

Analysis of Transport Phenomena

SECOND EDITION

William M. Deen
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

New York Oxford
OXFORD UNIVERSITY PRESS

Contents

Preface	xiii	
List of Symbols	xix	
Chapter 1	Diffusive Fluxes and Material Properties	1
1.1	Introduction	1
1.2	Basic Constitutive Equations	2
1.3	Diffusivities for Energy, Species, and Momentum	7
1.4	Magnitudes of Transport Coefficients	8
1.5	Molecular Interpretation of Transport Coefficients	13
1.6	Limitations on Length and Time Scales	19
	References	22
	Problems	23
Chapter 2	Fundamentals of Heat and Mass Transfer	26
2.1	Introduction	26
2.2	General Forms of Conservation Equations	27
2.3	Conservation of Mass	34
2.4	Conservation of Energy: Thermal Effects	36
2.5	Heat Transfer at Interfaces	38
2.6	Conservation of Chemical Species	41
2.7	Mass Transfer at Interfaces	43
2.8	Molecular View of Species Conservation	44
	References	48
	Problems	48
Chapter 3	Formulation and Approximation	53
3.1	Introduction	53
3.2	One-Dimensional Examples	54
3.3	Order-of-Magnitude Estimation and Scaling	69
3.4	"Dimensionality" in Modeling	77
3.5	Time Scales in Modeling	87
	References	97
	Problems	98
Chapter 4	Solution Methods Based on Scaling Concepts	113
4.1	Introduction	113
4.2	Similarity Method	114
4.3	Regular Perturbation Analysis	120

4.4	Singular Perturbation Analysis	127
	References	141
	Problems	141
Chapter 5	Solution Methods for Linear Problems	151
5.1	Introduction	151
5.2	Properties of Linear Boundary-Value Problems	152
5.3	Finite Fourier Transform Method	157
5.4	Basis Functions	162
5.5	Fourier Series	170
5.6	FFT Solutions for Rectangular Geometries	174
5.7	FFT Solutions for Cylindrical Geometries	184
5.8	FFT Solutions for Spherical Geometries	190
5.9	Point-Source Solutions	200
5.10	More on Self-Adjoint Eigenvalue Problems and FFT Solutions	204
	References	209
	Problems	210
Chapter 6	Fundamentals of Fluid Mechanics	220
6.1	Introduction	220
6.2	Conservation of Momentum	220
6.3	Total Stress, Pressure, and Viscous Stress	226
6.4	Fluid Kinematics	230
6.5	Constitutive Equations for Viscous Stress	236
6.6	Fluid Mechanics at Interfaces	243
6.7	Force Calculations	250
6.8	Stream Function	255
6.9	Dimensionless Groups and Flow Regimes	261
	References	265
	Problems	265
Chapter 7	Unidirectional and Nearly Unidirectional Flow	270
7.1	Introduction	270
7.2	Steady Flow with a Pressure Gradient	271
7.3	Steady Flow with a Moving Surface	277
7.4	Time-Dependent Flow	279
7.5	Limitations of Exact Solutions	282
7.6	Nearly Unidirectional Flow	288
	References	300
	Problems	300
Chapter 8	Creeping Flow	315
8.1	Introduction	315
8.2	General Features of Low Reynolds Number Flow	315
8.3	Unidirectional and Nearly Unidirectional Solutions	319
8.4	Stream-Function Solutions	324
8.5	Point-Force Solutions	331
8.6	Particles and Suspensions	334

8.7	Corrections to Stokes' Law	343
	References	350
	Problems	351
Chapter 9	Laminar Flow at High Reynolds Number	361
9.1	Introduction	361
9.2	General Features of High Reynolds Number Flow	362
9.3	Irrotational Flow	371
9.4	Boundary Layers at Solid Surfaces	378
9.5	Internal Boundary Layers	387
	References	393
	Problems	394
Chapter 10	Forced-Convection Heat and Mass Transfer in Confined Laminar Flows	401
10.1	Introduction	401
10.2	Péclet Number	402
10.3	Nusselt and Sherwood Numbers	406
10.4	Entrance Region	411
10.5	Fully Developed Region	415
10.6	Conservation of Energy: Mechanical Effects	423
10.7	Taylor Dispersion	427
	References	433
	Problems	434
Chapter 11	Forced-Convection Heat and Mass Transfer in Unconfined Laminar Flows	440
11.1	Introduction	440
11.2	Heat and Mass Transfer in Creeping Flow	441
11.3	Heat and Mass Transfer in Laminar Boundary Layers	446
11.4	Scaling Laws for Nusselt and Sherwood Numbers	451
	References	457
	Problems	458
Chapter 12	Transport in Buoyancy-Driven Flow	463
12.1	Introduction	463
12.2	Buoyancy and the Boussinesq Approximation	464
12.3	Confined Flows	466
12.4	Dimensional Analysis and Boundary-Layer Equations	474
12.5	Unconfined Flows	478
	References	485
	Problems	486
Chapter 13	Transport in Turbulent Flow	491
13.1	Introduction	491
13.2	Basic Features of Turbulence	491
13.3	Time-Smoothed Equations	499
13.4	Eddy Diffusivity Models	505

13.5	Other Approaches for Turbulent-Flow Calculations	518
	References	524
	Problems	525
Chapter 14	Simultaneous Energy and Mass Transfer and Multicomponent Systems	529
14.1	Introduction	529
14.2	Conservation of Energy: Multicomponent Systems	530
14.3	Simultaneous Heat and Mass Transfer	532
14.4	Introduction to Coupled Fluxes	545
14.5	Stefan–Maxwell Equations	550
14.6	Generalized Diffusion in Dilute Mixtures	553
14.7	Generalized Stefan–Maxwell Equations	557
	References	563
	Problems	564
Chapter 15	Transport in Electrolyte Solutions	573
15.1	Introduction	573
15.2	Formulation of Macroscopic Problems	574
15.3	Macroscopic Examples	580
15.4	Equilibrium Double Layers	585
15.5	Electrokinetic Phenomena	592
	References	601
	Problems	602
Appendix A	Vectors and Tensors	609
A.1	Introduction	609
A.2	Representation of Vectors and Tensors	609
A.3	Vector and Tensor Products	612
A.4	Vector-Differential Operators	617
A.5	Integral Transformations	620
A.6	Position Vectors	623
A.7	Orthogonal Curvilinear Coordinates	625
A.8	Surface Geometry	634
	References	638
Appendix B	Ordinary Differential Equations and Special Functions	639
B.1	Introduction	639
B.2	First-Order Equations	640
B.3	Equations with Constant Coefficients	641
B.4	Bessel and Spherical Bessel Equations	642
B.5	Other Equations with Variable Coefficients	647
	References	650
	Index	651