

# Contents

<b>1</b>			
<b>INTRODUCTION</b>	<b>3</b>		
1.1 Some Characteristics of Fluids	4		
1.2 Dimensions, Dimensional Homogeneity, and Units	5		
1.2.1 Systems of Units	7		
1.3 Analysis of Fluid Behavior	12		
1.4 Measures of Fluid Mass and Weight	12		
1.4.1 Density	12		
1.4.2 Specific Weight	13		
1.4.3 Specific Gravity	13		
1.5 Ideal Gas Law	14		
1.6 Viscosity	15		
1.7 Compressibility of Fluids	22		
1.7.1 Bulk Modulus	22		
1.7.2 Compression and Expansion of Gases	23		
1.7.3 Speed of Sound	24		
1.8 Vapor Pressure	25		
1.9 Surface Tension	26		
1.10 A Brief Look Back in History	28		
References	31		
Review Problems	31		
Problems	33		
<b>2</b>			
<b>FLUID STATICS</b>	<b>41</b>		
2.1 Pressure at a Point	41		
2.2 Basic Equation for Pressure Field	43		
2.3 Pressure Variation in a Fluid at Rest	45		
2.3.1 Incompressible Fluid	45		
2.3.2 Compressible Fluid	48		
2.4 Standard Atmosphere	50		
2.5 Measurement of Pressure	51		
2.6 Manometry	53		
2.6.1 Piezometer Tube	54		
2.6.2 U-Tube Manometer	54		
2.6.3 Inclined-Tube Manometer	58		
2.7 Mechanical and Electronic Pressure Measuring Devices	59		
2.8 Hydrostatic Force on a Plane Surface	61		
2.9 Pressure Prism	68		
2.10 Hydrostatic Force on a Curved Surface	72		
2.11 Buoyancy, Flotation, and Stability	74		
2.11.1 Archimedes' Principle	74		
2.11.2 Stability	76		
2.12 Pressure Variation in a Fluid with Rigid-Body Motion	78		
2.12.1 Linear Motion	78		
2.12.2 Rigid-Body Rotation	81		
References	84		
Review Problems	84		
Problems	87		
<b>3</b>			
<b>ELEMENTARY FLUID DYNAMICS—THE BERNOULLI EQUATION</b>	<b>103</b>		
3.1 Newton's Second Law	103		

3.2	$F = ma$ Along a Streamline	106
3.3	$F = ma$ Normal to a Streamline	111
3.4	Physical Interpretation	113
3.5	Static, Stagnation, Dynamic, and Total Pressure	117
3.6	Examples of Use of the Bernoulli Equation	121
3.6.1	Free Jets	121
3.6.2	Confined Flows	123
3.6.3	Flowrate Measurement	131
3.7	The Energy Line and the Hydraulic Grade Line	136
3.8	Restrictions on the Use of the Bernoulli Equation	139
3.8.1	Compressibility Effects	139
3.8.2	Unsteady Effects	142
3.8.3	Rotational Effects	144
3.8.4	Other Restrictions	146
	References	146
	Review Problems	146
	Problems	149

## 4

### FLUID KINEMATICS 165

4.1	The Velocity Field	165
4.1.1	Eulerian and Lagrangian Flow Descriptions	167
4.1.2	One-, Two-, and Three- Dimensional Flows	169
4.1.3	Steady and Unsteady Flows	170
4.1.4	Streamlines, Streaklines, and Pathlines	170
4.2	The Acceleration Field	175
4.2.1	The Material Derivative	175
4.2.2	Unsteady Effects	178
4.2.3	Convective Effects	179
4.2.4	Streamline Coordinates	182
4.3	Control Volume and System Representations	184
4.4	The Reynolds Transport Theorem	185
4.4.1	Derivation of the Reynolds Transport Theorem	188
4.4.2	Physical Interpretation	193
4.4.3	Relationship to Material Derivative	194
4.4.4	Steady Effects	195
4.4.5	Unsteady Effects	195
4.4.6	Moving Control Volumes	197
4.4.7	Selection of a Control Volume	198

References	199
Review Problems	199
Problems	201

## 5

### FINITE CONTROL VOLUME ANALYSIS 211

5.1	Conservation of Mass—The Continuity Equation	212
5.1.1	Derivation of the Continuity Equation	212
5.1.2	Fixed, Nondeforming Control Volume	214
5.1.3	Moving, Nondeforming Control Volume	221
5.1.4	Deforming Control Volume	224
5.2	Newton's Second Law—The Linear Momentum and Moment-of- Momentum Equations	227
5.2.1	Derivation of the Linear Momentum Equation	227
5.2.2	Application of the Linear Momentum Equation	229
5.2.3	Derivation of the Moment-of- Momentum Equation	247
5.2.4	Application of the Moment-of- Momentum Equation	249
5.3	First Law of Thermodynamics— The Energy Equation	257
5.3.1	Derivation of the Energy Equation	257
5.3.2	Application of the Energy Equation	260
5.3.3	Comparison of the Energy Equation with the Bernoulli Equation	265
5.3.4	Application of the Energy Equation to Nonuniform Flows	272
5.3.5	Combination of the Energy Equation and the Moment-of- Momentum Equation	276
5.4	Second Law of Thermodynamics— Irreversible Flow	278
5.4.1	Semi-infinitesimal Control Volume Statement of the Energy Equation	278
5.4.2	Semi-infinitesimal Control Volume Statement of the Second Law of Thermodynamics	279

5.4.3 Combination of the Equations of the First and Second Laws of Thermodynamics 280

5.4.4 Application of the Loss Form of the Energy Equation 281

References 283

Review Problems 283

Problems 288

**6**  
**DIFFERENTIAL ANALYSIS OF FLUID FLOW** 309

6.1 Fluid Element Kinematics 310

6.1.1 Velocity and Acceleration Fields Revisited 310

6.1.2 Linear Motion and Deformation 311

6.1.3 Angular Motion and Deformation 313

6.2 Conservation of Mass 316

6.2.1 Differential Form of Continuity Equation 316

6.2.2 Cylindrical Polar Coordinates 319

6.2.3 The Stream Function 320

6.3 Conservation of Linear Momentum 323

6.3.1 Description of Forces Acting on the Differential Element 324

6.3.2 Equations of Motion 326

6.4 Inviscid Flow 327

6.4.1 Euler's Equations of Motion 327

6.4.2 The Bernoulli Equation 328

6.4.3 Irrotational Flow 330

6.4.4 The Bernoulli Equation for Irrotational Flow 332

6.4.5 The Velocity Potential 332

6.5 Some Basic, Plane Potential Flows 336

6.5.1 Uniform Flow 338

6.5.2 Source and Sink 339

6.5.3 Vortex 341

6.5.4 Doublet 344

6.6 Superposition of Basic, Plane Potential Flows 346

6.6.1 Source in a Uniform Stream—Half-Body 347

6.6.2 Rankine Ovals 350

6.6.3 Flow Around a Circular Cylinder 352

6.7 Other Aspects of Potential Flow Analysis 358

6.8 Viscous Flow 359

6.8.1 Stress-Deformation Relationships 359

6.8.2 The Navier–Stokes Equations 360

6.9 Some Simple Solutions for Viscous, Incompressible Fluids 362

6.9.1 Steady, Laminar Flow Between Fixed Parallel Plates 362

6.9.2 Couette Flow 365

6.9.3 Steady, Laminar Flow in Circular Tubes 367

6.9.4 Steady, Axial, Laminar Flow in an Annulus 370

6.10 Other Aspects of Differential Analysis 372

6.10.1 Numerical Methods 373

References 381

Review Problems 381

Problems 383

**7**  
**SIMILITUDE, DIMENSIONAL ANALYSIS, AND MODELING** 397

7.1 Dimensional Analysis 397

7.2 Buckingham Pi Theorem 400

7.3 Determination of Pi Terms 400

7.4 Some Additional Comments About Dimensional Analysis 407

7.4.1 Selection of Variables 407

7.4.2 Determination of Reference Dimensions 409

7.4.3 Uniqueness of Pi Terms 411

7.5 Determination of Pi Terms by Inspection 412

7.6 Common Dimensionless Groups in Fluid Mechanics 414

7.7 Correlation of Experimental Data 418

7.7.1 Problems with One Pi Term 418

7.7.2 Problems with Two or More Pi Terms 420

7.8 Modeling and Similitude 423

7.8.1 Theory of Models 423

7.8.2 Model Scales 428

7.8.3 Practical Aspects of Using Models 428

7.9 Some Typical Model Studies 430

7.9.1 Flow Through Closed Conduits 430

7.9.2 Flow Around Immersed Bodies 433

7.9.3 Flow with a Free Surface 437

7.10 Similitude Based on Governing Differential Equations 441

References	444
Review Problems	444
Problems	446

## 8 VISCOUS FLOW IN PIPES 459

8.1 General Characteristics of Pipe Flow	460
8.1.1 Laminar or Turbulent Flow	461
8.1.2 Entrance Region and Fully Developed Flow	463
8.1.3 Pressure and Shear Stress	464
8.2 Fully Developed Laminar Flow	465
8.2.1 From $F = ma$ Applied to a Fluid Element	466
8.2.2 From the Navier–Stokes Equations	471
8.2.3 From Dimensional Analysis	472
8.2.4 Energy Considerations	474
8.3 Fully Developed Turbulent Flow	476
8.3.1 Transition from Laminar to Turbulent Flow	477
8.3.2 Turbulent Shear Stress	479
8.3.3 Turbulent Velocity Profile	483
8.3.4 Turbulence Modeling	488
8.3.5 Chaos and Turbulence	488
8.4 Dimensional Analysis of Pipe Flow	489
8.4.1 The Moody Chart	489
8.4.2 Minor Losses	496
8.4.3 Noncircular Conduits	508
8.5 Pipe Flow Examples	510
8.5.1 Single Pipes	511
8.5.2 Multiple Pipe Systems	523
8.6 Pipe Flowrate Measurement	529
8.6.1 Pipe Flowrate Meters	529
8.6.2 Volume Flow Meters	534
References	536
Review Problems	537
Problems	539

## 9 FLOW OVER IMMERSED BODIES 551

9.1 General External Flow Characteristics	552
9.1.1 Lift and Drag Concepts	553
9.1.2 Characteristics of Flow Past an Object	557
9.2 Boundary Layer Characteristics	562
9.2.1 Boundary Layer Structure and Thickness on a Flat Plate	562

9.2.2 Prandtl/Blasius Boundary Layer Solution	566
9.2.3 Momentum Integral Boundary Layer Equation for a Flat Plate	570
9.2.4 Transition from Laminar to Turbulent Flow	577
9.2.5 Turbulent Boundary Layer Flow	579
9.2.6 Effects of Pressure Gradient	585
9.2.7 Momentum-Integral Boundary Layer Equation with Nonzero Pressure Gradient	590
9.3 Drag	591
9.3.1 Friction Drag	591
9.3.2 Pressure Drag	593
9.3.3 Drag Coefficient Data and Examples	596
9.4 Lift	610
9.4.1 Surface Pressure Distribution	610
9.4.2 Circulation	621
References	625
Review Problems	626
Problems	628

## 10 OPEN-CHANNEL FLOW 639

10.1 General Characteristics of Open-Channel Flow	640
10.2 Surface Waves	641
10.2.1 Wave Speed	641
10.2.2 Froude Number Effects	644
10.3 Energy Considerations	645
10.3.1 Specific Energy	646
10.3.2 Channel Depth Variations	651
10.4 Uniform Depth Channel Flow	652
10.4.1 Uniform Flow Approximations	652
10.4.2 The Chezy and Manning Equations	653
10.4.3 Uniform Depth Examples	656
10.5 Gradually Varied Flow	665
10.5.1 Classification of Surface Shapes	666
10.5.2 Examples of Gradually Varied Flows	667
10.6 Rapidly Varied Flow	669
10.6.1 The Hydraulic Jump	671
10.6.2 Sharp-Crested Weirs	677
10.6.3 Broad-Crested Weirs	680
10.6.4 Underflow Gates	683
References	686
Review Problems	686
Problems	688

<b>11</b>			
<b>COMPRESSIBLE FLOW</b>		<b>699</b>	
11.1	Ideal Gas Relationships	700	
11.2	Mach Number and Speed of Sound	706	
11.3	Categories of Compressible Flow	709	
11.4	Isentropic Flow of an Ideal Gas	713	
11.4.1	Effect of Variations in Flow Cross-Section Area	714	
11.4.2	Converging-Diverging Duct Flow	716	
11.4.3	Constant-Area Duct Flow	734	
11.5	Nonisentropic Flow of an Ideal Gas	735	
11.5.1	Adiabatic Constant-Area Duct Flow with Friction (Fanno Flow)	735	
11.5.2	Frictionless Constant-Area Duct Flow with Heat Transfer (Rayleigh Flow)	750	
11.5.3	Normal Shock Waves	757	
11.6	Analogy Between Compressible and Open-Channel Flows	767	
11.7	Two-Dimensional Compressible Flow	768	
	References	771	
	Review Problems	772	
	Problems	772	
<b>12</b>			
<b>TURBOMACHINES</b>		<b>779</b>	
12.1	Introduction	780	
12.2	Basic Energy Considerations	782	
12.3	Basic Angular Momentum Considerations	786	
12.4	The Centrifugal Pump	788	
12.4.1	Theoretical Considerations	790	
12.4.2	Pump Performance Characteristics	794	
12.4.3	Net Positive Suction Head (NPSH)	796	
12.4.4	System Characteristics and Pump Selection	798	
12.5	Dimensionless Parameters and Similarity Laws	802	
12.5.1	Special Pump Scaling Laws	805	
12.5.2	Specific Speed	807	
12.5.3	Suction Specific Speed	807	
12.6	Axial-Flow and Mixed-Flow Pumps	808	
12.7	Fans	810	
12.8	Turbines	811	
12.8.1	Impulse Turbines	813	
12.8.2	Reaction Turbines	823	
12.9	Compressible Flow Turbomachines	827	
12.9.1	Compressors	827	
12.9.2	Compressible Flow Turbines	832	
	References	834	
	Review Problems	835	
	Problems	837	
<b>A</b>			
<b>UNIT CONVERSION TABLES</b>		<b>846</b>	
<b>B</b>			
<b>PHYSICAL PROPERTIES OF FLUIDS</b>		<b>850</b>	
<b>C</b>			
<b>PROPERTIES OF THE U.S. STANDARD ATMOSPHERE</b>		<b>856</b>	
<b>D</b>			
<b>COMPRESSIBLE FLOW DATA FOR AN IDEAL GAS</b>		<b>858</b>	
<b>ANSWERS</b>		<b>859</b>	
<b>INDEX</b>		<b>869</b>	