## Chapter One
**Introduction and Basic Concepts**

1-1 Introduction 2
   - What Is a Fluid? 2
   - Application Areas of Fluid Mechanics 4

1-2 The No-Slip Condition 6

1-3 A Brief History of Fluid Mechanics 7

1-4 Classification of Fluid Flows 9
   - Viscous versus Inviscid Regions of Flow 10
   - Internal versus External Flow 10
   - Compressible versus Incompressible Flow 10
   - Laminar versus Turbulent Flow 11
   - Natural (or Unforced) versus Forced Flow 11
   - Steady versus Unsteady Flow 12
   - One-, Two-, and Three-Dimensional Flows 13

1-5 System and Control Volume 14

1-6 Importance of Dimensions and Units 15
   - Some SI and English Units 17
   - Dimensional Homogeneity 19
   - Unity Conversion Ratios 20

1-7 Mathematical Modeling of Engineering Problems 21
   - Modeling in Engineering 22

1-8 Problem-Solving Technique 23
   - Step 1: Problem Statement 24
   - Step 2: Schematic 24
   - Step 3: Assumptions and Approximations 24
   - Step 4: Physical Laws 24
   - Step 5: Properties 24
   - Step 6: Calculations 25
   - Step 7: Reasoning, Verification, and Discussion 25

1-9 Engineering Software Packages 25
   - Engineering Equation Solver (EES) 26
   - FlowLab 27

1-10 Accuracy, Precision, and Significant Digits 28
   - Summary 31
   - References and Suggested Reading 31

## Chapter Two
**Properties of Fluids** 37

2-1 Introduction 38
   - Continuum 38

2-2 Density and Specific Gravity 39
   - Density of Ideal Gases 40

2-3 Vapor Pressure and Cavitation 41

2-4 Energy and Specific Heats 43

2-5 Compressibility and Speed of Sound 44
   - Coefficient of Compressibility 44
   - Coefficient of Volume Expansion 46
   - Speed of Sound and Mach Number 48

2-6 Viscosity 50

2-7 Surface Tension and Capillary Effect 55
   - Capillary Effect 58
   - Summary 61

## Chapter Three
**Pressure and Fluid Statics** 73

3-1 Pressure 74
   - Pressure at a Point 75
   - Variation of Pressure with Depth 76

3-2 Pressure Measurement Devices 79
   - The Barometer 79
   - The Manometer 82
   - Other Pressure Measurement Devices 86

3-3 Introduction to Fluid Statics 87
The Compressible Stream Function 440

9-4 The Differential Linear Momentum Equation—Cauchy’s Equation 441

Derivation Using the Divergence Theorem 441
Derivation Using an Infinitesimal Control Volume 442
Alternative Form of Cauchy’s Equation 445
Derivation Using Newton’s Second Law 445

9-5 The Navier–Stokes Equation 446

Introduction 446
Newtonian versus Non-Newtonian Fluids 447
Derivation of the Navier–Stokes Equation for Incompressible, Isothermal Flow 448
Continuity and Navier–Stokes Equations in Cartesian Coordinates 450
Continuity and Navier–Stokes Equations in Cylindrical Coordinates 451

9-6 Differential Analysis of Fluid Flow
Problems 452

Calculation of the Pressure Field for a Known Velocity Field 452
Exact Solutions of the Continuity and Navier–Stokes Equations 457

Summary 475
References and Suggested Reading 476

CHAPTER TEN
APPROXIMATE SOLUTIONS OF THE NAVIER–STOKES EQUATION 491

10-1 Introduction 492
10-2 Nondimensionalized Equations of Motion 493
10-3 The Creeping Flow Approximation 496
Drag on a Sphere in Creeping Flow 499
10-4 Approximation for Inviscid Regions of Flow 501

Derivation of the Bernoulli Equation in Inviscid Regions of Flow 502

10-5 The Irrotational Flow Approximation 505

Continuity Equation 505
Momentum Equation 507
Derivation of the Bernoulli Equation in Irrotational Regions of Flow 507
Two-Dimensional Irrotational Regions of Flow 510
Superposition in Irrotational Regions of Flow 514
Elementary Planar Irrotational Flows 514

Irrotational Flows Formed by Superposition 521

10-6 The Boundary Layer Approximation 530
The Boundary Layer Equations 535
The Boundary Layer Procedure 540
Displacement Thickness 544
Momentum Thickness 547
Turbulent Flat Plate Boundary Layer 548
Boundary Layers with Pressure Gradients 554
The Momentum Integral Technique for Boundary Layers 559

Summary 567
References and Suggested Reading 568

Application Spotlight: Droplet Formation 569
Problems 570

CHAPTER ELEVEN
EXTERNAL FLOW: DRAG AND LIFT 583

11-1 Introduction 584
11-2 Drag and Lift 586
11-3 Friction and Pressure Drag 590
Reducing Drag by Streamlining 591
Flow Separation 592

11-4 Drag Coefficients of Common Geometries 593
Biological Systems and Drag 597
Drag Coefficients of Vehicles 598
Superposition 599

11-5 Parallel Flow Over Flat Plates 601
Friction Coefficient 603

11-6 Flow Over Cylinders and Spheres 606
Effect of Surface Roughness 608

11-7 Lift 610
Finite-Span Wings and Induced Drag 614
Lift Generated by Spinning 615

Summary 619
References and Suggested Reading 620

Application Spotlight: Drag Reduction 621
Problems 622

CHAPTER TWELVE
COMPRESSIBLE FLOW 635

12-1 Stagnation Properties 636
12-2 One-Dimensional Isentropic Flow 639

Variation of Fluid Velocity with Flow Area 642
CONTENTS

Solution Procedure 855
Additional Equations of Motion 857
Grid Generation and Grid Independence 857
Boundary Conditions 863
Practice Makes Perfect 867

15-2 Laminar CFD Calculations 867
Pipe Flow Entrance Region at Re = 500 867
Flow around a Circular Cylinder at Re = 150 870

15-3 Turbulent CFD Calculations 877
Flow around a Circular Cylinder at Re = 10,000 879
Flow around a Circular Cylinder at Re = 107 881
Design of the Stator for a Vane-Axial Flow Fan 882

15-4 CFD With Heat Transfer 890
Temperature Rise through a Cross-Flow Heat Exchanger 890
Cooling of an Array of Integrated Circuit Chips 892

15-5 Compressible Flow CFD Calculations 897
Compressible Flow through a Converging-Diverging Nozzle 898
Oblique Shocks over a Wedge 902

15-6 Open-Channel Flow CFD Calculations 903
Flow over a Bump on the Bottom of a Channel 904
Flow through a Sluice Gate (Hydraulic Jump) 905

Application Spotlight: A Virtual Stomach 906

Summary 907
References and Suggested Reading 907
Problems 908

APPENDIX 1
PROPERTY TABLES AND CHARTS (SI UNITS) 921

TABLE A-1 Molar Mass, Gas Constant, and Ideal-Gas Specific Heats of Some Substances 922
TABLE A-2 Boiling and Freezing Point Properties 923
TABLE A-3 Properties of Saturated Water 924
TABLE A-4 Properties of Saturated Refrigerant-134a 925
TABLE A-5 Properties of Saturated Ammonia 926
TABLE A-6 Properties of Saturated Propane 927
TABLE A-7 Properties of Liquids 928
TABLE A-8 Properties of Liquid Metals 929

TABLE A-9 Properties of Air at 1 atm Pressure 930
TABLE A-10 Properties of Gases at 1 atm Pressure 931
TABLE A-11 Properties of the Atmosphere at High Altitude 933
TABLE A-13 One-Dimensional Isentropic Compressible Flow Functions for an Ideal Gas with k = 1.4 935
TABLE A-14 One-Dimensional Normal Shock Functions for an Ideal Gas with k = 1.4 936
TABLE A-15 Rayleigh Flow Functions for an Ideal Gas with k = 1.4 937
TABLE A-16 Fanno flow Functions for an Ideal Gas with k = 1.4 938

APPENDIX 2
PROPERTY TABLES AND CHARTS (ENGLISH UNITS) 939

TABLE A-1E Molar Mass, Gas Constant, and Ideal-Gas Specific Heats of Some Substances 940
TABLE A-2E Boiling and Freezing Point Properties 941
TABLE A-3E Properties of Saturated Water 942
TABLE A-4E Properties of Saturated Refrigerant-134a 943
TABLE A-5E Properties of Saturated Ammonia 944
TABLE A-6E Properties of Saturated Propane 945
TABLE A-7E Properties of Liquids 946
TABLE A-8E Properties of Liquid Metals 947
TABLE A-9E Properties of Air at 1 Atm Pressure 948
TABLE A-10E Properties of Gases at 1 Atm Pressure 949
TABLE A-11E Properties of the Atmosphere at High Altitude 951

Glossary 953
Index 967