.4 Heat Transfer Through Piston Crown 228

5 Steady-State Two-Dimensional Heat Conduction 247
5.1 Introduction. 247
5.2 Analytical Solution of Two-Dimensional Heat Conduction Problems. 248
5.3 Conduction Through a Flat Semi-Infinite Homogeneous Plate. 253
5.4 Mean Value Theorem 258
5.5 Graphical Analysis of Two-Dimensional Steady-State Conduction: Thermal Flux Plotting and Shape Factor 263
5.6 Experimental Investigation of Conduction Process by Method of Analogy: Electro-Thermal Analogy 277
5.7 Numerical Solution Methods 278
  5.7.1 Finite-Difference Method. 279
  5.7.2 Solution of Nodal Equations 287
5.8 Two-Dimensional Steady-State Heat Conduction with Heat Generation 305

6 Unsteady or Transient Heat Conduction. 309
6.1 Introduction. 309
6.2 Lumped Heat Capacity Analysis. 309
  6.2.1 Instantaneous and Total Heat Flow 314
  6.2.2 Applicability of the Lumped Heat Capacity Analysis 315

6.3 Lumped Capacitance, Varying Fluid Temperature 322
6.4 Multiple Lumped Capacity Systems 324
6.5 Transient Heat Flow in Semi-infinite Solids 329
6.6 Transient Heat Conduction in Infinite Plate 337
6.7 Heisler and Grober Charts 339
6.8 Two- and Three-Dimensional Transient Heat Conduction Systems 351
  6.8.1 Two-Dimensional Systems 352
  6.8.2 Three-Dimensional Systems 353
6.9 Numerical Method of Solving Transient Conduction Problems 359
  6.9.1 The Explicit and Implicit Formulations 364
6.10 The Schmidt Graphical Method for One-Dimensional Problems 372
References 379

7 Convective Heat Transfer 381
7.1 Introduction 381
  7.1.1 Natural Convective Heat Transfer 381
  7.1.2 Forced Convection Heat Transfer 382
7.2 Flow of Fluid Past a Flat Plate 383
7.3 Flow in Tubes 385
  7.3.1 Laminar Flow Through a Tube 386
  7.3.2 Turbulent Flow Through a Tube 388
7.4 Equation of Continuity 389
  7.4.1 The Displacement and Momentum Thickness 390
  7.4.2 The Enthalpy and Conduction Thickness 395
7.5 Momentum Equation of Laminar Boundary Layer Over a Flat Plate 396
  7.5.1 Solution of Momentum Equation (Blausius Solution) 399
7.6 Integral Momentum Equation of Laminar Boundary Layer Over a Flat Plate: Von Karman Solution 409
7.7 Energy Equation of Laminar Boundary Layer Over a Flat Plate 431
  7.7.1 Pohlhausen's Solution 436
  7.7.2 Von Karman Integral Technique (Integral Analysis of Energy Equation for the Laminar Boundary Layer) 442
7.8 Turbulent Boundary Layer Over a Flat Surface 459
7.9 Laminar Flow in Tubes 466
7.10 Turbulent Flow in Tubes 482
7.11 Momentum and Heat Exchange in Turbulent Flow (Eddy Viscosity and Eddy Thermal Diffusivity) 485
7.12 Reynolds Analogy for Flow Past a Flat Surface 490

7.12.1 Reynolds-Colburn Analogy 493
7.12.2 Application of Colburn Analogy to Turbulent Heat Transfer from a Flat Plate 494
7.13 Prandtl–Taylor Modification of Reynolds Analogy for Turbulent Flow Over Flat Plates 500
7.13.1 von Karman Analogy for Flat Plates 504
7.14 Reynolds Analogy for Turbulent Flow in Tubes 505
7.14.1 Prandtl–Taylor Modification of Reynolds Analogy for Turbulent Flow in Tubes 509
7.14.2 Friction Drag: Flow Over a Flat Plate Parallel to the Flow 510
7.15 Natural or Free Convection 515
7.16 Integral Momentum and Energy Equation of Free Convection on a Vertical Plate 516
7.17 Liquid Metal Heat Transfer for Laminar Flow Over a Flat Plate 529
References 538

8 Empirical Relations for Forced Convection Heat Transfer 539
8.1 Introduction 539
8.2 Dimensional Analysis 539
8.3 Dimensional Analysis Applied to Forced Convection 541
8.3.1 Rayleigh's Method 541
8.3.2 Buckingham's Pi-Method 542
8.3.3 Physical Significance of Dimensionless Numbers . . . 549
8.4 Experimental Determination of Forced Convection Heat Transfer Coefficient 550
8.4.1 Uniform Temperature Condition 550
8.4.2 Uniform Heat Flux Condition 551
8.5 Friction Factor and Heat Transfer Coefficient Correlations for Circular Ducts 553
8.5.1 Laminar Flow in Circular Tubes 553
8.5.2 Turbulent Flow in Circular Tubes 560
8.6 Effects of Temperature Varying Properties 570
8.6.1 Correction of Constant Property Results 571
8.7 Heat Transfer and Friction in Concentric Circular Tube Annuli and Parallel Plate Duct 572
8.7.1 Laminar Flow 573
8.7.2 Turbulent Flow 577
8.8 Heat Transfer and Friction in Rectangular Duct 580
8.8.1 Laminar Flow 580
8.8.2 Turbulent Flow 581
8.9 Correlations for External Forced Flow Over a Flat Plate 583
8.9.1 Laminar Flow 583
8.9.2 Turbulent Flow 584

8.10 Forced Convection Laminar and Turbulent Flows Around Submerged Bodies 587
8.10.1 Cylinder in Cross Flow 587
8.10.2 Flow Around a Sphere 591
8.10.3 Flow Across Tube Banks. 593
8.11 Heat Transfer in Liquid Metals 600
8.12 Influence of Duct Wall Roughness in Turbulent Flow. 602
References 620

9 Empirical Relations for Natural or Free Convection 623
9.1 Introduction. 623
9.2 Buoyancy Force in Natural Convection. 623
9.3 Dimensional Analysis Applied to Natural Convection 625
9.3.1 Rayleigh's Method 625
9.3.2 Buckingham's Pi Method 626
9.3.3 Physical Interpretation of Grashof Number. 630
9.4 Experimental Determination of Natural Convection Heat Transfer Coefficient. 631
9.5 Empirical Relations for Free or Natural Convection 633
9.5.1 Vertical Plate and Cylinders. 633
9.5.2 Inclined Plate. 636
9.5.3 Horizontal Plate 636
9.5.4 Horizontal Cylinder of Diameter d and Length L $\gg$ d. 637
9.5.5 Sphere of Diameter *d* 638
9.6 Free Convection in Parallel Plate Channels 649
9.6.1 Vertical Channels 650
9.6.2 Inclined Channels. 650
9.7 Empirical Correlations for Enclosed Spaces 650
9.8 Combined Free and Forced Convection (Kays and Crawford 1980; Gebhart 1961; Holman 1992; Cengel 2007) 655
References 663

10 Laws of Thermal Radiation 665
10.1 Introduction. 665
10.2 Reflection, Absorption, and Transmission of Radiation 667
10.3 Emissivity and a Perfect Blackbody 669
10.4 Planck's Spectral Distribution of Emissive Power. 670
10.5 Wein's Displacement Law. 672
10.6 Total Emissive Power: Stefan–Boltzmann Law. 673
10.7 Blackbody Radiation in a Wave Length Interval. 676
10.8 Real and Gray Bodies. 681
10.9 Kirchhoff's Law. 684
10.10 Intensity of Radiation and Lambert's Cosine Law. 689
References 696

11 Exchange of Thermal Radiation Between Surfaces Separated by Transparent Medium 697
11.1 Introduction 697
11.2 Radiation Heat Exchange Between Two Black Surfaces and the Shape Factor 697
11.3 Evaluation of the Shape Factor 700
11.3.1 Salient Features of the Radiation Shape Factor 703
11.4 Radiation Exchange Between Infinite Parallel Plates 736
11.5 Radiation Exchange Between Infinite Long Concentric Cylinders 738
11.6 Radiation from a Gray Cavity 741
11.7 Small Gray Bodies 742
11.8 Electric Network Method for Solving Radiation Problems 749
11.8.1 Electric Network for a System Consisting of Two Gray Surfaces 751
11.8.2 System Consisting of Two Black Surfaces 753
11.8.3 Closed System of *n*-Black Surfaces 753
11.8.4 Systems Consisting of Two Black Surfaces Connected by a Single Refractory Surface 754
11.8.5 System Consisting of Two Gray Surfaces Connected by a Single Refractory Surface 759
11.8.6 System Consisting of Four Gray Surfaces Which See Each Other and Nothing Else 760
11.9 Radiation Shields 762
11.10 Radiation from a Gray Cavity (Alternative Method) 787
11.11 Newton's Law of Cooling and Overall Heat Transfer Coefficient 788
11.11.1 Determination of Specific Heat Using Newton's Law of Cooling 790
11.12 Radiation Heat Transfer Coefficient 791
References 808

12 Heat Transfer in Absorbing and Emitting Media (Gaseous Radiation) 809
12.1 Introduction 809
12.2 Specific Features of Gaseous Radiation 809
12.2.1 Selective Emitters 809
12.2.2 Beer's Law 810
12.2.3 Transmissivity, Emissivity, and Absorptivity 811
12.2.4 Total Emissive Power 812
12.3 Heat Exchange 812
12.3.1 Radiation Emitted by a Gas 813
12.3.2 Radiation Heat from Surface (Wall) 815

12.3.3 Net Rate of Heat Transfer 815
12.3.4 Mixture of CO_2 and H_2O Vapour 818
12.3.5 Gray Enclosure. 818
12.4 Gray Gas Surrounded by Diffuse Gray Surfaces at Different Temperatures 828
12.5 Flames 831
12.5.1 Luminous Flames 832
12.5.2 Nonluminous Flames. 833
References 835

13 Heat Transfer in Condensing Vapours and Boiling Liquids 837
13.1 Part A: Heat Transfer in Condensing Vapours 837
13.1.1 Introduction 837
13.1.2 Nusselt's Film Condensation Theory 838
13.1.3 Factors Affecting Film Condensation. 852
13.2 Part B: Heat Transfer in Boiling Liquids 854
13.2.1 Introduction 854
13.2.2 Boiling Heat Transfer 854
13.2.3 Relations for Boiling Heat Transfer in Pool Boiling. 860
References 864

14 Heat Exchangers 865
14.1 Part A: Heat Exchangers Fundamentals. 865
14.1.1 Introduction 865
14.1.2 Heat Transfer Equation for Double Pipe (Concentric Tube) Heat Exchanger 867
14.1.3 Log Mean Temperature Difference (LMTD). 868
14.1.4 LMTD for Other Flow Arrangements 880
14.1.5 Effectiveness-NTU Method 887
14.1.6 Effectiveness-NTU Relations for Other Flow Arrangements. 895
14.2 Part B: Design of Heat Exchangers. 910
14.2.1 Introduction 910
14.2.2 Double Pipe Exchangers 911
14.2.3 Clean and Design Overall Heat Transfer Coefficients 912
References 928

15 Mass Transfer 929
15.1 Introduction. 929
15.2 Fick's Law of Diffusion 930
15.2.1 Fick's Law for Gases in Terms of Partial Pressures 931
15.2.2 Fick's Law on Mass Basis and Mole Basis 933

15.3 Diffusion Coefficient 935
15.4 Diffusion of Vapour Through a Stationary Gas: Stefan Law 936
15.5 Convective Mass Transfer 938
15.5.1 Convective Mass Transfer Equation in Terms of Partial Pressure Difference 939
15.6 Dimensional Analysis Applied to Convective Mass Transfer 940
15.6.1 Forced 940
15.6.2 Free 942
15.7 Mass Transfer Correlations 944
15.8 Reynolds and Colburn (or Chilton–Colburn) Analogies 945

16 Special Topic: Performance of Solar Air Heater 949
16.1 Introduction 950
16.2 Mathematical Model for Thermohydraulic Performance Prediction (Karwa et al. 2007; Karwa and Chauhan 2010) 952
16.2.1 Top Loss 953
16.2.2 Wind Heat Transfer Coefficient 954
16.2.3 Sky Temperature 955
16.2.4 Convective Heat Transfer Coefficient Between the Absorber Plate and Glass Cover 957
16.2.5 Back and Edge Losses 958
16.2.6 Heat Transfer and Friction Factor Correlations 959
16.3 Enhanced Performance Solar Air Heaters 965
16.3.1 Introduction 965
16.3.2 Artificial Roughness for Heat Transfer Enhancement 966
16.4 Heat Transfer and Friction Factor Correlations for Roughened Rectangular Ducts 970
References 975

Appendix A 979

Appendix B 989

Bibliography 1015

Index 1017

About the Author

Dr. Rajendra Karwa received his Bachelor of Engineering in Mechanical Engineering from University of Jodhpur, Jodhpur (India) in 1973 and Master of Engineering in Mechanical Engineering (Thermal Engineering) with honors from the same university. He obtained his Ph.D. in 1998 from IIT Roorkee (formerly University of Roorkee), India. He retired from M.B.M. Engineering College, Faculty of Engineering & Architecture, Jai Narain Vyas University, Jodhpur (India) in 2012 as Professor and Head, Department of Mechanical Engineering after a service of more than 30 years. He served as visiting faculty in Addis Ababa University, Addis Ababa (Ethiopia) from 2003–2005. Currently he is working as Director of Jodhpur Institute of Engineering & Technology, Jodhpur. He has published about 70 research papers of which 21 are in journals. He has authored two books and edited one conference proceedings. He has guided many research scholars. His areas of interest are machine design, heat transfer, solar energy, and exergy analysis.

Symbols

A	Frontal area, m^2
A	Heat transfer surface area (m^2)
A_c	Cross-sectional area (m^2)
b	Width (m)
c	Speed of light (m/s)
c	Specific heat of solids and liquids (J/kgK)
c_p	Specific heat at constant pressure (J/kgK)
c_v	Specific heat at constant volume (J/kgK)
c_{fx}	Local skin friction coefficient = $\tau_{wx}/(1/2\rho U_\infty^2)$
C_D	Drag coefficient = $(F_D/A)/(1/2\rho U_\infty^2)$
C	Heat capacity = mc (J/K)
C	Mass concentration (kg/m^3)
C	Molar concentration (kmol/m^3)
d, D	Characteristic dimension (m)
d, D	Diameter (m)
D	Diffusion coefficient (m^2/s)
D_h, d_h	Hydraulic diameter = $4A/P$ (m)
e	Roughness height (m)
e/D_h, e/D	Relative roughness height
E	Electric potential
E	Energy (J)
$E_{b\lambda}$	Monochromatic hemispherical emissive power of black body (W/m.m^2)
f	Fanning friction factor = $\tau_w/(1/2\rho U^2)$
f_{app}	Apparent Fanning friction factor in the hydrodynamic entrance region
F_D	Drag force (N)
F_{ij}	View factor
g	Gravitational acceleration (m/s^2)
G	Mass velocity (kg/sm^2)
G	Irradiation (W/m^2)
h	Heat transfer coefficient (W/m^{2}K)

h_{fg}	Enthalpy of evaporation (latent heat) (J/kg)
h_{m}	Mass transfer coefficient (m/s)
h_r	Radiation heat transfer coefficient ($\mathrm{W/m^2K}$)
h_{x}	Local heat transfer coefficient at position x ($\mathrm{W/m^2K}$)
h_{w}	Wind heat transfer coefficient ($\mathrm{W/m^2K}$)
H	Height (m)
I	Solar radiation intensity (insolation) ($\mathrm{W/m^2}$)
I_λ	Monochromatic intensity of radiation
J	Radiosity ($\mathrm{W/m^2}$)
k	Thermal conductivity (W/mK)
l	Mean free path (m)
L	Length (m)
L	Fundamental dimension of length
L_{c}	Corrected fin length (m)
L_{hy}	Hydrodynamic entrance length (m)
L_{th}	Thermal entrance length (m)
m	Mass flow rate (kg/s)
m	A fin parameter ($\mathrm{m^{-1}}$)
M	Molecular weight
M	Fundamental dimension of mass
n	Number of radiation shields
N	Molal diffusion rate
NTU	Number of transfer units
p	Pressure (Pa)
p_{i}	Partial pressure (Pa)
P	Power (W)
P	Perimeter (m)
q	Heat transfer rate (W)
q'', q_{w}	Heat flux ($\mathrm{W/m^2}$)
Q	Quantity of heat (J)
q_{g}	Volumetric heat generation rate ($\mathrm{W/m^3}$)
r	Radius (usually variable) (m)
R	Radius (m)
R	Gas constant (J/kg K)
R	Temperature group $(T_1 - T_2)/(t_2 - t_1)$
R_{k}	Thermal resistance to heat conduction (K/W)
S	Temperature group $(t_2 - t_1)/(T_1 - t_1)$
S	Conduction shape factor
T_{a}	Ambient temperature ($^{\circ}$C, K)
T_{b}, T_{fm}	Bulk mean air temperature = $(T_{\mathrm{o}} + T_{\mathrm{i}})/2$ ($^{\circ}$C, K)
T_i	Inlet temperature ($^{\circ}$C)
T_o	Outlet temperature ($^{\circ}$C)
T_{sky}	Sky temperature ($^{\circ}$C, K)
T_{sat}	Saturation temperature (K)
T_∞	Free stream temperature (K)

u, v, w	Velocity (m/s)
U	Overall heat transfer coefficient (W/m^{2}K)
U_∞	Free stream velocity (m/s)
v	Specific volume (m^3/kg)
V	Volume (m^3)
W	Weight (N)
W	Width of the duct (m)
W/H	Duct aspect ratio
x, y, z	Variable distances in space
x_i	Mole fraction

Dimensionless Numbers

Bi	Biot number = hL/k_solid
e^+	Roughness Reynolds number, Eq. (8.63)
Ec	Eckert number = $u^2/c_\mathrm{p}\Delta t$
Fo	Fourier number = $\alpha\tau/L^2$
g	Heat transfer function, Eq. (8.69)
Gr	Grashof number = $\mathrm{g}\beta L^3\Delta t/\nu^2$
Gz	Graetz number = Re Pr (D/L)
Le	Lewis number[a] = Sc/Pr = α/D
p/e	Relative roughness pitch
Nu	Nusselt number = hL/k_fluid
Pe	Peclet number = Re Pr
Pr	Prandtl number = $\mu c_p/k$
$\mathrm{Pr_t}$	Turbulent Prandtl number = $\varepsilon_\mathrm{M}/\varepsilon_\mathrm{H}$
R	Roughness function, Eq. (8.67)
Ra	Rayleigh number = Gr Pr = $g\beta H^3\Delta t/\alpha\nu$
Ra^*	Rayleigh number (based on heat flux) = $g\beta q'' H^4/\alpha\nu k$
Re	Reynolds number = $\frac{\rho U d}{\mu} = GL/\mu$
$\mathrm{Re_x}$	Reynolds number based on longitudinal length = $U_\infty x/\nu$
$\mathrm{Re_{cr}}$	Critical Reynolds number
Sc	Schmidt number[a] = $\nu/D = \mu/\rho D$ = Le Pr
Sh	Sherwood number[a] = $h_\mathrm{m}L/D$
$\mathrm{St_m}$	Mass transfer Stanton number = h_m/U
St	Stanton number = $h/(Gc_\mathrm{p})$
$\mathrm{St_x}$	Local Stanton number = $h_\mathrm{x}/(Gc_\mathrm{p})$
[a]Diffusion	D is mass diffusivity (m^2/s)

Greek Symbols

α, β, γ, ϕ, ψ	Angle (degree or rad)
α	Thermal diffusivity = $k/\rho c$ (m^2/s)
α	Absorptivity (radiation)
β	Coefficient of volumetric expansion (1/K)
β	Temperature coefficient of thermal conductivity (1/K)
β	Collector slope (degree)
δ	Velocity boundary layer thickness (m)
δ	Thickness (m)
δ_{md}	Momentum displacement thickness (m)
δ_{vd}	Velocity displacement thickness (m)
δp, Δp	Pressure drop in the duct (Pa)
δ_{t}	Thermal boundary layer thickness
Δt	Temperature difference ($^{\mathrm{o}}$C, K)
ε	Fin effectiveness
ε	Heat exchanger effectiveness
ε	Emissivity
ε_{H}	Thermal eddy diffusivity (m^2/s)
ε_{M}	Momentum eddy diffusivity or viscosity (m^2/s)
ϕ	Relative humidity
η	Thermal efficiency
η_{f}	Efficiency of fin
λ	Darcy friction factor (=4f)
λ	Wave length (m)
λ_{max}	Wave length at maximum value of $E_{\mathrm{b}\lambda}$
μ	Dynamic viscosity (Pa s, Ns/m^2, kg/ms)
v	Kinematic viscosity = μ/ρ (m^2/s)
π	Dimensionless group
θ	Excess temperature (K)
θ	Time (s)
ρ	Density of fluid (kg/m^3)
ρ	Reflectivity
σ	Stefan–Boltzmann constant
σ	Surface tension (N/m)
τ	Time (s)
τ	Shear stress between fluid layers (Pa)
$(\tau\alpha)$	Transmittance-absorptance product
ω	Solid angle (sr)
ω	Specific humidity
ψ	Stream function

Superscript and Subscript

a	Ambient
b	Bulk, blackbody
cr	Critical state
f	Fluid
f	Film
fd	Fully developed
g	Gas
hy	Hydrodynamic
i, 1	Inlet or initial
i	Based on the inside surface of a pipe
l	Laminar or liquid
m	Mass transfer quantity
m	Mean
max	Maximum
min	Minimum
o, 2	Outlet
o	Based on the outside surface of a pipe
o	Stagnation
s	Smooth surface
s	Surface
th	Thermal
v	Vapour
w	Wall
x	Based on variable length
∞	Free stream condition
$\bar{}$	(overbar) mean or molar

Space Coordinates

r, θ, z	Cylindrical (m, rad, m)
r, θ, ϕ	Spherical (m, rad, rad)
x, y, z	Cartesian (m, m, m)

Note The symbol L in the dimensionless groups stands for a generic length and is defined according to the particular geometry under consideration; it may be diameter, hydraulic diameter, plate length, etc.