



FUNDAMENTALS OF  
**GAS  
DYNAMICS**

SECOND EDITION

**ROBERT D. ZUCKER      OSCAR BIBLARZ**

# *Contents*

<b>PREFACE</b>	<b>xi</b>
<b>TO THE STUDENT</b>	<b>xiii</b>
<b>1 REVIEW OF ELEMENTARY PRINCIPLES</b>	<b>1</b>
1.1 Introduction	1
1.2 Units and Notation	1
1.3 Some Mathematical Concepts	7
1.4 Thermodynamic Concepts for Control Mass Analysis	10
Review Questions	18
Review Problems	20
<b>2 CONTROL VOLUME ANALYSIS—PART I</b>	<b>23</b>
2.1 Introduction	23
2.2 Objectives	23
2.3 Flow Dimensionality and Average Velocity	24
2.4 Transformation of a Material Derivative to a Control Volume Approach	27
2.5 Conservation of Mass	32
2.6 Conservation of Energy	35
2.7 Summary	44
Problems	46
Check Test	48
<b>3 CONTROL VOLUME ANALYSIS—PART II</b>	<b>51</b>
3.1 Introduction	51

**vi** CONTENTS

3.2	Objectives	51
3.3	Comments on Entropy	52
3.4	Pressure–Energy Equation	54
3.5	The Stagnation Concept	55
3.6	Stagnation Pressure–Energy Equation	59
3.7	Consequences of Constant Density	61
3.8	Momentum Equation	66
3.9	Summary	75
	Problems	77
	Check Test	81
<b>4</b>	<b>INTRODUCTION TO COMPRESSIBLE FLOW</b>	<b>83</b>
4.1	Introduction	83
4.2	Objectives	83
4.3	Sonic Velocity and Mach Number	84
4.4	Wave Propagation	89
4.5	Equations for Perfect Gases in Terms of Mach Number	92
4.6	<i>h</i> – <i>s</i> and <i>T</i> – <i>s</i> Diagrams	97
4.7	Summary	99
	Problems	100
	Check Test	102
<b>5</b>	<b>VARYING-AREA ADIABATIC FLOW</b>	<b>105</b>
5.1	Introduction	105
5.2	Objectives	105
5.3	General Fluid—No Losses	106
5.4	Perfect Gases with Losses	111
5.5	The * Reference Concept	115
5.6	Isentropic Table	118
5.7	Nozzle Operation	124
5.8	Nozzle Performance	131
5.9	Diffuser Performance	133
5.10	When $\gamma$ Is Not Equal to 1.4	135
5.11	(Optional) Beyond the Tables	135
5.12	Summary	138
	Problems	139
	Check Test	144

<b>6 STANDING NORMAL SHOCKS</b>	<b>147</b>
6.1 Introduction	147
6.2 Objectives	147
6.3 Shock Analysis—General Fluid	148
6.4 Working Equations for Perfect Gases	151
6.5 Normal-Shock Table	154
6.6 Shocks in Nozzles	159
6.7 Supersonic Wind Tunnel Operation	164
6.8 When $\gamma$ Is Not Equal to 1.4	166
6.9 (Optional) Beyond the Tables	168
6.10 Summary	169
Problems	170
Check Test	174
<b>7 MOVING AND OBLIQUE SHOCKS</b>	<b>175</b>
7.1 Introduction	175
7.2 Objectives	175
7.3 Normal Velocity Superposition: Moving Normal Shocks	176
7.4 Tangential Velocity Superposition: Oblique Shocks	179
7.5 Oblique-Shock Analysis: Perfect Gas	185
7.6 Oblique-Shock Table and Charts	187
7.7 Boundary Condition of Flow Direction	189
7.8 Boundary Condition of Pressure Equilibrium	193
7.9 Conical Shocks	195
7.10 (Optional) Beyond the Tables	198
7.11 Summary	200
Problems	201
Check Test	205
<b>8 PRANDTL-MEYER FLOW</b>	<b>207</b>
8.1 Introduction	207
8.2 Objectives	207
8.3 Argument for Isentropic Turning Flow	208
8.4 Analysis of Prandtl-Meyer Flow	214
8.5 Prandtl-Meyer Function	218
8.6 Overexpanded and Underexpanded Nozzles	221
8.7 Supersonic Airfoils	226

8.8	When $\gamma$ Is Not Equal to 1.4	230
8.9	(Optional) Beyond the Tables	231
8.10	Summary	232
	Problems	233
	Check Test	238
<b>9</b>	<b>FANNO FLOW</b>	<b>241</b>
9.1	Introduction	241
9.2	Objectives	241
9.3	Analysis for a General Fluid	242
9.4	Working Equations for Perfect Gases	248
9.5	Reference State and Fanno Table	253
9.6	Applications	257
9.7	Correlation with Shocks	261
9.8	Friction Choking	264
9.9	When $\gamma$ Is Not Equal to 1.4	267
9.10	(Optional) Beyond the Tables	268
9.11	Summary	269
	Problems	270
	Check Test	274
<b>10</b>	<b>RAYLEIGH FLOW</b>	<b>277</b>
10.1	Introduction	277
10.2	Objectives	278
10.3	Analysis for a General Fluid	278
10.4	Working Equations for Perfect Gases	288
10.5	Reference State and the Rayleigh Table	293
10.6	Applications	295
10.7	Correlation with Shocks	298
10.8	Thermal Choking due to Heating	302
10.9	When $\gamma$ Is Not Equal to 1.4	305
10.10	(Optional) Beyond the Tables	306
10.11	Summary	307
	Problems	308
	Check Test	313
<b>11</b>	<b>REAL GAS EFFECTS</b>	<b>315</b>
11.1	Introduction	315
11.2	Objectives	316

11.3	What's Really Going On	317
11.4	Semiperfect Gas Behavior, Development of the Gas Table	319
11.5	Real Gas Behavior, Equations of State and Compressibility Factors	325
11.6	Variable $\gamma$ —Variable-Area Flows	329
11.7	Variable $\gamma$ —Constant-Area Flows	336
11.8	Summary	338
	Problems	340
	Check Test	341
<b>12</b>	<b>PROPULSION SYSTEMS</b>	<b>343</b>
12.1	Introduction	343
12.2	Objectives	343
12.3	Brayton Cycle	344
12.4	Propulsion Engines	353
12.5	General Performance Parameters, Thrust, Power, and Efficiency	369
12.6	Air-Breathing Propulsion Systems Performance Parameters	375
12.7	Air-Breathing Propulsion Systems Incorporating Real Gas Effects	380
12.8	Rocket Propulsion Systems Performance Parameters	381
12.9	Supersonic Diffusers	384
12.10	Summary	387
	Problems	388
	Check Test	392

## APPENDIXES

A.	Summary of the English Engineering (EE) System of Units	396
B.	Summary of the International System (SI) of Units	400
C.	Friction-Factor Chart	404
D.	Oblique-Shock Charts ( $\gamma = 1.4$ ) (Two-Dimensional)	406
E.	Conical-Shock Charts ( $\gamma = 1.4$ ) (Three-Dimensional)	410
F.	Generalized Compressibility Factor Chart	414
G.	Isentropic Flow Parameters ( $\gamma = 1.4$ ) (including Prandtl-Meyer Function)	416
H.	Normal-Shock Parameters ( $\gamma = 1.4$ )	428
I.	Fanno Flow Parameters ( $\gamma = 1.4$ )	438