

Table of contents

Symbols xix

Chapter 1 Introduction 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 28

1.4 Units and Dimensions 33

1.5 Analysis of Heat Transfer Problems: Methodology 35

1.6 Relevance of Heat Transfer 38

1.7 Summary 42

References 45

Problems 45

Chapter 2 Introduction to Conduction 59

2.1 The Conduction Rate Equation 60

2.2 The Thermal Properties of Matter 62

2.2.1 Thermal Conductivity 63

2.2.2 Other Relevant Properties 70

2.3 The Heat Diffusion Equation 74

2.4 Boundary and Initial Conditions 82

2.5 Summary 86

References 87

Problems 87

Chapter 3 One-Dimensional, Steady-State Conduction 99

3.1 The Plane Wall 100

3.1.1 Temperature Distribution 100

3.1.2 Thermal Resistance 102

3.1.3 The Composite Wall 103

3.1.4 Contact Resistance 105

3.1.5 Porous Media 107

3.2 An Alternative Conduction Analysis 121

3.3 Radial Systems 125

3.3.1 The Cylinder 125

3.3.2 The Sphere 130

3.4 Summary of One-Dimensional Conduction Results 131

3.5 Conduction with Thermal Energy Generation 131

3.5.1 The Plane Wall 132

3.5.2 Radial Systems 138

3.5.3 Tabulated Solutions 139

3.5.4 Application of Resistance Concepts 139

3.6 Heat Transfer from Extended Surfaces 143

3.6.1 A General Conduction Analysis	145
3.6.2 Fins of Uniform Cross-Sectional Area	147
3.6.3 Fin Performance Parameters	153
3.6.4 Fins of Nonuniform Cross-Sectional Area	156
3.6.5 Overall Surface Efficiency	159
3.7 Other Applications of One-Dimensional, Steady-State Conduction	163
3.7.1 The Bioheat Equation	163
3.7.2 Thermoelectric Power Generation	167
3.7.3 Nanoscale Conduction	175
3.8 Summary	179
References	181
Problems	182

Chapter 4 Two-Dimensional, Steady-State Conduction 209

4.1 General Considerations and Solution Techniques	210
4.2 The Method of Separation of Variables	211
4.3 The Conduction Shape Factor and the Dimensionless Conduction Heat Rate	215
4.4 Finite-Difference Equations	221
4.4.1 The Nodal Network	221
4.4.2 Finite-Difference Form of the Heat Equation: No Generation and Constant Properties	222
4.4.3 Finite-Difference Form of the Heat Equation: The Energy Balance Method	223
4.5 Solving the Finite-Difference Equations	230
4.5.1 Formulation as a Matrix Equation	230
4.5.2 Verifying the Accuracy of the Solution	231

4.6 Summary 236

References 237

Problems 237

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-10

Problems W-10

Chapter 5 Transient Conduction 253

5.1 The Lumped Capacitance Method 254

5.2 Validity of the Lumped Capacitance Method 257

5.3 General Lumped Capacitance Analysis 261

5.3.1 Radiation Only 262

5.3.2 Negligible Radiation 262

5.3.3 Convection Only with Variable Convection Coefficient 263

5.3.4 Additional Considerations 263

5.4 Spatial Effects 272

5.5 The Plane Wall with Convection 273

5.5.1 Exact Solution 274

5.5.2 Approximate Solution 274

5.5.3 Total Energy Transfer: Approximate Solution 276

5.5.4 Additional Considerations	276
5.6 Radial Systems with Convection	277
5.6.1 Exact Solutions	277
5.6.2 Approximate Solutions	278
5.6.3 Total Energy Transfer: Approximate Solutions	278
5.6.4 Additional Considerations	279
5.7 The Semi-Infinite Solid	284
5.8 Objects with Constant Surface Temperatures or Surface Heat Fluxes	291
5.8.1 Constant Temperature Boundary Conditions	291
5.8.2 Constant Heat Flux Boundary Conditions	293
5.8.3 Approximate Solutions	294
5.9 Periodic Heating	301
5.10 Finite-Difference Methods	304
5.10.1 Discretization of the Heat Equation: The Explicit Method	304
5.10.2 Discretization of the Heat Equation: The Implicit Method	311
5.11 Summary	318
References	319
Problems	319
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	343

6.1	The Convection Boundary Layers	344
6.1.1	The Velocity Boundary Layer	344
6.1.2	The Thermal Boundary Layer	345
6.1.3	The Concentration Boundary Layer	347
6.1.4	Significance of the Boundary Layers	348
6.2	Local and Average Convection Coefficients	348
6.2.1	Heat Transfer	348
6.2.2	Mass Transfer	349
6.3	Laminar and Turbulent Flow	355
6.3.1	Laminar and Turbulent Velocity Boundary Layers	355
6.3.2	Laminar and Turbulent Thermal and Species Concentration Boundary Layers	357
6.4	The Boundary Layer Equations	360
6.4.1	Boundary Layer Equations for Laminar Flow	361
6.4.2	Compressible Flow	364
6.5	Boundary Layer Similarity: The Normalized Boundary Layer Equations	364
6.5.1	Boundary Layer Similarity Parameters	365
6.5.2	Dependent Dimensionless Parameters	365
6.6	Physical Interpretation of the Dimensionless Parameters	374
6.7	Boundary Layer Analogies	376
6.7.1	The Heat and Mass Transfer Analogy	377
6.7.2	Evaporative Cooling	380
6.7.3	The Reynolds Analogy	383
6.8	Summary	384

References 385

Problems 386

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 399

7.1 The Empirical Method 401

7.2 The Flat Plate in Parallel Flow 402

7.2.1 Laminar Flow over an Isothermal Plate: A Similarity Solution 403

7.2.2 Turbulent Flow over an Isothermal Plate 409

7.2.3 Mixed Boundary Layer Conditions 410

7.2.4 Unheated Starting Length 411

7.2.5 Flat Plates with Constant Heat Flux Conditions 412

7.2.6 Limitations on Use of Convection Coefficients 413

7.3 Methodology for a Convection Calculation 413

7.4 The Cylinder in Cross Flow 421

7.4.1 Flow Considerations 421

7.4.2 Convection Heat and Mass Transfer 423

7.5 The Sphere 431

7.6 Flow Across Banks of Tubes 434

7.7 Impinging Jets 443

7.7.1 Hydrodynamic and Geometric Considerations 443

7.7.2 Convection Heat and Mass Transfer 444

7.8 Packed Beds 448

7.9 Summary 449

References 452

Problems 452

Chapter 8 Internal Flow 475

8.1 Hydrodynamic Considerations 476

8.1.1 Flow Conditions 476

8.1.2 The Mean Velocity 477

8.1.3 Velocity Profile in the Fully Developed Region 478

8.1.4 Pressure Gradient and Friction Factor in Fully Developed Flow 480

8.2 Thermal Considerations 481

8.2.1 The Mean Temperature 482

8.2.2 Newton's Law of Cooling 483

8.2.3 Fully Developed Conditions 483

8.3 The Energy Balance 487

8.3.1 General Considerations 487

8.3.2 Constant Surface Heat Flux 488

8.3.3 Constant Surface Temperature 491

8.4 Laminar Flow in Circular Tubes: Thermal Analysis and Convection Correlations 495

8.4.1 The Fully Developed Region 495

8.4.2 The Entry Region 500

8.4.3 Temperature-Dependent Properties 502

8.5 Convection Correlations: Turbulent Flow in Circular Tubes 502

8.6 Convection Correlations: Noncircular Tubes and the Concentric Tube Annulus 510

8.7 Heat Transfer Enhancement 513

8.8 Forced Convection in Small Channels 516

8.8.1 Microscale Convection in Gases ($0.1 \mu\text{m} \lesssim Dh \lesssim 100 \mu\text{m}$) 516

8.8.2 Microscale Convection in Liquids 517

8.8.3 Nanoscale Convection ($Dh \lesssim 100 \text{ nm}$) 518

8.9 Convection Mass Transfer 521

8.10 Summary 523

References 526

Problems 527

Chapter 9 Free Convection 547

9.1 Physical Considerations 548

9.2 The Governing Equations for Laminar Boundary Layers 550

9.3 Similarity Considerations 552

9.4 Laminar Free Convection on a Vertical Surface 553

9.5 The Effects of Turbulence 556

9.6 Empirical Correlations: External Free Convection Flows 558

9.6.1 The Vertical Plate 559

9.6.2 Inclined and Horizontal Plates 562

9.6.3 The Long Horizontal Cylinder 567

9.6.4 Spheres 571

9.7 Free Convection Within Parallel Plate Channels 572

9.7.1 Vertical Channels 573

9.7.2 Inclined Channels 575

9.8 Empirical Correlations: Enclosures 575

9.8.1 Rectangular Cavities 575

9.8.2 Concentric Cylinders 578

9.8.3 Concentric Spheres 579

9.9 Combined Free and Forced Convection 581

9.10 Convection Mass Transfer 582

9.11 Summary 583

References 584

Problems 585

Chapter 10 Boiling and Condensation 603

10.1 Dimensionless Parameters in Boiling and Condensation 604

10.2 Boiling Modes 605

10.3 Pool Boiling 606

10.3.1 The Boiling Curve 606

10.3.2 Modes of Pool Boiling 607

10.4 Pool Boiling Correlations 610

10.4.1 Nucleate Pool Boiling 610

10.4.2 Critical Heat Flux for Nucleate Pool Boiling 612

10.4.3	Minimum Heat Flux	613
10.4.4	Film Pool Boiling	613
10.4.5	Parametric Effects on Pool Boiling	614
10.5	Forced Convection Boiling	619
10.5.1	External Forced Convection Boiling	620
10.5.2	Two-Phase Flow	620
10.5.3	Two-Phase Flow in Microchannels	623
10.6	Condensation: Physical Mechanisms	623
10.7	Laminar Film Condensation on a Vertical Plate	625
10.8	Turbulent Film Condensation	629
10.9	Film Condensation on Radial Systems	634
10.10	Condensation in Horizontal Tubes	639
10.11	Dropwise Condensation	640
10.12	Summary	641
	References	641
	Problems	643

Chapter 11 Heat Exchangers 653

11.1	Heat Exchanger Types	654
11.2	The Overall Heat Transfer Coefficient	656
11.3	Heat Exchanger Analysis: Use of the Log Mean Temperature Difference	659
11.3.1	The Parallel-Flow Heat Exchanger	660
11.3.2	The Counterflow Heat Exchanger	662
11.3.3	Special Operating Conditions	663

11.4 Heat Exchanger Analysis: The Effectiveness–NTU Method 670

11.4.1 Definitions 670

11.4.2 Effectiveness–NTU Relations 671

11.5 Heat Exchanger Design and Performance Calculations 678

11.6 Additional Considerations 687

11.7 Summary 695

References 696

Problems 696

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 711

12.1 Fundamental Concepts 712

12.2 Radiation Heat Fluxes 715

12.3 Radiation Intensity 717

12.3.1 Mathematical Definitions 717

12.3.2 Radiation Intensity and Its Relation to Emission 718

12.3.3 Relation to Irradiation 723

12.3.4 Relation to Radiosity for an Opaque Surface 725

12.3.5 Relation to the Net Radiative Flux for an Opaque Surface 726

12.4 Blackbody Radiation 726

12.4.1 The Planck Distribution 727

12.4.2	Wien's Displacement Law	728
12.4.3	The Stefan–Boltzmann Law	728
12.4.4	Band Emission	729
12.5	Emission from Real Surfaces	736
12.6	Absorption, Reflection, and Transmission by Real Surfaces	745
12.6.1	Absorptivity	746
12.6.2	Reflectivity	747
12.6.3	Transmissivity	749
12.6.4	Special Considerations	749
12.7	Kirchhoff's Law	754
12.8	The Gray Surface	756
12.9	Environmental Radiation	762
12.9.1	Solar Radiation	763
12.9.2	The Atmospheric Radiation Balance	765
12.9.3	Terrestrial Solar Irradiation	767
12.10	Summary	770
	References	774
	Problems	774
	Chapter 13 Radiation Exchange Between Surfaces	797
13.1	The View Factor	798
13.1.1	The View Factor Integral	798
13.1.2	View Factor Relations	799
13.2	Blackbody Radiation Exchange	808

13.3 Radiation Exchange Between Opaque, Diffuse, Gray Surfaces in an Enclosure 812

13.3.1 Net Radiation Exchange at a Surface 813

13.3.2 Radiation Exchange Between Surfaces 814

13.3.3 The Two-Surface Enclosure 820

13.3.4 Two-Surface Enclosures in Series and Radiation Shields 822

13.3.5 The Reradiating Surface 824

13.4 Multimode Heat Transfer 829

13.5 Implications of the Simplifying Assumptions 832

13.6 Radiation Exchange with Participating Media 832

13.6.1 Volumetric Absorption 832

13.6.2 Gaseous Emission and Absorption 833

13.7 Summary 837

References 838

Problems 839

Chapter 14 Diffusion Mass Transfer 863

14.1 Physical Origins and Rate Equations 864

14.1.1 Physical Origins 864

14.1.2 Mixture Composition 865

14.1.3 Fick's Law of Diffusion 866

14.1.4 Mass Diffusivity 867

14.2 Mass Transfer in Nonstationary Media 869

14.2.1 Absolute and Diffusive Species Fluxes 869

14.2.2 Evaporation in a Column 872

14.3	The Stationary Medium Approximation	877
14.4	Conservation of Species for a Stationary Medium	877
14.4.1	Conservation of Species for a Control Volume	878
14.4.2	The Mass Diffusion Equation	878
14.4.3	Stationary Media with Specified Surface Concentrations	880
14.5	Boundary Conditions and Discontinuous Concentrations at Interfaces	884
14.5.1	Evaporation and Sublimation	885
14.5.2	Solubility of Gases in Liquids and Solids	885
14.5.3	Catalytic Surface Reactions	890
14.6	Mass Diffusion with Homogeneous Chemical Reactions	892
14.7	Transient Diffusion	895
14.8	Summary	901
	References	902
	Problems	902

Appendix A Thermophysical Properties of Matter 911

Appendix B Mathematical Relations and Functions 943

Appendix C Thermal Conditions Associated with Uniform Energy Generation in One-Dimensional, Steady-State Systems 949

Appendix D The Gauss–Seidel Method 955

Appendix E The Convection Transfer Equations 957

E.1	Conservation of Mass	958
E.2	Newton’s Second Law of Motion	958
E.3	Conservation of Energy	959
E.4	Conservation of Species	960

Appendix F Boundary Layer Equations for Turbulent Flow 961

Appendix G An Integral Laminar Boundary Layer Solution for Parallel Flow over a Flat Plate 965

Index 969