

Contents

Symbols	xxi
CHAPTER 1 <i>Introduction</i>	1
1.1 What and How?	2
1.2 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
1.3 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
1.4 Units and Dimensions	36
1.5 Analysis of Heat Transfer Problems: Methodology	38

1.6	Relevance of Heat Transfer	41
1.7	Summary	45
	References	48
	Problems	49

CHAPTER 2 *Introduction to Conduction* 67

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

CHAPTER 3 *One-Dimensional, Steady-State Conduction* 111

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

CHAPTER 4	<i>Two-Dimensional, Steady-State Conduction</i>	229
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
CHAPTER 5	<i>Transient Conduction</i>	279
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

5.9	Periodic Heating	327
5.10	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
5.11	Summary	345
	References	346
	Problems	346
5S.1	Graphical Representation of One-Dimensional, Transient Conduction in the Plane Wall, Long Cylinder, and Sphere	W-12
5S.2	Analytical Solutions of Multidimensional Effects	W-16
	References	W-22
	Problems	W-22

CHAPTER 6 *Introduction to Convection* 377

6.1	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
6.2	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
6.3	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
6.4	The Boundary Layer Equations	394
6.4.1	Boundary Layer Equations for Laminar Flow	394
6.4.2	Compressible Flow	397
6.5	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
6.6	Physical Interpretation of the Dimensionless Parameters	407
6.7	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
6.8	Summary	417
	References	418
	Problems	419
 6S.1	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

8.8	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
8.9	Convection Mass Transfer	563
8.10	Summary	565
	References	568
	Problems	569

CHAPTER 9 *Free Convection* 593

9.1	Physical Considerations	594
9.2	The Governing Equations for Laminar Boundary Layers	597
9.3	Similarity Considerations	598
9.4	Laminar Free Convection on a Vertical Surface	599
9.5	The Effects of Turbulence	602
9.6	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
9.7	Free Convection Within Parallel Plate Channels	618
9.7.1	Vertical Channels	619
9.7.2	Inclined Channels	621
9.8	Empirical Correlations: Enclosures	621
9.8.1	Rectangular Cavities	621
9.8.2	Concentric Cylinders	624
9.8.3	Concentric Spheres	625
9.9	Combined Free and Forced Convection	627
9.10	Convection Mass Transfer	628
9.11	Summary	629
	References	630
	Problems	631

CHAPTER 10 *Boiling and Condensation* 653

10.1	Dimensionless Parameters in Boiling and Condensation	654
10.2	Boiling Modes	655
10.3	Pool Boiling	656
10.3.1	The Boiling Curve	656
10.3.2	Modes of Pool Boiling	657
10.4	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

10.5	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
10.6	Condensation: Physical Mechanisms	673
10.7	Laminar Film Condensation on a Vertical Plate	675
10.8	Turbulent Film Condensation	679
10.9	Film Condensation on Radial Systems	684
10.10	Condensation in Horizontal Tubes	689
10.11	Dropwise Condensation	690
10.12	Summary	691
	References	691
	Problems	693

CHAPTER 11 *Heat Exchangers* **705**

11.1	Heat Exchanger Types	706
11.2	The Overall Heat Transfer Coefficient	708
11.3	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
11.4	Heat Exchanger Analysis: The Effectiveness–NTU Method	722
11.4.1	Definitions	722
11.4.2	Effectiveness–NTU Relations	723
11.5	Heat Exchanger Design and Performance Calculations	730
11.6	Additional Considerations	739
11.7	Summary	747
	References	748
	Problems	748
 11S.1	Log Mean Temperature Difference Method for Multipass and Cross-Flow Heat Exchangers	W-40
11S.2	Compact Heat Exchangers	W-44
	References	W-49
	Problems	W-50

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

12.1	Fundamental Concepts	768
12.2	Radiation Heat Fluxes	771
12.3	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

14.1	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

14.2	Mass Transfer in Nonstationary Media	939
14.2.1	Absolute and Diffusive Species Fluxes	939
14.2.2	Evaporation in a Column	942
14.3	The Stationary Medium Approximation	947
14.4	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
14.5	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
14.6	Mass Diffusion with Homogeneous Chemical Reactions	962
14.7	Transient Diffusion	965
14.8	Summary	971
	References	972
	Problems	972
APPENDIX A	<i>Thermophysical Properties of Matter</i>	981
APPENDIX B	<i>Mathematical Relations and Functions</i>	1013
APPENDIX C	<i>Thermal Conditions Associated with Uniform Energy Generation in One-Dimensional, Steady-State Systems</i>	1019
APPENDIX D	<i>The Gauss–Seidel Method</i>	1025
APPENDIX E	<i>The Convection Transfer Equations</i>	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	<i>Boundary Layer Equations for Turbulent Flow</i>	1031
APPENDIX G	<i>An Integral Laminar Boundary Layer Solution for Parallel Flow over a Flat Plate</i>	1035
	<i>Index</i>	1039