

CONTENTS

Preface to the Third Edition xiii

Preface to the First Edition xv

Chapter 1

Compressible Flow—Some History and Introductory Thoughts 1

- 1.1 Historical High-Water Marks 9
- 1.2 Definition of Compressible Flow 12
- 1.3 Flow Regimes 15
- 1.4 A Brief Review of Thermodynamics 19
- 1.5 Aerodynamic Forces on a Body 33
- 1.6 Modern Compressible Flow 36
- 1.7 Summary 38
Problems 38

Chapter 2

Integral Forms of the Conservation Equations for Inviscid Flows 41

- 2.1 Philosophy 43
- 2.2 Approach 43
- 2.3 Continuity Equation 45
- 2.4 Momentum Equation 46
- 2.5 A Comment 49
- 2.6 Energy Equation 50
- 2.7 Final Comment 53
- 2.8 An Application of the Momentum Equation: Jet Propulsion Engine Thrust 54
- 2.9 Summary 63
Problems 64

Chapter 3

One-Dimensional Flow 65

- 3.1 Introduction 67
- 3.2 One-Dimensional Flow Equations 71
- 3.3 Speed of Sound and Mach Number 74
- 3.4 Some Conveniently Defined Flow Parameters 77
- 3.5 Alternative Forms of the Energy Equation 78
- 3.6 Normal Shock Relations 86
- 3.7 Hugoniot Equation 98
- 3.8 One-Dimensional Flow with Heat Addition 102
- 3.9 One-Dimensional Flow with Friction 111
- 3.10 Historical Note: Sound Waves and Shock Waves 117
- 3.11 Summary 121
Problems 124

Chapter 4

Oblique Shock and Expansion Waves 127

- 4.1 Introduction 129
- 4.2 Source of Oblique Waves 131
- 4.3 Oblique Shock Relations 133
- 4.4 Supersonic Flow over Wedges and Cones 145
- 4.5 Shock Polar 149
- 4.6 Regular Reflection from a Solid Boundary 152
- 4.7 Comment on Flow Through Multiple Shock Systems 157
- 4.8 Pressure-Deflection Diagrams 158
- 4.9 Intersection of Shocks of Opposite Families 159

- 4.10** Intersection of Shocks of the Same Family 161
- 4.11** Mach Reflection 163
- 4.12** Detached Shock Wave in Front of a Blunt Body 165
- 4.13** Three-Dimensional Shock Waves 166
- 4.14** Prandtl–Meyer Expansion Waves 167
- 4.15** Shock-Expansion Theory 174
- 4.16** Historical Note: Prandtl’s Early Research on Supersonic Flows and the Origin of the Prandtl–Meyer Theory 183
- 4.17** Summary 186
Problems 187
- Chapter 5**
Quasi-One-Dimensional Flow 191
- 5.1** Introduction 195
- 5.2** Governing Equations 196
- 5.3** Area-Velocity Relation 199
- 5.4** Nozzles 202
- 5.5** Diffusers 218
- 5.6** Wave Reflection from a Free Boundary 226
- 5.7** Summary 228
- 5.8** Historical Note: de Laval—A Biographical Sketch 228
- 5.9** Historical Note: Stodola, and the First Definitive Supersonic Nozzle Experiments 230
- 5.10** Summary 232
Problems 234

Chapter 6
Differential Conservation Equations for Inviscid Flows 239

- 6.1** Introduction 241
- 6.2** Differential Equations in Conservation Form 242
- 6.3** The Substantial Derivative 244
- 6.4** Differential Equations in Nonconservation Form 247

- 6.5** The Entropy Equation 253
- 6.6** Crocco’s Theorem: A Relation between the Thermodynamics and Fluid Kinematics of a Compressible Flow 254
- 6.7** Historical Note: Early Development of the Conservation Equations 256
- 6.8** Historical Note: Leonhard Euler—The Man 258
- 6.9** Summary 260

Chapter 7
Unsteady Wave Motion 261

- 7.1** Introduction 263
- 7.2** Moving Normal Shock Waves 266
- 7.3** Reflected Shock Wave 273
- 7.4** Physical Picture of Wave Propagation 277
- 7.5** Elements of Acoustic Theory 279
- 7.6** Finite (Nonlinear) Waves 285
- 7.7** Incident and Reflected Expansion Waves 291
- 7.8** Shock Tube Relations 297
- 7.9** Finite Compression Waves 298
- 7.10** Summary 300
Problems 300

Chapter 8
General Conservation Equations Revisited: Velocity Potential Equation 303

- 8.1** Introduction 304
- 8.2** Irrotational Flow 304
- 8.3** The Velocity Potential Equation 308
- 8.4** Historical Note: Origin of the Concepts of Fluid Rotation and Velocity Potential 312

Chapter 9
Linearized Flow 315

- 9.1** Introduction 317
- 9.2** Linearized Velocity Potential Equation 318
- 9.3** Linearized Pressure Coefficient 322

- 9.4** Linearized Subsonic Flow 324
- 9.5** Improved Compressibility Corrections 333
- 9.6** Linearized Supersonic Flow 335
- 9.7** Critical Mach Number 342
- 9.8** Summary 348
- 9.9** Historical Note: The 1935 Volta Conference—Threshold to Modern Compressible Flow; with Associated Events Before and After 349
- 9.10** Historical Note: Prandtl—A Biographical Sketch 354
- 9.11** Historical Note: Glauert—A Biographical Sketch 357
- 9.12** Summary 358
Problems 360

Chapter 10
Conical Flow 363

- 10.1** Introduction 364
- 10.2** Physical Aspects of Conical Flow 366
- 10.3** Quantitative Formulation (after Taylor and Maccoll) 366
- 10.4** Numerical Procedure 371
- 10.5** Physical Aspects of Supersonic Flow over Cones 372
Problems 375

Chapter 11
Numerical Techniques for Steady Supersonic Flow 377

- 11.1** An Introduction to Computational Fluid Dynamics 380
- 11.2** Philosophy of the Method of Characteristics 383
- 11.3** Determination of the Characteristic Lines: Two-Dimensional Irrotational Flow 386
- 11.4** Determination of the Compatibility Equations 391
- 11.5** Unit Processes 392

- 11.6** Regions of Influence and Domains of Dependence 396
- 11.7** Supersonic Nozzle Design 397
- 11.8** Method of Characteristics for Axisymmetric Irrotational Flow 403
- 11.9** Method of Characteristics for Rotational (Nonisentropic and Nonadiabatic) Flow 407
- 11.10** Three-Dimensional Method of Characteristics 409
- 11.11** Introduction to Finite Differences 411
- 11.12** MacCormack’s Technique 417
- 11.13** Boundary Conditions 418
- 11.14** Stability Criterion: The CFL Criterion 420
- 11.15** Shock Capturing versus Shock Fitting; Conservation versus Nonconservation Forms of the Equations 422
- 11.16** Comparison of Characteristics and Finite-Difference Solutions with Application to the Space Shuttle 423
- 11.17** Historical Note: The First Practical Application of the Method of Characteristics to Supersonic Flow 426
- 11.18** Summary 428
Problems 429

Chapter 12
The Time-Marching Technique: With Application to Supersonic Blunt Bodies and Nozzles 431

- 12.1** Introduction to the Philosophy of Time-Marching Solutions for Steady Flows 434
- 12.2** Stability Criterion 440
- 12.3** The Blunt Body Problem—Qualitative Aspects and Limiting Characteristics 441
- 12.4** Newtonian Theory 443
- 12.5** Time-Marching Solution of the Blunt Body Problem 445
- 12.6** Results for the Blunt Body Flowfield 450

- 12.7** Time-Marching Solution of Two-Dimensional Nozzle Flows 453
- 12.8** Other Aspects of the Time-Marching Technique; Artificial Viscosity 455
- 12.9** Historical Note: Newton's Sine-Squared Law—Some Further Comments 458
- 12.10** Summary 460
Problems 461

Chapter 13

Three-Dimensional Flow 463

- 13.1** Introduction 464
- 13.2** Cones at Angle of Attack: Qualitative Aspects 466
- 13.3** Cones at Angle of Attack: Quantitative Aspects 474
- 13.4** Blunt-Nosed Bodies at Angle of Attack 484
- 13.5** Stagnation and Maximum Entropy Streamlines 494
- 13.6** Comments and Summary 495

Chapter 14

Transonic Flow 497

- 14.1** Introduction 500
- 14.2** Some Physical Aspects of Transonic Flows 501
- 14.3** Some Theoretical Aspects of Transonic Flows; Transonic Similarity 505
- 14.4** Solutions of the Small-Perturbation Velocity Potential Equation: The Murman and Cole Method 510
- 14.5** Solutions of the Full Velocity Potential Equation 516
- 14.6** Solutions of the Euler Equations 525
- 14.7** Historical Note: Transonic Flight—Its Evolution, Challenges, Failures, and Successes 532
- 14.8** Summary and Comments 544

Chapter 15

Hypersonic Flow 547

- 15.1** Introduction 549
- 15.2** Hypersonic Flow—What Is It? 550
- 15.3** Hypersonic Shock Wave Relations 555
- 15.4** A Local Surface Inclination Method: Newtonian Theory 559
- 15.5** Mach Number Independence 565
- 15.6** The Hypersonic Small-Disturbance Equations 570
- 15.7** Hypersonic Similarity 574
- 15.8** Computational Fluid Dynamics Applied to Hypersonic Flow; Some Comments 581
- 15.9** Summary and Final Comments 583

Chapter 16

Properties of High-Temperature Gases 585

- 16.1** Introduction 587
- 16.2** Microscopic Description of Gases 590
- 16.3** Counting the Number of Microstates for a Given Macrostate 598
- 16.4** The Most Probable Macrostate 600
- 16.5** The Limiting Case: Boltzmann Distribution 602
- 16.6** Evaluation of Thermodynamic Properties in Terms of the Partition Function 604
- 16.7** Evaluation of the Partition Function in Terms of T and V 606
- 16.8** Practical Evaluation of Thermodynamic Properties for a Single Species 610
- 16.9** The Equilibrium Constant 614
- 16.10** Chemical Equilibrium—Qualitative Discussion 618
- 16.11** Practical Calculation of the Equilibrium Composition 619
- 16.12** Equilibrium Gas Mixture Thermodynamic Properties 621

- 16.13** Introduction to Nonequilibrium Systems 628
- 16.14** Vibrational Rate Equation 629
- 16.15** Chemical Rate Equations 635
- 16.16** Chemical Nonequilibrium in High-Temperature Air 639
- 16.17** Summary of Chemical Nonequilibrium 641
- 16.18** Chapter Summary 641
Problems 643

Chapter 17

High-Temperature Flows: Basic Examples 645

- 17.1** Introduction to Local Thermodynamic and Chemical Equilibrium 647
- 17.2** Equilibrium Normal Shock Wave Flows 648
- 17.3** Equilibrium Quasi-One-Dimensional Nozzle Flows 653
- 17.4** Frozen and Equilibrium Flows: Specific Heats 659
- 17.5** Equilibrium Speed of Sound 664
- 17.6** On the Use of $\gamma = c_p/c_v$ 668
- 17.7** Nonequilibrium Flows: Species Continuity Equation 669
- 17.8** Rate Equation for Vibrationally Nonequilibrium Flow 672
- 17.9** Summary of Governing Equations for Nonequilibrium Flows 672
- 17.10** Nonequilibrium Normal Shock Wave Flows 674

- 17.11** Nonequilibrium Quasi-One-Dimensional Nozzle Flows 680
- 17.12** Summary 688
Problems 689

Appendix A

- Table A.1** Isentropic Flow Properties 691
- Table A.2** Normal Shock Properties 696
- Table A.3** One-Dimensional Flow with Heat Addition 700
- Table A.4** One-Dimensional Flow with Friction 705
- Table A.5** Prandtl–Meyer Function and Mach Angle 710

Appendix B

An Illustration and Exercise of Computational Fluid Dynamics 712

- The Equations 712
- Intermediate Numerical Results:
The First Few Steps 725
- Final Numerical Results:
The Steady-State Solution 730
- Summary 741
- Isentropic Nozzle Flow—Subsonic/Supersonic (Nonconservation Form) 741

References 745

Index 751