contents

1 Fundamental Considerations 1
1.1 Introduction 1
1.2 Definitions in thermodynamics 2
1.3 Units and dimensions 3
1.4 Laws of thermodynamics 5
1.5 Properties of fluids 8
1.6 Viscosity 11
1.7 Dimensional analysis and the Buckingham pi theorem 14
1.8 Fluid friction 17
1.9 Laminar flow 19
1.10 Turbulent flow 20
1.11 Configuration and drag losses 21

2 Conservation Laws in Fluid Flow 24
2.1 Introduction 24
2.2 Conservation of mass; continuity equation 25
2.3 Conservation of energy (first law of thermodynamics); steady flow energy equation 27
2.4 Momentum equation 31
2.5 Entropy changes in fluid flow 35
2.6 Stagnation states 37

3 Wave Motion, Mach Number 42
3.1 Pressure waves and sonic velocity 42
3.2 Acoustic waves 45
3.3 Finite waves 49
3.4 Mach number 52
3.5 One-dimensional steady flow equations in terms of Mach number 55

4 Force Balance and Thrust 60
4.1 Introduction 60
4.2 Calculation of propulsive forces 61
4.3 External thrust and drag 65
4.4 Special considerations of rocket thrust 67
4.5 Thrust as a pressure integral 69
4.6 The thrust function 70

5 Adiabatic Flow 74
5.1 Introduction 74
5.2 Fluid properties in adiabatic flow 75
5.3 Effects of area variation 79
5.4 Reference states 82
5.5 Tables for isentropic flow 85
5.6 Mass flow and choking in isentropic flow 88
5.7 Thrust in isentropic flow 94
5.8 Losses in adiabatic flow 95

6 Adiabatic Flow in Constant-Area Ducts 103
6.1 Introduction—Fanno lines 103
6.2 Fanno relations for perfect gases 106
6.3 The nature of the loss 108
6.4 Reference states 111
6.5 Fanno tables 112
6.6 Choking resulting from friction or drag 113

7 Normal Shock 116
7.1 Occurrence of shocks 116
7.2 Fundamental equations for normal shock 117
7.3 Normal shock equations for a perfect gas 118
7.4 Tables for normal shock 120
7.5 Impossibility of shock from subsonic to supersonic flow 121
7.6 Shock strength 123
7.7 Shocks in a converging-diverging nozzle 124

8 Flow with Heating or Cooling 131
8.1 Introduction to heat-exchange systems 131
8.2 Fundamental equations for simple heating or simple cooling—the Rayleigh line 132
8.3 Rayleigh equations for a perfect gas 136
8.4 Reference state and Rayleigh tables 138
8.5 Isothermal flows in long ducts 139
8.6 Heating or cooling with friction 142

9 Moving and Oblique Shock Waves 146
9.1 Introduction 146
9.2 Propagating normal shock waves 147
9.3 Oblique shocks 150
9.4 The deflection angle 153
9.5 Mach lines 155
9.6 Compression by turning in supersonic flow 156
9.7 Prandtl-Meyer expansions 157

10 Method of Characteristics 163
10.1 Natural coordinate system 163
10.2 Equations of motion for isentropic (irrotational) flow 166
10.3 Characteristics 167
10.4 Dependence and influence—networks for flow types 170
10.5 Calculation procedures 172
10.6 Example of computation with method of characteristics 175
10.7 The design of supersonic nozzles 176
10.8 Weak waves as characteristics—field method 177

11 Generalized One-Dimensional Gas Dynamics 181
11.1 Introduction 181
11.2 The generalized flow equation 182
11.3 The reference state and the generalized compressible flow function 183
11.4 Application of generalized compressible flow function to specific processes 187

Appendix 195

Index 269