Contents

Preface xi

Chapter 1
Introduction 2

1.1 Preliminary Remarks 3
1.2 The Concept of a Fluid 4
1.3 The Fluid as a Continuum 6
1.4 Dimensions and Units 7
1.5 System and Control Volume 16
1.6 Thermodynamic Properties of a Fluid 18
1.7 Viscosity and Other Secondary Properties 25
1.8 Flow Patterns: Streamlines, Pathlines, and Streaklines 41
1.9 Basic Flow Analysis Techniques 44
1.10 The Fundamentals of Engineering (FE) Examination 45
1.11 The History of Fluid Mechanics 46
Summary 46
Problems 47
Fundamentals of Engineering Exam Problems 55
Comprehensive Problems 55
References 58

Chapter 2
Pressure Distribution in a Fluid 60

2.1 Pressure and Pressure Gradient 61
2.2 Equilibrium of a Fluid Element 63
2.3 Hydrostatic Pressure Distributions 64
2.4 Application to Manometry 71
2.5 Hydrostatic Forces on Plane Surfaces 75
2.6 Hydrostatic Forces on Curved Surfaces 82
2.7 Hydrostatic Forces in Layered Fluids 85
2.8 Buoyancy and Stability 88
2.9 Pressure Distribution in Rigid-Body Motion 93
2.10 Pressure Measurement 101
Summary 105
Problems 105
Word Problems 128
Fundamentals of Engineering Exam Problems 128
Comprehensive Problems 129
Design Projects 131
References 132

Chapter 3
Integral Relations for a Control Volume 134

3.1 Basic Physical Laws of Fluid Mechanics 135
3.2 The Reynolds Transport Theorem 139
3.3 Conservation of Mass 147
3.4 The Linear Momentum Equation 152
3.5 Frictionless Flow: The Bernoulli Equation 168
3.6 The Angular Momentum Theorem 178
3.7 The Energy Equation 184
Summary 195
Problems 196
Word Problems 224
Fundamentals of Engineering Exam Problems 224
Comprehensive Problems 225
Design Project 227
References 227

Chapter 4
Differential Relations for Fluid Flow 228

4.1 The Acceleration Field of a Fluid 230
4.2 The Differential Equation of Mass Conservation 232

4.3 The Differential Equation of Linear Momentum 238
4.4 The Differential Equation of Angular Momentum 245
4.5 The Differential Equation of Energy 246
4.6 Boundary Conditions for the Basic Equations 249
4.7 The Stream Function 255
4.8 Vorticity and Irrotationality 262
4.9 Frictionless Irrotational Flows 264
4.10 Some Illustrative Incompressible Viscous Flows 270
Summary 279
Problems 279
Word Problems 290
Fundamentals of Engineering Exam Problems 291
Comprehensive Problems 291
References 292

Chapter 5
Dimensional Analysis and Similarity 294

5.1 Introduction 295
5.2 The Principle of Dimensional Homogeneity 299
5.3 The Pi Theorem 301
5.4 Nondimensionalization of the Basic Equations 312
5.5 Modeling and Similarity 321
Summary 333
Problems 334
Word Problems 342
Fundamentals of Engineering Exam Problems 342
Comprehensive Problems 343
Design Projects 344
References 345

Chapter 6
Viscous Flow in Ducts 346

6.1 Reynolds Number Regimes 347
6.2 Internal Viscous Flows 352
6.3 Head Loss—The Friction Factor 354
6.4 Laminar Fully Developed Pipe Flow 356
6.5 Turbulence Modeling 359
6.6 Turbulent Pipe Flow 366
6.7 Four Types of Pipe Flow Problems 374
6.8 Flow in Noncircular Ducts 380
6.9 Minor or Local Losses in Pipe Systems 389
6.10 Multiple-Pipe Systems 398
6.11 Experimental Duct Flows: Diffuser Performance 404
6.12 Fluid Meters 409
Summary 431
Problems 432
Word Problems 451
Fundamentals of Engineering Exam Problems 451
Comprehensive Problems 452
Design Projects 454
References 455

Chapter 7
Flow Past Immersed Bodies 458

7.1 Reynolds Number and Geometry Effects 459
7.2 Momentum Integral Estimates 463
7.3 The Boundary Layer Equations 467
7.4 The Flat-Plate Boundary Layer 469
7.5 Boundary Layers with Pressure Gradient 479
7.6 Drag of Two- and Three-Dimensional Bodies 485
7.7 Forces on Lifting Bodies 504
Summary 513
Problems 514
Word Problems 527
Fundamentals of Engineering Exam Problems 527
Comprehensive Problems 528
Design Project 529
References 529

Chapter 8
Potential Flow 532

8.1 Introduction and Review 533
8.2 Elementary Plane Flow Solutions 536
8.3 Superposition of Plane Flow Solutions 544
8.4 Plane Flow Past Closed-Body Shapes 550
8.5 Other Plane Potential Flows 559
8.6 Images 563
8.7 Airfoil Theory 566
8.8 Axisymmetric Potential Flow 574
Summary 580
Problems 580
Word Problems 590

Comprehensive Problems 590
Design Projects 591
References 591

Chapter 9
Compressible Flow 594

9.1 Introduction: Review of Thermodynamics 596
9.2 The Speed of Sound 600
9.3 Adiabatic and Isentropic Steady Flow 603
9.4 Isentropic Flow with Area Changes 609
9.5 The Normal Shock Wave 616
9.6 Operation of Converging and Diverging Nozzles 624
9.7 Compressible Duct Flow with Friction 629
9.8 Frictionless Duct Flow with Heat Transfer 640
9.9 Mach Waves and Oblique Shock Waves 645
9.10 Prandtl–Meyer Expansion Waves 655
Summary 668
Problems 669
Word Problems 682
Fundamentals of Engineering Exam Problems 682
Comprehensive Problems 683
Design Projects 684
References 685

Chapter 10
Open-Channel Flow 686

10.1 Introduction 687
10.2 Uniform Flow; The Chézy Formula and the Manning Formula 693
10.3 Efficient Uniform-Flow Channels 699
10.4 Specific Energy; Critical Depth 702
10.5 The Hydraulic Jump 710
10.6 Gradually Varied Flow 714
10.7 Flow Measurement and Control by Weirs 722
Summary 730
Problems 730
Word Problems 742
Fundamentals of Engineering Exam Problems 743
Comprehensive Problems 743
Design Projects 744
References 744

Chapter 11
Turbomachinery 746

11.1 Introduction and Classification 747
11.2 The Centrifugal Pump 750
11.3 Pump Performance Curves and Similarity Rules 756
11.4 Mixed- and Axial-Flow Pumps: The Specific Speed 767
11.5 Matching Pumps to System Characteristics 775
11.6 Turbines 782
Summary 796
Problems 797
Word Problems 810
Comprehensive Problems 810
Design Project 812
References 812

Appendix A Physical Properties of Fluids 814

Appendix B Compressible Flow Tables 819

Appendix C Conversion Factors 826

Appendix D Equations of Motion in Cylindrical Coordinates 828

Appendix E Estimating Uncertainty in Experimental Data 830

Appendix F Numerical Methods 832

Answers to Selected Problems 846

Index 853

Conversion Factors 864

Moody Chart 866