



# Contents

---

	Symbols	xxi
<b>CHAPTER 1</b>	<b><i>Introduction</i></b>	<b>1</b>
	<b>1.1</b> What and How?	2
	<b>1.2</b> Physical Origins and Rate Equations	3
	1.2.1 Conduction	3
	1.2.2 Convection	6
	1.2.3 Radiation	8
	1.2.4 The Thermal Resistance Concept	12
	<b>1.3</b> Relationship to Thermodynamics	12
	1.3.1 Relationship to the First Law of Thermodynamics (Conservation of Energy)	13
	1.3.2 Relationship to the Second Law of Thermodynamics and the Efficiency of Heat Engines	31
	<b>1.4</b> Units and Dimensions	36
	<b>1.5</b> Analysis of Heat Transfer Problems: Methodology	38


1.6	Relevance of Heat Transfer	41
1.7	Summary	45
	References	48
	Problems	49
<b>CHAPTER 2 Introduction to Conduction</b>		<b>67</b>
<hr/>		
2.1	The Conduction Rate Equation	68
2.2	The Thermal Properties of Matter	70
	2.2.1 Thermal Conductivity	70
	2.2.2 Other Relevant Properties	78
2.3	The Heat Diffusion Equation	82
2.4	Boundary and Initial Conditions	90
2.5	Summary	94
	References	95
	Problems	95
<b>CHAPTER 3 One-Dimensional, Steady-State Conduction</b>		<b>111</b>
<hr/>		
3.1	The Plane Wall	112
	3.1.1 Temperature Distribution	112
	3.1.2 Thermal Resistance	114
	3.1.3 The Composite Wall	115
	3.1.4 Contact Resistance	117
	3.1.5 Porous Media	119
3.2	An Alternative Conduction Analysis	132
3.3	Radial Systems	136
	3.3.1 The Cylinder	136
	3.3.2 The Sphere	141
3.4	Summary of One-Dimensional Conduction Results	142
3.5	Conduction with Thermal Energy Generation	142
	3.5.1 The Plane Wall	143
	3.5.2 Radial Systems	149
	3.5.3 Tabulated Solutions	150
	3.5.4 Application of Resistance Concepts	150
3.6	Heat Transfer from Extended Surfaces	154
	3.6.1 A General Conduction Analysis	156
	3.6.2 Fins of Uniform Cross-Sectional Area	158
	3.6.3 Fin Performance	164
	3.6.4 Fins of Nonuniform Cross-Sectional Area	167
	3.6.5 Overall Surface Efficiency	170
3.7	The Bioheat Equation	178
3.8	Thermoelectric Power Generation	182
3.9	Micro- and Nanoscale Conduction	189
	3.9.1 Conduction Through Thin Gas Layers	189
	3.9.2 Conduction Through Thin Solid Films	190
3.10	Summary	190
	References	193
	Problems	193

<b>CHAPTER 4</b>	<b><i>Two-Dimensional, Steady-State Conduction</i></b>	<b>229</b>
<hr/>		
4.1	Alternative Approaches	230
4.2	The Method of Separation of Variables	231
4.3	The Conduction Shape Factor and the Dimensionless Conduction Heat Rate	235
4.4	Finite-Difference Equations	241
4.4.1	The Nodal Network	241
4.4.2	Finite-Difference Form of the Heat Equation	242
4.4.3	The Energy Balance Method	243
4.5	Solving the Finite-Difference Equations	250
4.5.1	Formulation as a Matrix Equation	250
4.5.2	Verifying the Accuracy of the Solution	251
4.6	Summary	256
	References	257
	Problems	257
 4S.1	The Graphical Method	W-1
4S.1.1	Methodology of Constructing a Flux Plot	W-1
4S.1.2	Determination of the Heat Transfer Rate	W-2
4S.1.3	The Conduction Shape Factor	W-3
4S.2	The Gauss–Seidel Method: Example of Usage	W-5
	References	W-9
	Problems	W-10
<b>CHAPTER 5</b>	<b><i>Transient Conduction</i></b>	<b>279</b>
<hr/>		
5.1	The Lumped Capacitance Method	280
5.2	Validity of the Lumped Capacitance Method	283
5.3	General Lumped Capacitance Analysis	287
5.3.1	Radiation Only	288
5.3.2	Negligible Radiation	288
5.3.3	Convection Only with Variable Convection Coefficient	289
5.3.4	Additional Considerations	289
5.4	Spatial Effects	298
5.5	The Plane Wall with Convection	299
5.5.1	Exact Solution	300
5.5.2	Approximate Solution	300
5.5.3	Total Energy Transfer	302
5.5.4	Additional Considerations	302
5.6	Radial Systems with Convection	303
5.6.1	Exact Solutions	303
5.6.2	Approximate Solutions	304
5.6.3	Total Energy Transfer	304
5.6.4	Additional Considerations	305
5.7	The Semi-Infinite Solid	310
5.8	Objects with Constant Surface Temperatures or Surface Heat Fluxes	317
5.8.1	Constant Temperature Boundary Conditions	317
5.8.2	Constant Heat Flux Boundary Conditions	319
5.8.3	Approximate Solutions	320

<b>5.9</b>	Periodic Heating	327
<b>5.10</b>	Finite-Difference Methods	330
5.10.1	Discretization of the Heat Equation: The Explicit Method	330
5.10.2	Discretization of the Heat Equation: The Implicit Method	337
<b>5.11</b>	Summary	345
	References	346
	Problems	346
 <b>5S.1</b>	Graphical Representation of One-Dimensional, Transient Conduction in the Plane Wall, Long Cylinder, and Sphere	W-12
<b>5S.2</b>	Analytical Solutions of Multidimensional Effects	W-16
	References	W-22
	Problems	W-22

---

**CHAPTER 6 Introduction to Convection** **377**

<b>6.1</b>	The Convection Boundary Layers	378
6.1.1	The Velocity Boundary Layer	378
6.1.2	The Thermal Boundary Layer	379
6.1.3	The Concentration Boundary Layer	380
6.1.4	Significance of the Boundary Layers	382
<b>6.2</b>	Local and Average Convection Coefficients	382
6.2.1	Heat Transfer	382
6.2.2	Mass Transfer	383
6.2.3	The Problem of Convection	385
<b>6.3</b>	Laminar and Turbulent Flow	389
6.3.1	Laminar and Turbulent Velocity Boundary Layers	389
6.3.2	Laminar and Turbulent Thermal and Species Concentration Boundary Layers	391
<b>6.4</b>	The Boundary Layer Equations	394
6.4.1	Boundary Layer Equations for Laminar Flow	394
6.4.2	Compressible Flow	397
<b>6.5</b>	Boundary Layer Similarity: The Normalized Boundary Layer Equations	398
6.5.1	Boundary Layer Similarity Parameters	398
6.5.2	Functional Form of the Solutions	400
<b>6.6</b>	Physical Interpretation of the Dimensionless Parameters	407
<b>6.7</b>	Boundary Layer Analogies	409
6.7.1	The Heat and Mass Transfer Analogy	410
6.7.2	Evaporative Cooling	413
6.7.3	The Reynolds Analogy	416
<b>6.8</b>	Summary	417
	References	418
	Problems	419
 <b>6S.1</b>	Derivation of the Convection Transfer Equations	W-25
6S.1.1	Conservation of Mass	W-25
6S.1.2	Newton's Second Law of Motion	W-26
6S.1.3	Conservation of Energy	W-29
6S.1.4	Conservation of Species	W-32
	References	W-36
	Problems	W-36

**CHAPTER 7 External Flow 433**

---

7.1	The Empirical Method	435
7.2	The Flat Plate in Parallel Flow	436
7.2.1	Laminar Flow over an Isothermal Plate: A Similarity Solution	437
7.2.2	Turbulent Flow over an Isothermal Plate	443
7.2.3	Mixed Boundary Layer Conditions	444
7.2.4	Unheated Starting Length	445
7.2.5	Flat Plates with Constant Heat Flux Conditions	446
7.2.6	Limitations on Use of Convection Coefficients	446
7.3	Methodology for a Convection Calculation	447
7.4	The Cylinder in Cross Flow	455
7.4.1	Flow Considerations	455
7.4.2	Convection Heat and Mass Transfer	457
7.5	The Sphere	465
7.6	Flow Across Banks of Tubes	468
7.7	Impinging Jets	477
7.7.1	Hydrodynamic and Geometric Considerations	477
7.7.2	Convection Heat and Mass Transfer	478
7.8	Packed Beds	482
7.9	Summary	483
	References	486
	Problems	486

**CHAPTER 8 Internal Flow 517**

---

8.1	Hydrodynamic Considerations	518
8.1.1	Flow Conditions	518
8.1.2	The Mean Velocity	519
8.1.3	Velocity Profile in the Fully Developed Region	520
8.1.4	Pressure Gradient and Friction Factor in Fully Developed Flow	522
8.2	Thermal Considerations	523
8.2.1	The Mean Temperature	524
8.2.2	Newton's Law of Cooling	525
8.2.3	Fully Developed Conditions	525
8.3	The Energy Balance	529
8.3.1	General Considerations	529
8.3.2	Constant Surface Heat Flux	530
8.3.3	Constant Surface Temperature	533
8.4	Laminar Flow in Circular Tubes: Thermal Analysis and Convection Correlations	537
8.4.1	The Fully Developed Region	537
8.4.2	The Entry Region	542
8.4.3	Temperature-Dependent Properties	544
8.5	Convection Correlations: Turbulent Flow in Circular Tubes	544
8.6	Convection Correlations: Noncircular Tubes and the Concentric Tube Annulus	552
8.7	Heat Transfer Enhancement	555

<b>8.8</b>	Flow in Small Channels	558
8.8.1	Microscale Convection in Gases ( $0.1 \mu\text{m} \leq D_h \leq 100 \mu\text{m}$ )	558
8.8.2	Microscale Convection in Liquids	559
8.8.3	Nanoscale Convection ( $D_h \leq 100 \text{ nm}$ )	560
<b>8.9</b>	Convection Mass Transfer	563
<b>8.10</b>	Summary	565
	References	568
	Problems	569

---

**CHAPTER 9** *Free Convection* **593**

<b>9.1</b>	Physical Considerations	594
<b>9.2</b>	The Governing Equations for Laminar Boundary Layers	597
<b>9.3</b>	Similarity Considerations	598
<b>9.4</b>	Laminar Free Convection on a Vertical Surface	599
<b>9.5</b>	The Effects of Turbulence	602
<b>9.6</b>	Empirical Correlations: External Free Convection Flows	604
9.6.1	The Vertical Plate	605
9.6.2	Inclined and Horizontal Plates	608
9.6.3	The Long Horizontal Cylinder	613
9.6.4	Spheres	617
<b>9.7</b>	Free Convection Within Parallel Plate Channels	618
9.7.1	Vertical Channels	619
9.7.2	Inclined Channels	621
<b>9.8</b>	Empirical Correlations: Enclosures	621
9.8.1	Rectangular Cavities	621
9.8.2	Concentric Cylinders	624
9.8.3	Concentric Spheres	625
<b>9.9</b>	Combined Free and Forced Convection	627
<b>9.10</b>	Convection Mass Transfer	628
<b>9.11</b>	Summary	629
	References	630
	Problems	631

---

**CHAPTER 10** *Boiling and Condensation* **653**

<b>10.1</b>	Dimensionless Parameters in Boiling and Condensation	654
<b>10.2</b>	Boiling Modes	655
<b>10.3</b>	Pool Boiling	656
10.3.1	The Boiling Curve	656
10.3.2	Modes of Pool Boiling	657
<b>10.4</b>	Pool Boiling Correlations	660
10.4.1	Nucleate Pool Boiling	660
10.4.2	Critical Heat Flux for Nucleate Pool Boiling	662
10.4.3	Minimum Heat Flux	663
10.4.4	Film Pool Boiling	663
10.4.5	Parametric Effects on Pool Boiling	664

**Contents** **xvii**

<b>10.5</b>	Forced Convection Boiling	669
10.5.1	External Forced Convection Boiling 670	
10.5.2	Two-Phase Flow 670	
10.5.3	Two-Phase Flow in Microchannels 673	
<b>10.6</b>	Condensation: Physical Mechanisms	673
<b>10.7</b>	Laminar Film Condensation on a Vertical Plate	675
<b>10.8</b>	Turbulent Film Condensation	679
<b>10.9</b>	Film Condensation on Radial Systems	684
<b>10.10</b>	Condensation in Horizontal Tubes	689
<b>10.11</b>	Dropwise Condensation	690
<b>10.12</b>	Summary	691
	References	691
	Problems	693

---

**CHAPTER 11 Heat Exchangers** **705**

<b>11.1</b>	Heat Exchanger Types	706
<b>11.2</b>	The Overall Heat Transfer Coefficient	708
<b>11.3</b>	Heat Exchanger Analysis: Use of the Log Mean Temperature Difference	711
11.3.1	The Parallel-Flow Heat Exchanger 712	
11.3.2	The Counterflow Heat Exchanger 714	
11.3.3	Special Operating Conditions 715	
<b>11.4</b>	Heat Exchanger Analysis: The Effectiveness–NTU Method	722
11.4.1	Definitions 722	
11.4.2	Effectiveness–NTU Relations 723	
<b>11.5</b>	Heat Exchanger Design and Performance Calculations	730
<b>11.6</b>	Additional Considerations	739
<b>11.7</b>	Summary	747
	References	748
	Problems	748
<b>11S.1</b>	Log Mean Temperature Difference Method for Multipass and Cross-Flow Heat Exchangers	W-40
<b>11S.2</b>	Compact Heat Exchangers	W-44
	References	W-49
	Problems	W-50

---

**CHAPTER 12 Radiation: Processes and Properties** **767**

<b>12.1</b>	Fundamental Concepts	768
<b>12.2</b>	Radiation Heat Fluxes	771
<b>12.3</b>	Radiation Intensity	773
12.3.1	Mathematical Definitions 773	
12.3.2	Radiation Intensity and Its Relation to Emission 774	
12.3.3	Relation to Irradiation 779	
12.3.4	Relation to Radiosity for an Opaque Surface 781	
12.3.5	Relation to the Net Radiative Flux for an Opaque Surface 782	

<b>12.4</b>	Blackbody Radiation	782
12.4.1	The Planck Distribution	783
12.4.2	Wien's Displacement Law	784
12.4.3	The Stefan–Boltzmann Law	784
12.4.4	Band Emission	785
<b>12.5</b>	Emission from Real Surfaces	792
<b>12.6</b>	Absorption, Reflection, and Transmission by Real Surfaces	801
12.6.1	Absorptivity	802
12.6.2	Reflectivity	803
12.6.3	Transmissivity	805
12.6.4	Special Considerations	805
<b>12.7</b>	Kirchhoff's Law	810
<b>12.8</b>	The Gray Surface	812
<b>12.9</b>	Environmental Radiation	818
12.9.1	Solar Radiation	819
12.9.2	The Atmospheric Radiation Balance	821
12.9.3	Terrestrial Solar Irradiation	823
<b>12.10</b>	Summary	826
	References	830
	Problems	830
<b>CHAPTER 13 Radiation Exchange Between Surfaces</b>		<b>861</b>
<b>13.1</b>	The View Factor	862
13.1.1	The View Factor Integral	862
13.1.2	View Factor Relations	863
<b>13.2</b>	Blackbody Radiation Exchange	872
<b>13.3</b>	Radiation Exchange Between Opaque, Diffuse, Gray Surfaces in an Enclosure	876
13.3.1	Net Radiation Exchange at a Surface	877
13.3.2	Radiation Exchange Between Surfaces	878
13.3.3	The Two-Surface Enclosure	884
13.3.4	Radiation Shields	886
13.3.5	The Reradiating Surface	888
<b>13.4</b>	Multimode Heat Transfer	893
<b>13.5</b>	Implications of the Simplifying Assumptions	896
<b>13.6</b>	Radiation Exchange with Participating Media	896
13.6.1	Volumetric Absorption	896
13.6.2	Gaseous Emission and Absorption	897
<b>13.7</b>	Summary	901
	References	902
	Problems	903
<b>CHAPTER 14 Diffusion Mass Transfer</b>		<b>933</b>
<b>14.1</b>	Physical Origins and Rate Equations	934
14.1.1	Physical Origins	934
14.1.2	Mixture Composition	935
14.1.3	Fick's Law of Diffusion	936
14.1.4	Mass Diffusivity	937



*Contents* **xix**

<b>14.2</b>	Mass Transfer in Nonstationary Media	939
14.2.1	Absolute and Diffusive Species Fluxes	939
14.2.2	Evaporation in a Column	942
<b>14.3</b>	The Stationary Medium Approximation	947
<b>14.4</b>	Conservation of Species for a Stationary Medium	947
14.4.1	Conservation of Species for a Control Volume	948
14.4.2	The Mass Diffusion Equation	948
14.4.3	Stationary Media with Specified Surface Concentrations	950
<b>14.5</b>	Boundary Conditions and Discontinuous Concentrations at Interfaces	954
14.5.1	Evaporation and Sublimation	955
14.5.2	Solubility of Gases in Liquids and Solids	955
14.5.3	Catalytic Surface Reactions	960
<b>14.6</b>	Mass Diffusion with Homogeneous Chemical Reactions	962
<b>14.7</b>	Transient Diffusion	965
<b>14.8</b>	Summary	971
	References	972
	Problems	972

---

**APPENDIX A** *Thermophysical Properties of Matter* **981**

---

**APPENDIX B** *Mathematical Relations and Functions* **1013**

---

**APPENDIX C** *Thermal Conditions Associated with Uniform Energy Generation in One-Dimensional, Steady-State Systems* **1019**

---

**APPENDIX D** *The Gauss–Seidel Method* **1025**

---

**APPENDIX E** *The Convection Transfer Equations* **1027**

E.1	Conservation of Mass	1028
E.2	Newton’s Second Law of Motion	1028
E.3	Conservation of Energy	1029
E.4	Conservation of Species	1030

---

**APPENDIX F** *Boundary Layer Equations for Turbulent Flow* **1031**

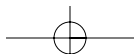
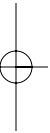
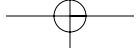
---

**APPENDIX G** *An Integral Laminar Boundary Layer Solution for Parallel Flow over a Flat Plate* **1035**

---

*Index* **1039**

---



# Symbols

---

$A$	area, m <sup>2</sup>	$ Fo$	Fourier number
$A_b$	area of prime (unfinned) surface, m <sup>2</sup>	$ Fr$	Froude number
$A_c$	cross-sectional area, m <sup>2</sup>	$ f$	friction factor; similarity variable
$A_p$	fin profile area, m <sup>2</sup>	$ G$	irradiation, W/m <sup>2</sup> ; mass velocity, kg/s · m <sup>2</sup>
$A_r$	nozzle area ratio	$ Gr$	Grashof number
$a$	acceleration, m/s <sup>2</sup> ; speed of sound, m/s	$ Gz$	Graetz number
$ Bi$	Biot number	$ g$	gravitational acceleration, m/s <sup>2</sup>
$ Bo$	Bond number	$ H$	nozzle height, m; Henry's constant, bars
$ C$	molar concentration, kmol/m <sup>3</sup> ; heat capacity rate, W/K	$ h$	convection heat transfer coefficient, W/m <sup>2</sup> · K; Planck's constant, J · s
$ C_D$	drag coefficient	$ h_{fg}$	latent heat of vaporization, J/kg
$ C_f$	friction coefficient	$ h'_{fg}$	modified heat of vaporization, J/kg
$ C_t$	thermal capacitance, J/K	$ h_{sf}$	latent heat of fusion, J/kg
$ Co$	Confinement number	$ h_m$	convection mass transfer coefficient, m/s
$ c$	specific heat, J/kg · K; speed of light, m/s	$ h_{rad}$	radiation heat transfer coefficient, W/m <sup>2</sup> · K
$ c_p$	specific heat at constant pressure, J/kg · K	$ I$	electric current, A; radiation intensity, W/m <sup>2</sup> · sr
$ c_v$	specific heat at constant volume, J/kg · K	$ i$	electric current density, A/m <sup>2</sup> ; enthalpy per unit mass, J/kg
$ D$	diameter, m	$ J$	radiosity, W/m <sup>2</sup>
$ D_{AB}$	binary mass diffusivity, m <sup>2</sup> /s	$ Ja$	Jakob number
$ D_b$	bubble diameter, m	$ J_i^*$	diffusive molar flux of species $i$ relative to the mixture molar average velocity, kmol/s · m <sup>2</sup>
$ D_h$	hydraulic diameter, m	$ j_i$	diffusive mass flux of species $i$ relative to the mixture mass average velocity, kg/s · m <sup>2</sup>
$ d$	diameter of gas molecule, nm	$ j_H$	Colburn $j$ factor for heat transfer
$ E$	thermal plus mechanical energy, J; electric potential, V; emissive power, W/m <sup>2</sup>	$ j_m$	Colburn $j$ factor for mass transfer
$ E^{tot}$	total energy, J	$ k$	thermal conductivity, W/m · K
$ Ec$	Eckert number	$ k_B$	Boltzmann's constant, J/K
$ \dot{E}_g$	rate of energy generation, W	$ k_0$	zero-order, homogeneous reaction rate constant, kmol/s · m <sup>3</sup>
$ \dot{E}_{in}$	rate of energy transfer into a control volume, W	$ k_1$	first-order, homogeneous reaction rate constant, s <sup>-1</sup>
$ \dot{E}_{out}$	rate of energy transfer out of control volume, W	$ k_1'$	first-order, surface reaction rate constant, m/s
$ \dot{E}_{st}$	rate of increase of energy stored within a control volume, W	$ L$	length, m
$ e$	thermal internal energy per unit mass, J/kg; surface roughness, m	$ Le$	Lewis number
$ F$	force, N; fraction of blackbody radiation in a wavelength band; view factor		

**Symbols**

$M$	mass, kg	$R_{t,o}$	thermal resistance of fin array, K/W
$\dot{M}_i$	rate of transfer of mass for species, $i$ , kg/s	$r_o$	cylinder or sphere radius, m
$\dot{M}_{i,g}$	rate of increase of mass of species $i$ due to chemical reactions, kg/s	$r, \phi, z$	cylindrical coordinates
$\dot{M}_{in}$	rate at which mass enters a control volume, kg/s	$r, \theta, \phi$	spherical coordinates
$\dot{M}_{out}$	rate at which mass leaves a control volume, kg/s	$S$	solubility, kmol/m <sup>3</sup> · atm; shape factor for two-dimensional conduction, m; nozzle pitch, m; plate spacing, m; Seebeck coefficient, V/K
$\dot{M}_{st}$	rate of increase of mass stored within a control volume, kg/s	$S_c$	solar constant, W/m <sup>2</sup>
$M_i$	molecular weight of species $i$ , kg/kmol	$S_D, S_L, S_T$	diagonal, longitudinal, and transverse pitch of a tube bank, m
$Ma$	Mach number	$Sc$	Schmidt number
$m$	mass, kg	$Sh$	Sherwood number
$\dot{m}$	mass flow rate, kg/s	$St$	Stanton number
$m_i$	mass fraction of species $i$ , $\rho_i/\rho$	$T$	temperature, K
$N$	integer number	$t$	time, s
$N_L, N_T$	number of tubes in longitudinal and transverse directions	$U$	overall heat transfer coefficient, W/m <sup>2</sup> · K; internal energy, J
$Nu$	Nusselt number	$u, v, w$	mass average fluid velocity components, m/s
NTU	number of transfer units	$u^*, v^*, w^*$	molar average velocity components, m/s
$N_i$	molar transfer rate of species $i$ relative to fixed coordinates, kmol/s	$V$	volume, m <sup>3</sup> ; fluid velocity, m/s
$N_i''$	molar flux of species $i$ relative to fixed coordinates, kmol/s · m <sup>2</sup>	$v$	specific volume, m <sup>3</sup> /kg
$\dot{N}_i$	molar rate of increase of species $i$ per unit volume due to chemical reactions, kmol/s · m <sup>3</sup>	$W$	width of a slot nozzle, m
$\dot{N}_i''$	surface reaction rate of species $i$ , kmol/s · m <sup>2</sup>	$\dot{W}$	rate at which work is performed, W
$\mathcal{N}$	Avogadro's number	$We$	Weber number
$n_i''$	mass flux of species $i$ relative to fixed coordinates, kg/s · m <sup>2</sup>	$X$	vapor quality
$\dot{n}_i$	mass rate of increase of species $i$ per unit volume due to chemical reactions, kg/s · m <sup>3</sup>	$X_{it}$	Martinelli parameter
$P$	power, W; perimeter, m	$X, Y, Z$	components of the body force per unit volume, N/m <sup>3</sup>
$P_L, P_T$	dimensionless longitudinal and transverse pitch of a tube bank	$x, y, z$	rectangular coordinates, m
$Pe$	Peclet number	$x_c$	critical location for transition to turbulence, m
$Pr$	Prandtl number	$x_{fd,c}$	concentration entry length, m
$p$	pressure, N/m <sup>2</sup>	$x_{fd,h}$	hydrodynamic entry length, m
$Q$	energy transfer, J	$x_{fd,t}$	thermal entry length, m
$q$	heat transfer rate, W	$x_i$	mole fraction of species $i$ , $C_i/C$
$\dot{q}$	rate of energy generation per unit volume, W/m <sup>3</sup>	$Z$	thermoelectric material property, K <sup>-1</sup>
$q'$	heat transfer rate per unit length, W/m	<b>Greek Letters</b>	
$q''$	heat flux, W/m <sup>2</sup>	$\alpha$	thermal diffusivity, m <sup>2</sup> /s; accommodation coefficient; absorptivity
$q^*$	dimensionless conduction heat rate	$\beta$	volumetric thermal expansion coefficient, K <sup>-1</sup>
$R$	cylinder radius, m; gas constant, J/kg · K	$\Gamma$	mass flow rate per unit width in film condensation, kg/s · m
$\mathcal{R}$	universal gas constant, J/kmol · K	$\gamma$	ratio of specific heats
$Ra$	Rayleigh number	$\delta$	hydrodynamic boundary layer thickness, m
$Re$	Reynolds number	$\delta_c$	concentration boundary layer thickness, m
$R_e$	electric resistance, $\Omega$	$\delta_p$	thermal penetration depth, m
$R_f$	fouling factor, m <sup>2</sup> · K/W	$\delta_t$	thermal boundary layer thickness, m
$R_m$	mass transfer resistance, s/m <sup>3</sup>	$\varepsilon$	emissivity; porosity; heat exchanger effectiveness
$R_{m,n}$	residual for the $m, n$ nodal point	$\varepsilon_f$	fin effectiveness
$R_t$	thermal resistance, K/W	$\eta$	thermodynamic efficiency; similarity variable
$R_{t,c}$	thermal contact resistance, K/W	$\eta_f$	fin efficiency
$R_{t,f}$	fin thermal resistance, K/W	$\eta_o$	overall efficiency of fin array
		$\theta$	zenith angle, rad; temperature difference, K
		$\kappa$	absorption coefficient, m <sup>-1</sup>
		$\lambda$	wavelength, $\mu\text{m}$
		$\lambda_{mfp}$	mean free path length, nm

**Symbols**

$\mu$	viscosity, kg/s · m	$h$	hydrodynamic; hot fluid; helical
$\nu$	kinematic viscosity, m <sup>2</sup> /s; frequency of radiation, s <sup>-1</sup>	$i$	general species designation; inner surface of an annulus; initial condition; tube inlet condition; incident radiation
$\rho$	mass density, kg/m <sup>3</sup> ; reflectivity	$L$	based on characteristic length
$\rho_e$	electric resistivity, $\Omega$ /m	$l$	saturated liquid conditions
$\sigma$	Stefan–Boltzmann constant, W/m <sup>2</sup> · K <sup>4</sup> ; electrical conductivity, 1/ $\Omega$ · m; normal viscous stress, N/m <sup>2</sup> ; surface tension, N/m	lat	latent energy
$\Phi$	viscous dissipation function, s <sup>-2</sup>	lm	log mean condition
$\varphi$	volume fraction	$m$	mean value over a tube cross section
$\phi$	azimuthal angle, rad	max	maximum
$\psi$	stream function, m <sup>2</sup> /s	$o$	center or midplane condition; tube outlet condition; outer
$\tau$	shear stress, N/m <sup>2</sup> ; transmissivity	$p$	momentum
$\omega$	solid angle, sr; perfusion rate, s <sup>-1</sup>	ph	phonon
		$R$	reradiating surface
<b>Subscripts</b>		$r, \text{ref}$	reflected radiation
A, B	species in a binary mixture	rad	radiation
abs	absorbed	$S$	solar conditions
am	arithmetic mean	$s$	surface conditions; solid properties; saturated solid conditions
atm	atmospheric	sat	saturated conditions
$b$	base of an extended surface; blackbody	sens	sensible energy
$C$	carnot	sky	sky conditions
$c$	cross-sectional; concentration; cold fluid; critical	ss	steady state
cr	critical insulation thickness	sur	surroundings
cond	conduction	$t$	thermal
conv	convection	tr	transmitted
CF	counterflow	$v$	saturated vapor conditions
$D$	diameter; drag	$x$	local conditions on a surface
dif	diffusion	$\lambda$	spectral
$e$	excess; emission; electron	$\infty$	free stream conditions
evap	evaporation		
$f$	fluid properties; fin conditions; saturated liquid conditions	<b>Superscripts</b>	
fc	forced convection	*	molar average; dimensionless quantity
fd	fully developed conditions		
$g$	saturated vapor conditions	<b>Overbar</b>	
$H$	heat transfer conditions	$\bar{\quad}$	surface average conditions; time mean

