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



viii Contents

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 2995.3 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