

Contents

Symbols	xix
---------	-----

CHAPTER I

Introduction

	2
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	9
1.2.4 Relationship to Thermodynamics	12
1.3 The Conservation of Energy Requirement	13
1.3.1 Conservation of Energy for a Control Volume	13
1.3.2 The Surface Energy Balance	21
1.3.3 Application of the Conservation Laws: Methodology	24
1.4 Analysis of Heat Transfer Problems: Methodology	24
1.5 Relevance of Heat Transfer	27
1.6 Units and Dimensions	28

1.7	Summary	31
	Problems	34

CHAPTER 2

Introduction to Conduction **51**

2.1	The Conduction Rate Equation	52
2.2	The Thermal Properties of Matter	54
	2.2.1 Thermal Conductivity	54
	2.2.2 Other Relevant Properties	58
2.3	The Heat Diffusion Equation	61
2.4	Boundary and Initial Conditions	68
2.5	Summary	72
	References	73
	Problems	73

CHAPTER 3

One-Dimensional, Steady-State Conduction **87**

3.1	The Plane Wall	88
	3.1.1 Temperature Distribution	88
	3.1.2 Thermal Resistance	90
	3.1.3 The Composite Wall	91
	3.1.4 Contact Resistance	93
3.2	An Alternative Conduction Analysis	101
3.3	Radial Systems	104
	3.3.1 The Cylinder	105
	3.3.2 The Sphere	110
3.4	Summary of One-Dimensional Conduction Results	114
3.5	Conduction with Thermal Energy Generation	114
	3.5.1 The Plane Wall	115
	3.5.2 Radial Systems	121
	3.5.3 Application of Resistance Concepts	126
3.6	Heat Transfer from Extended Surfaces	126
	3.6.1 A General Conduction Analysis	128
	3.6.2 Fins of Uniform Cross-Sectional Area	130
	3.6.3 Fin Performance	136
	3.6.4 Fins of Nonuniform Cross-Sectional Area	139
	3.6.5 Overall Surface Efficiency	140
3.7	Summary	149
	References	152
	Problems	152

CHAPTER 4

Two-Dimensional, Steady-State Conduction **183**

4.1	Alternative Approaches	184
4.2	The Method of Separation of Variables	185

4.3	The Graphical Method	189
4.3.1	Methodology of Constructing a Flux Plot	190
4.3.2	Determination of the Heat Transfer Rate	191
4.3.3	The Conduction Shape Factor	192
4.4	Finite-Difference Equations	196
4.4.1	The Nodal Network	196
4.4.2	Finite-Difference Form of the Heat Equation	197
4.4.3	The Energy Balance Method	198
4.5	Finite-Difference Solutions	205
4.5.1	The Matrix Inversion Method	206
4.5.2	Gauss-Seidel Iteration	207
4.5.3	Some Precautions	213
4.6	Summary	218
	References	219
	Problems	219

CHAPTER 5

Transient Conduction

239

5.1	The Lumped Capacitance Method	240
5.2	Validity of the Lumped Capacitance Method	243
5.3	General Lumped Capacitance Analysis	247
5.4	Spatial Effects	254
5.5	The Plane Wall with Convection	256
5.5.1	Exact Solution	256
5.5.2	Approximate Solution	257
5.5.3	Total Energy Transfer	258
5.5.4	Additional Considerations	259
5.6	Radial Systems with Convection	260
5.6.1	Exact Solutions	260
5.6.2	Approximate Solutions	261
5.6.3	Total Energy Transfer	261
5.6.4	Additional Considerations	262
5.7	The Semi-Infinite Solid	268
5.8	Multidimensional Effects	274
5.9	Finite-Difference Methods	280
5.9.1	Discretization of the Heat Equation: The Explicit Method	280
5.9.2	Discretization of the Heat Equation: The Implicit Method	288
5.10	Summary	296
	References	297
	Problems	297

CHAPTER 6

Introduction to Convection

325

6.1	The Convection Transfer Problem	326
6.2	The Convection Boundary Layers	331
6.2.1	The Velocity Boundary Layer	331
6.2.2	The Thermal Boundary Layer	332

6.2.3	The Concentration Boundary Layer	333
6.2.4	Significance of the Boundary Layers	336
6.3	Laminar and Turbulent Flow	338
6.4	Boundary Layer Equations	339
6.4.1	The Convection Transfer Equations	344
6.4.2	The Boundary Layer Approximations	346
6.5	Boundary Layer Similarity: The Normalized Boundary Layer Equations	346
6.5.1	Boundary Layer Similarity Parameters	348
6.5.2	Functional Form of the Solutions	353
6.6	Physical Significance of the Dimensionless Parameters	356
6.7	Boundary Layer Analogies	360
6.7.1	The Heat and Mass Transfer Analogy	363
6.7.2	Evaporative Cooling	364
6.7.3	The Reynolds Analogy	367
6.8	The Effects of Turbulence	368
6.9	The Convection Coefficients	369
6.10	Summary	369
	References	369
	Problems	369

CHAPTER 7

External Flow

385

7.1	The Empirical Method	387
7.2	The Flat Plate in Parallel Flow	389
7.2.1	Laminar Flow: A Similarity Solution	395
7.2.2	Turbulent Flow	396
7.2.3	Mixed Boundary Layer Conditions	397
7.2.4	Special Cases	399
7.3	Methodology for a Convection Calculation	401
7.4	The Cylinder in Cross Flow	415
7.4.1	Flow Considerations	418
7.4.2	Convection Heat and Mass Transfer	428
7.5	The Sphere	434
7.6	Flow Across Banks of Tubes	435
7.7	Impinging Jets	437
7.7.1	Hydrodynamic and Geometric Considerations	438
7.7.2	Convection Heat and Mass Transfer	439
7.8	Packed Beds	443
7.9	Summary	443
	References	443
	Problems	443

CHAPTER 8

Internal Flow

465

8.1	Hydrodynamic Considerations	466
8.1.1	Flow Conditions	467
8.1.2	The Mean Velocity	468
8.1.3	Velocity Profile in the Fully Developed Region	470
8.1.4	Pressure Gradient and Friction Factor in Fully Developed Flow	470

8.2	Thermal Considerations	471
8.2.1	The Mean Temperature	472
8.2.2	Newton's Law of Cooling	473
8.2.3	Fully Developed Conditions	473
8.3	The Energy Balance	477
8.3.1	General Considerations	477
8.3.2	Constant Surface Heat Flux	478
8.3.3	Constant Surface Temperature	481
8.4	Laminar Flow in Circular Tubes: Thermal Analysis and Convection Correlations	485
8.4.1	The Fully Developed Region	485
8.4.2	The Entry Region	489
8.5	Convection Correlations: Turbulent Flow in Circular Tubes	491
8.6	Convection Correlations: Noncircular Tubes	495
8.7	The Concentric Tube Annulus	500
8.8	Heat Transfer Enhancement	502
8.9	Convection Mass Transfer	503
8.10	Summary	506
	References	509
	Problems	509

CHAPTER 9

Free Convection

533

9.1	Physical Considerations	534
9.2	The Governing Equations	537
9.3	Similarity Considerations	539
9.4	Laminar Free Convection on a Vertical Surface	540
9.5	The Effects of Turbulence	542
9.6	Empirical Correlations: External Free Convection Flows	545
9.6.1	The Vertical Plate	545
9.6.2	Inclined and Horizontal Plates	548
9.6.3	The Long Horizontal Cylinder	554
9.6.4	Spheres	557
9.7	Free Convection within Parallel Plate Channels	558
9.7.1	Vertical Channels	559
9.7.2	Inclined Channels	561
9.8	Empirical Correlations: Enclosures	561
9.8.1	Rectangular Cavities	561
9.8.2	Concentric Cylinders	564
9.8.3	Concentric Spheres	565
9.9	Combined Free and Forced Convection	567
9.10	Convection Mass Transfer	568
9.11	Summary	569
	References	570
	Problems	572

CHAPTER 10

Boiling and Condensation

593

10.1	Dimensionless Parameters in Boiling and Condensation	594
10.2	Boiling Modes	595

10.3	Pool Boiling	596
10.3.1	The Boiling Curve	596
10.3.2	Modes of Pool Boiling	598
10.4	Pool Boiling Correlations	601
10.4.1	Nucleate Pool Boiling	602
10.4.2	Critical Heat Flux for Nucleate Pool Boiling	603
10.4.3	Minimum Heat Flux	603
10.4.4	Film Pool Boiling	604
10.4.5	Parametric Effects on Pool Boiling	605
10.5	Forced-Convection Boiling	610
10.5.1	External Forced-Convection Boiling	611
10.5.2	Two-Phase Flow	611
10.6	Condensation: Physical Mechanisms	613
10.7	Laminar Film Condensation on a Vertical Plate	615
10.8	Turbulent Film Condensation	619
10.9	Film Condensation on Radial Systems	623
10.10	Film Condensation in Horizontal Tubes	626
10.11	Dropwise Condensation	627
10.12	Summary	627
	References	628
	Problems	630

CHAPTER 11

Heat Exchangers

641

11.1	Heat Exchanger Types	642
11.2	The Overall Heat Transfer Coefficient	645
11.3	Heat Exchanger Analysis: Use of the Log Mean Temperature Difference	647
11.3.1	The Parallel-Flow Heat Exchanger	648
11.3.2	The Counterflow Heat Exchanger	651
11.3.3	Special Operating Conditions	652
11.3.4	Multipass and Cross-Flow Heat Exchangers	652
11.4	Heat Exchanger Analysis: The Effectiveness-NTU Method	659
11.4.1	Definitions	660
11.4.2	Effectiveness-NTU Relations	661
11.5	Methodology of a Heat Exchanger Calculation	668
11.6	Compact Heat Exchangers	674
11.7	Summary	679
	References	680
	Problems	681

CHAPTER 12

Radiation: Processes and Properties

699

12.1	Fundamental Concepts	700
12.2	Radiation Intensity	703
12.2.1	Definitions	703
12.2.2	Relation to Emission	706
12.2.3	Relation to Irradiation	709
12.2.4	Relation to Radiosity	711

12.3	Blackbody Radiation	712
12.3.1	The Planck Distribution	713
12.3.2	Wien's Displacement Law	713
12.3.3	The Stefan-Boltzmann Law	714
12.3.4	Band Emission	715
12.4	Surface Emission	720
12.5	Surface Absorption, Reflection, and Transmission	728
12.5.1	Absorptivity	730
12.5.2	Reflectivity	731
12.5.3	Transmissivity	732
12.5.4	Special Considerations	733
12.6	Kirchhoff's Law	738
12.7	The Gray Surface	740
12.8	Environmental Radiation	746
12.9	Summary	752
	References	756
	Problems	756

CHAPTER 13

Radiation Exchange Between Surfaces

789

13.1	The View Factor	790
13.1.1	The View Factor Integral	790
13.1.2	View Factor Relations	791
13.2	Blackbody Radiation Exchange	800
13.3	Radiation Exchange Between Diffuse, Gray Surfaces in an Enclosure	803
13.3.1	Net Radiation Exchange at a Surface	803
13.3.2	Radiation Exchange Between Surfaces	805
13.3.3	The Two-Surface Enclosure	810
13.3.4	Radiation Shields	812
13.3.5	The Reradiating Surface	814
13.4	Multimode Heat Transfer	818
13.5	Additional Effects	821
13.5.1	Volumetric Absorption	822
13.5.2	Gaseous Emission and Absorption	822
13.6	Summary	827
	References	828
	Problems	828

CHAPTER 14

Diffusion Mass Transfer

859

14.1	Physical Origins and Rate Equations	860
14.1.1	Physical Origins	860
14.1.2	Mixture Composition	861
14.1.3	Fick's Law of Diffusion	862
14.1.4	Restrictive Conditions	863
14.1.5	Mass Diffusion Coefficient	867
14.2	Conservation of Species	867
14.2.1	Conservation of Species for a Control Volume	868
14.2.2	The Mass Diffusion Equation	868

14.3	Boundary and Initial Conditions	871
14.4	Mass Diffusion Without Homogeneous Chemical Reactions	874
14.4.1	Stationary Media with Specified Surface Concentrations	875
14.4.2	Stationary Media with Catalytic Surface Reactions	878
14.4.3	Equimolar Counterdiffusion	881
14.4.4	Evaporation in a Column	884
14.5	Mass Diffusion with Homogeneous Chemical Reactions	886
14.6	Transient Diffusion	889
14.7	Summary	893
	References	894
	Problems	895

APPENDIX A

<i>Thermophysical Properties of Matter</i>	903
--	-----

APPENDIX B

<i>Mathematical Relations and Functions</i>	933
---	-----

APPENDIX C

<i>Thermal Conditions Associated with Uniform Energy Generation in One-Dimensional, Steady-State Systems</i>	939
--	-----

APPENDIX D

<i>Graphical Representation of One-Dimensional, Transient Conduction in the Plane Wall, Long Cylinder, and Sphere</i>	947
---	-----

APPENDIX E

<i>The Convection Transfer Equations</i>	953
--	-----

E.1	Conservation of Mass	954
E.2	Newton's Second Law of Motion	955
E.3	Conservation of Energy	958
E.4	Conservation of Species	961

APPENDIX F

<i>An Integral Laminar Boundary Layer Solution for Parallel Flow Over a Flat Plate</i>	963
--	-----

<i>Index</i>	969
--------------	-----