INTRODUCTION TO UNSTEADY THERMOFLUID MECHANICS

Frederick J. Moody
General Electric Company
San Jose, California
and
Mechanical Engineering Department
San Jose State University
San Jose, California

WILEY
A WILEY-INTERSCIENCE PUBLICATION
JOHN WILEY & SONS
New York • Chichester • Brisbane • Toronto • Singapore
CONTENTS

PREFACE xiii

1 FOUNDATIONS OF UNSTEADY THERMOFLUID MECHANICS 1

1.1 Propagative and Bulk Flows, 1
1.2 Quasi-Equilibrium States, 4
1.3 Property Flows and Storage Rates, 8
1.4 Mass Conservation, 10
1.5 Liquid Filling and Draining of Containers, 11
1.6 Momentum Creation, 17
1.7 Surface Forces, 19
1.8 Body Forces, 20
1.9 Accelerating Flow in a Pipe, Stationary CV, 21
1.10 Liquid Expulsion from a Uniform Pipe, Distorting CV, 23
1.11 Liquid Impact, Moving CV, 28
1.12 Energy Conservation, 30
1.13 Missile Propulsion from a Tube, 34

References, 36
Problems, 37

2 UNSTEADY THERMODYNAMICS 51

2.1 Systems, 51
2.2 Properties, 52
2.3 Equilibrium Response Time, 54
2.4 Stability, 55
2.5 Transport Properties, 56
2.6 State Equations, Simple Compressible Substance (SCS), 59
2.7 Entropy, 59
2.8 The Second Law, 63
2.9 Dissipation without Friction, 64
2.10 Most Stable Dynamic Properties from Second Law, 68
2.11 Speed of Small Pressure Disturbances, 70
2.12 Sound Speed, Bubbly, Saturated Liquid-Vapor Mixtures, 72
2.13 Critical Flow, 76
2.14 Simultaneous Charging and Discharging of a Vessel, 87
2.15 Pressure Vessel Blowdown, 89
2.16 Vessel Charging, 96
2.17 Charging and Discharging Perfect Gas, 98
2.18 Charging and Discharging Saturated Mixture, 101
2.19 Vaporization and Condensation, 102
2.20 Hot Bubble Response in Saturated Liquid, 104
2.21 Useful Thermodynamic Relationships, 108
References, 110
Problems, 111

3 CONVECTIVE PROPAGATION
3.1 Incompressible, One-Dimensional Fluid Jets, 123
3.2 One-Dimensional Jets, Basic Formulation, 124
3.3 Unsteady Fluid Jet Solution, 126
3.4 Fluid Jet Shocking, 128
3.5 Steady Jet Properties, 129
3.6 Liquid Jet, Step-Ramp Discharge, 130
3.7 Submerged Liquid Jet, Step-Ramp Discharge, 132
3.8 Vertical Liquid Jets in Gas, 135
3.9 Comparison with Rigorous Two-Dimensional Calculation, 136
3.10 Heated Liquid Flows in Pipes, Basic Formulation, 140
3.11 Path Integral Solution, 142
3.12 Cases for Pipes with Negligible Thermal Capacity, 144
3.13 Thin-Walled Pipe, Thermal Capacity Important, 149
3.14 Coupled Fluid and Pipe Wall Temperatures, 150
3.15 Finite Difference Solution of Coupled Equations, 151
3.16 Solution by Laplace Transformation, 154
3.17 Eigenvalue Solution for Thick-Walled Pipes, 155
References, 164
Problems, 164

4 HYDROSTATIC WAVES, SMALL-AMPLITUDE APPLICATIONS
4.1 One-Dimensional Hydrostatic Waves, 175
4.2 Small-Amplitude Linearization, 179
4.3 Uniform Channels and Surface Pressure, 179
4.4 Meaning of the General Solutions, 181
4.5 The General Solution in Its Crudest Form, 184
4.6 Refined Solution, Initial and Boundary Conditions, 189
4.7 Outward Propagation Only, 205
4.8 Energy of a Wave in a Uniform Channel, 207
4.9 Wave Transmission at a Channel Discontinuity, 210
4.10 Other Methods for Solving Small-Amplitude Wave Flows, 215
4.11 Subcritical, Critical, and Supercritical Flows, 215
4.12 Variable Channel Width, 219
6.15 Unsteady Steam Discharge from a Pipe, 336
6.16 Relief Tank Pressurization, 340
6.17 Scale-Modeling Coupled Systems, 346
References, 347
Problems, 347

7 ONE-DIMENSIONAL BULK AND WATERHAMMER FLOWS

7.1 Restrictions for Bulk Flow, 358
7.2 Bulk Flow Formulation, 359
7.3 Incompressible Accelerating Flows, 360
7.4 Pipe Reaction Forces, 365
7.5 Boundary Conditions, 367
7.6 Restrictions for Waterhammer Flows, 373
7.7 Waterhammer Formulation, 373
7.8 General Solutions, Uniform, Frictionless Pipes, 374
7.9 Approximate Waterhammer Solutions, 386
7.10 Disturbance Arrival at Discontinuity, 391
7.11 Orifice Effects, 394
7.12 Orifice in Pipe End Wall, 395
7.13 Gas Cushion Boundary, 396
7.14 Spring-Mass Boundary, 398
7.15 Frictional Attenuation, 400
7.16 Continuous Area Variation, 401
7.17 Waterhammer Force at Pipe Area Change, 402
7.18 Column Separation, 404
7.19 Swing Check Valve, 406
7.20 Ideal Pipe Branch Boundary, 407
7.21 Waterhammer Solutions by the Method of Characteristics, 408
7.22 Characteristic Boundary Equations, 413
7.23 Synthesis of Piping Systems for Waterhammer Solution, 417
References, 422
Problems, 423

8 ONE-DIMENSIONAL LARGE-AMPLITUDE PRESSURE WAVES

8.1 Uniform Pipes, Simple Wave Propagation, 431
8.2 Accelerating Piston Withdrawal, Simple Waves, 434
8.3 Piston Acceleration into Gas, Simple Waves, 437
8.4 Sudden Pipe Rupture and Discharge, 440
8.5 Disturbance Signal Distortion, 441
8.6 Solution by the Method of Characteristics (MOC), 444
8.7 Appropriate Boundary Conditions, 449
8.8 Unsteady Blowdown from Gas-Filled Pipes, 451
8.9 Moving Normal Shocks, General Fluid, 454
8.10 Moving Shocks in a Perfect Gas, 456
8.11 Characteristics and Approximate Shocks, 458
8.12 Comparison with Pressure Data, 461
8.13 Forces from Instantaneous Pipe Rupture, 464
8.14 Pipe Forces from Safety Valve Charging, 471
8.15 Gas Pressure Relief, Slow Valve Opening, 473
8.16 Gas Pressure Relief, Rapid Valve Opening, 476
8.17 Sudden Liquid-Vapor Discharge into a Gas-Filled Pipe, 480
8.18 Moving Shocks in a Gas-Liquid Mixture, 490
References, 493
Problems, 494

9 MULTIDIMENSIONAL INCOMPRESSIBLE BULK AND WATERHAMMER FLOWS

9.1 Incompressible Bulk Flow Formulation, 500
9.2 Ideal Flow Approximation, 501
9.3 The Velocity Potential, 503
9.4 Ideal Fluid Formulations, 504
9.5 The Rayleigh Bubble, 509
9.6 Constant Pressure Bubble Response, 510
9.7 Small-Amplitude Bubble Oscillation, 512
9.8 Large-Amplitude Bubble Oscillation, 513
9.9 Surface Tension Effects, 515
9.10 Flat Wall Simulation near a Bubble, 517
9.11 Other Geometries by Superposition, 521
9.12 Submerged Sparger Discharge, 524
9.13 Small-Amplitude Liquid Sloshing, 526
9.14 Large-Amplitude Liquid Motion, 532
9.15 Other Large-Amplitude Methods, 537
9.16 Interface Stability, 537
9.17 Acceleration of Submerged Structures, 544
9.18 Virtual Mass, 546
9.19 Waterhammer Formulation, 549
9.20 Spherical Waterhammer Propagation, 551
9.21 Cylindrical Waterhammer Propagation, 558
9.22 Superposition of Waterhammer Flow Patterns, 562
9.23 Spherical Waterhammer Source near a Flat Wall, 562
9.24 Spherical Source and Parallel Flat Walls, 564
9.25 Superposition of Cylindrical Sources, 566
9.26 Pressure Force on Structural Surfaces, 566
References, 570
Problems, 571
10 MISCELLANEOUS TOPICS IN UNSTEADY THERMOFLUID MECHANICS

10.1 The Momentum Equation for Moving Reference Frames, 586
10.2 Thermal Damping in Bubbly Mixtures, 590
10.3 One-Dimensional Bubbly Mixture Response, 594
10.4 Acoustic Penetration, 595
10.5 Ringout Damping, 598
10.6 Fluid Structure Interaction (FSI), 599
10.7 Plane Wave Arrival at a Submerged Structure, 604
10.8 Fluid-Structure Interaction Normalization, 606
10.9 The Method of Lagrangian Mechanics, 613

References, 622
Problems, 623

APPENDIX A

A.1 Unit Conversion Factors, 633
A.2 Approximate Propagation Speeds, 634
A.3 Selected Transport Properties, 1.0 ATM, 636

APPENDIX B

Fig. B.1 Pipe Friction Factor, 637

APPENDIX C

C.1 Second-Order Runge-Kutta Solution Method for Second-Order Differential Equations, 638
C.2 Regular Perturbation Solution of Differential Equations with a Small Parameter or Small Disturbance, 639
C.3 Vector Differentiation in Different Reference Frames, 641

Nomenclature

Index