
Contents

Preface to the Third Edition	xiii
Authors.....	xvii
Acknowledgments.....	xix

Chapter 1 Introduction to Transport Phenomena in Materials	
Processing	1
1.1 Transport Phenomena.....	1
1.2 Examples of Transport Phenomena in Materials	
Processing.....	3
1.2.1 Fluid Flow	3
1.2.2 Heat Transfer	4
1.2.3 Mass Transfer	7
1.2.4 Multimode Transport Phenomena.....	8
1.2.5 Nonuniform Distribution of Microstructure	9
1.3 Constitutive Relations for Transport Phenomena.....	10
1.3.1 Shear in Fluids.....	11
1.3.2 Modes of Heat Transfer.....	22
1.3.3 Mass Transfer	33
1.3.4 Summary of Constitutive Equations	39
1.4 Finding Solutions to Models of Transport Phenomena	40
1.4.1 Mathematical Solutions	41
1.4.2 Numerical Solutions	43
1.4.3 Scaling Analysis.....	45
1.4.4 A Note on Selection of Solution Approach	48
1.5 Engineering Units.....	50
1.6 Summary	52
References	53
Chapter 2 Steady State Conduction Heat Transfer.....	55
2.1 Introduction	55
2.2 Thermal Resistances.....	55
2.2.1 Conduction Resistance	55
2.2.2 Convection Resistance.....	59
2.2.3 Radiation Resistance	60
2.2.4 Interface Resistance	60
2.3 Resistance Networks.....	63
2.4 General Heat Conduction Equation.....	67
2.5 Heat Transfer Boundary Conditions.....	71
2.6 One-Dimensional Heat Conduction	73
2.7 Conduction with Heat Generation	85

2.8	Multidimensional Conduction	91
2.8.1	Scaling Analysis.....	91
2.8.2	Two-Dimensional Paths in Resistance Networks: Branches and Shape Factors.....	97
2.8.3	Exact Solutions	105
2.9	Summary	109
2.10	Homework Problems	109
	References	118
Chapter 3	Transient Conduction Heat Transfer.....	120
3.1	Introduction	120
3.2	Scaling Analysis of General Transient Conduction	120
3.3	Lumped Capacitance Analysis: Convection Resistance Dominated ($Bi \ll 1$).....	122
3.3.1	Convection Heat Loss.....	122
3.3.2	Radiation Heat Loss	126
3.4	Spatial Dependence: Conduction Resistance Dominated ($Bi \gg 1$).....	129
3.4.1	Cooling in a Slab: Early Times for $Bi \gg 1$	130
3.4.2	Cooling in a Slab: Late Times for $Bi \gg 1$	137
3.4.3	Heating in a Radial System.....	144
3.5	Spatial Dependence: The General Solution with a Balance of Conduction and Convection Resistances ($Bi \sim 1$)	150
3.5.1	Heating in a Slab: Early Times for $Bi \sim 1$	150
3.5.2	Heating in a Slab: Late Times for $Bi \sim 1$	153
3.6	Solidification.....	160
3.6.1	Energy Balances with Phase Change	161
3.6.2	Solidification of a Pure Substance.....	165
3.7	Summary	174
3.8	Homework Problems	174
	References	185
Chapter 4	Mass Diffusion in the Solid State	187
4.1	Introduction	187
4.2	Steady State Mass Diffusion	187
4.3	Fick's Second Law of Diffusion: Transient Diffusion.....	188
4.4	Infinite Diffusion Couple.....	195
4.5	Diffusion Involving Solid-Solid Phase Change.....	197
4.6	Diffusion in Substitutional Solid Solutions	208
4.7	Darken's Analysis	209
4.8	Self-Diffusion Coefficient	213
4.9	Measurement of the Interdiffusion Coefficient: Boltzmann–Matano Analysis	216
4.10	Influence of Temperature on the Diffusion Coefficient.....	221

4.11	Summary	225
4.12	Homework Problems	227
	References	231
Chapter 5	Fluid Statics.....	232
5.1	Introduction	232
5.2	Concept of Pressure.....	232
5.2.1	Pressure at a Point and in a Column	232
5.2.2	Atmospheric Pressure.....	235
5.3	Measurement of Pressure	237
5.4	Pressure in Incompressible Fluids.....	241
5.5	Buoyancy	244
5.6	Summary	246
5.7	Homework Problems	247
	Reference.....	250
Chapter 6	Mechanical Energy Balance in Fluid Flow.....	251
6.1	Introduction	251
6.2	Laminar and Turbulent Flows	251
6.3	Bernoulli's Equation.....	253
6.4	Friction Losses.....	255
6.5	Influence of Bends, Fittings, and Changes in Pipe Radius.....	261
6.6	Steady-State Applications of the Modified Bernoulli Equation	263
6.7	Concept of Hydrostatic Head.....	269
6.8	Fluid Flow in an Open Channel	270
6.9	Transient Applications of the Modified Bernoulli Equation	273
6.10	Summary	277
6.11	Homework Problems	278
	References	283
Chapter 7	Equations of Fluid Motion	285
7.1	Introduction	285
7.2	Conservation of Mass	285
7.3	Momentum Balance: The Navier-Stokes Equations.....	291
7.4	Boundary Conditions for Fluid Flow	296
7.5	Characteristics of Pressure-Driven Flow Behavior in a Channel	299
7.6	Summary	303
7.7	Homework Problems	303
	References	306

Chapter 8	Internal Flows.....	307
8.1	Introduction	307
8.2	Simplifications of Equations of Motion for Internal Flows...	307
8.3	Shear-Driven Flow between Flat Parallel Plates	309
8.4	Pressure-Driven Flow between Flat Parallel Plates	311
8.5	Fluid Flow in a Vertical Cylindrical Tube.....	319
8.6	Capillary Flowmeter.....	325
8.7	Non-Newtonian Internal Flows	328
8.7.1	Shear-Driven Flow of a Power-Law Fluid.....	328
8.7.2	Pressure-Driven Flow of a Power-Law Fluid	329
8.7.3	Pressure-Driven Flow of a Bingham Plastic	334
8.8	Flow through Porous Media	336
8.8.1	Resistance to Flow.....	336
8.8.2	Effect of Porous Media Structure on Flow	342
8.9	Fluidized Beds.....	349
8.10	Summary	354
8.11	Homework Problems	354
	References	359
Chapter 9	External Flows.....	360
9.1	Introduction	360
9.2	Fully Developed Flow Down an Inclined Plane.....	360
9.3	Flow over a Horizontal Flat Plane.....	363
9.4	Momentum Integral Solution for Boundary Layer on a Horizontal Flat Plate.....	367
	9.4.1 Entry Length at Entrance to a Pipe	373
9.5	Turbulent Flow.....	375
	9.5.1 Characteristics of Turbulent Flows.....	376
	9.5.2 Transition and Turbulent Flow over a Flat Plate	383
9.6	Flow Past Submerged Bluff Objects.....	390
9.7	Summary	398
9.8	Homework Problems	399
	References	403
Chapter 10	Convection Heat Transfer.....	405
10.1	Introduction	405
10.2	General Energy Equation with Advection and Diffusion	408
10.3	Advection in Rigid, Moving Media.....	413
10.4	External Forced Convection	420
	10.4.1 Forced Convection from a Horizontal Flat Plate	420
	10.4.2 Forced Convection Correlations in Other Geometries	439
10.5	Internal Forced Convection	451

10.6	Natural Convection Heat Transfer	460
10.6.1	Natural Convection from an Isothermal Vertical Flat Plate.....	462
10.6.2	Natural Convection from Other Geometries.....	467
10.7	Boiling Heat Transfer	469
10.8	Summary	474
10.9	Homework Problems	475
	References	481
Chapter 11	Mass Transfer in Fluids	484
11.1	Introduction	484
11.2	Mass and Molar Fluxes in a Fluid	484
11.3	Equations of Diffusion with Advection in a Binary Mixture <i>A-B</i>	486
11.4	Equimolar Counterdiffusion.....	489
11.5	One-Dimensional Steady-State Diffusion of Gas <i>A</i> through Stationary Gas <i>B</i>	490
11.6	Sublimation of a Sphere into a Stationary Gas.....	496
11.7	Film Model	498
11.8	Catalytic Surface Reactions	500
11.9	Diffusion and Chemical Reaction in Stagnant Film	502
11.10	Mass Transfer at Large Fluxes and Large Concentrations....	506
11.11	Influence of Mass Transport on Heat Transfer in Stagnant Film	509
11.12	Mass Transfer Coefficient for Concentration Boundary Layer on a Flat Plate.....	512
11.13	Simultaneous Heat and Mass Transfer: Evaporative Cooling.....	517
11.14	Summary	520
11.15	Homework Problems	520
Chapter 12	Radiation Heat Transfer	523
12.1	Introduction	523
12.2	Intensity and Emissive Power.....	524
12.2.1	Emissive Flux	526
12.2.2	Irradiation.....	527
12.2.3	Radiosity.....	528
12.3	Blackbody Radiation	528
12.4	Surface Properties	531
12.5	Kirchhoff's Law and the <i>Hohlraum</i>	537
12.6	Radiation Exchange in an Enclosure: View Factors.....	540
12.7	Radiation Exchange among Blackbodies	551
12.8	Radiation Exchange among Diffuse-Gray Surfaces	554
12.9	Notes on the Electrical Analogy	559

12.10 Radiation Shields.....	562
12.11 Reradiating Surfaces	564
12.12 Summary	568
12.13 Homework Problems	569
References	574
Appendix I Math Practice for Transport Phenomena Course.....	575
Appendix II Equations of Motion and Thermal Energy Balance.....	579
Appendix III Unit Conversions.....	581
Appendix IV Selected Thermophysical Properties	583
Index.....	591