

3-3-1

2-533-3-1



ELEMENTS OF GASDYNAMICS

BY
H. W. LIEPMANN
A. ROSHKO
California Institute of Technology

GALCIT AERONAUTICAL SERIES

JOHN WILEY & SONS, INC.
New York • Chichester • Brisbane • Toronto • Singapore

Contents

CHAPTER 1. CONCEPTS FROM THERMODYNAMICS

1.1	INTRODUCTION	1
1.2	THERMODYNAMIC SYSTEMS	2
1.3	VARIABLES OF STATE	3
1.4	THE FIRST PRINCIPAL LAW	4
1.5	IRREVERSIBLE AND REVERSIBLE PROCESSES	6
1.6	PERFECT GASES	7
1.7	THE FIRST LAW APPLIED TO REVERSIBLE PROCESSES. SPECIFIC HEATS	10
1.8	THE FIRST LAW APPLIED TO IRREVERSIBLE PROCESSES	14
1.9	THE CONCEPT OF ENTROPY. THE SECOND LAW	17
1.10	THE CANONICAL EQUATION OF STATE. FREE ENERGY AND FREE ENTHALPY	20
1.11	RECIPROCITY RELATIONS	22
1.12	ENTROPY AND TRANSPORT PROCESSES	23
1.13*	EQUILIBRIUM CONDITIONS	24
1.14*	MIXTURES OF PERFECT GASES	25
1.15*	THE LAW OF MASS ACTION	27
1.16*	DISSOCIATION	29
1.17*	CONDENSATION	33
1.18	REAL GASES IN GASDYNAMICS	34

CHAPTER 2. ONE-DIMENSIONAL GASDYNAMICS

2.1	INTRODUCTION	39
2.2	THE CONTINUITY EQUATION	40
2.3	THE ENERGY EQUATION	41
2.4	RESERVOIR CONDITIONS	43
2.5	EULER'S EQUATION	45
2.6	THE MOMENTUM EQUATION	47
2.7	ISENTROPIC CONDITIONS	49
2.8	SPEED OF SOUND; MACH NUMBER	50
2.9	THE AREA-VELOCITY RELATION	51
2.10	RESULTS FROM THE ENERGY EQUATION	53
2.11	BERNOULLI EQUATION; DYNAMIC PRESSURE	55
2.12	FLOW AT CONSTANT AREA	56
2.13	THE NORMAL SHOCK RELATIONS FOR A PERFECT GAS	57

CHAPTER 3. ONE-DIMENSIONAL WAVE MOTION

3.1	INTRODUCTION	62
3.2	THE PROPAGATING SHOCK WAVE	62
3.3	ONE-DIMENSIONAL ISENTROPIC EQUATIONS	65

3.4	THE ACOUSTIC EQUATIONS	67
3.5	PROPAGATION OF ACOUSTIC WAVES	68
3.6	THE SPEED OF SOUND	69
3.7	PRESSURE AND PARTICLE VELOCITY IN A SOUND WAVE	71
3.8	"LINEARIZED" SHOCK TUBE	72
3.9	ISENTROPIC WAVES OF FINITE AMPLITUDE	74
3.10	PROPAGATION OF FINITE WAVES	76
3.11	CENTERED EXPANSION WAVE	78
3.12	THE SHOCK TUBE	79

CHAPTER 4. WAVES IN SUPERSONIC FLOW

4.1	INTRODUCTION	84
4.2	OBLIQUE SHOCK WAVES	85
4.3	RELATION BETWEEN β AND θ	86
4.4	SUPERSONIC FLOW OVER A WEDGE	88
4.5	MACH LINES	89
4.6	PISTON ANALOGY	91
4.7	WEAK OBLIQUE SHOCKS	92
4.8	SUPERSONIC COMPRESSION BY TURNING	93
4.9	SUPERSONIC EXPANSION BY TURNING	97
4.10	THE PRANDTL-MEYER FUNCTION	98
4.11	SIMPLE AND NONSIMPLE REGIONS	100
4.12	REFLECTION AND INTERSECTION OF OBLIQUE SHOCKS	101
4.13	INTERSECTION OF SHOCKS OF THE SAME FAMILY	102
4.14	DETACHED SHOCKS	103
4.15	MACH REFLECTION	106
4.16	SHOCK-EXPANSION THEORY	107
4.17	THIN AIRFOIL THEORY	109
4.18*	FLAT LIFTING WINGS	113
4.19*	DRAG REDUCTION	115
4.20*	THE HODOGRAPH PLANE	118
4.21	CONE IN SUPERSONIC FLOW	120

CHAPTER 5. FLOW IN DUCTS AND WIND TUNNELS

5.1	INTRODUCTION	124
5.2	FLOW IN CHANNEL OF VARYING AREA	124
5.3	AREA RELATIONS	125
5.4	NOZZLE FLOW	127
5.5	NORMAL SHOCK RECOVERY	130
5.6	EFFECTS OF SECOND THROAT	131
5.7	ACTUAL PERFORMANCE OF WIND TUNNEL DIFFUSERS	133
5.8	WIND TUNNEL PRESSURE RATIO	133
5.9	SUPERSONIC WIND TUNNELS	136
5.10	WIND TUNNEL CHARACTERISTICS	137
5.11	COMPRESSOR MATCHING	139
5.12	OTHER WIND TUNNELS AND TESTING METHODS	142

CHAPTER 6. METHODS OF MEASUREMENT

6.1	INTRODUCTION	144
-----	--------------	-----

CONTENTS

xiii

6.2	STATIC PRESSURE	144
6.3	TOTAL PRESSURE	147
6.4	MACH NUMBER FROM PRESSURE MEASUREMENTS	148
6.5	WEDGE AND CONE MEASUREMENTS	149
6.6	VELOCITY	150
6.7	TEMPERATURE AND HEAT TRANSFER MEASUREMENTS	151
6.8	DENSITY MEASUREMENTS	153
6.9	INDEX OF REFRACTION	153
6.10	SCHLIEREN SYSTEM	157
6.11	THE KNIFE EDGE	159
6.12	SOME PRACTICAL CONSIDERATIONS	161
6.13	THE SHADOW METHOD	162
6.14	INTERFERENCE METHOD	164
6.15	MACH-ZEHNDER INTERFEROMETER	165
6.16	INTERFEROMETER TECHNIQUES	168
6.17	X-RAY ABSORPTION AND OTHER METHODS	170
6.18	DIRECT MEASUREMENT OF SKIN FRICTION	171
6.19	HOT-WIRE PROBE	172
6.20	SHOCK TUBE INSTRUMENTATION	177

CHAPTER 7. THE EQUATIONS OF FRICTIONLESS FLOW

7.1	INTRODUCTION	178
7.2	NOTATION	178
7.3	THE EQUATION OF CONTINUITY	180
7.4	THE MOMENTUM EQUATION	182
7.5	THE ENERGY EQUATION	185
7.6	THE EULERIAN DERIVATIVE	186
7.7	SPLITTING THE ENERGY EQUATION	188
7.8	THE TOTAL ENTHALPY	190
7.9	NATURAL COORDINATES. CROCCO'S THEOREM	191
7.10	RELATION OF VORTICITY TO CIRCULATION AND ROTATION	194
7.11	THE VELOCITY POTENTIAL	196
7.12	IRROTATIONAL FLOW	197
7.13	REMARKS ON THE EQUATIONS OF MOTION	200

CHAPTER 8. SMALL-PERTURBATION THEORY

8.1	INTRODUCTION	202
8.2	DERIVATION OF THE PERTURBATION EQUATIONS	203
8.3	PRESSURE COEFFICIENT	206
8.4	BOUNDARY CONDITIONS	206
8.5	TWO-DIMENSIONAL FLOW PAST A WAVE-SHAPED WALL	208
8.6	WAVY WALL IN SUPERSONIC FLOW	212
8.7	SUPERSONIC THIN AIRFOIL THEORY	215
8.8	PLANAR FLOWS	216

CHAPTER 9. BODIES OF REVOLUTION. SLENDER BODY THEORY

9.1	INTRODUCTION	218
9.2	CYLINDRICAL COORDINATES	219
9.3	BOUNDARY CONDITIONS	221

9.4	PRESSURE COEFFICIENT	224
9.5	AXIALLY SYMMETRIC FLOW	224
9.6	SUBSONIC FLOW	226
9.7	SUPERSONIC FLOW	226
9.8	VELOCITIES IN THE SUPERSONIC FIELD	229
9.9	SOLUTION FOR A CONE	230
9.10	OTHER MERIDIAN SHAPES	232
9.11	SOLUTION FOR SLENDER CONE	233
9.12	SLENDER BODY DRAG	235
9.13*	YAWED BODY OF REVOLUTION IN SUPERSONIC FLOW	239
9.14*	CROSS-FLOW BOUNDARY CONDITIONS	241
9.15*	CROSS-FLOW SOLUTIONS	242
9.16	CROSS FLOW FOR SLENDER BODIES OF REVOLUTION	242
9.17	LIFT OF SLENDER BODIES OF REVOLUTION	243
9.18	SLENDER BODY THEORY	246
9.19*	RAYLEIGH'S FORMULA	247

CHAPTER 10. THE SIMILARITY RULES OF HIGH-SPEED FLOW

10.1	INTRODUCTION	252
10.2	TWO-DIMENSIONAL LINEARIZED FLOW. PRANDTL-GLAUERT AND GÖTHERT RULES	253
10.3	TWO-DIMENSIONAL TRANSONIC FLOW. VON KÁRMÁN'S RULES	256
10.4	LINEARIZED AXIALLY SYMMETRIC FLOW	258
10.5	PLANAR FLOW	260
10.6	SUMMARY AND APPLICATION OF THE SIMILARITY LAWS	262
10.7	HIGH MACH NUMBERS. HYPERSONIC SIMILARITY	263

CHAPTER 11. TRANSONIC FLOW

11.1	INTRODUCTION	270
11.2	DEFINITION OF THE TRANSONIC RANGE	270
11.3	TRANSONIC FLOW PAST WEDGE SECTIONS	271
11.4	TRANSONIC FLOW PAST A CONE	276
11.5	TRANSONIC FLOW PAST SMOOTH TWO-DIMENSIONAL SHAPES. THE QUESTION OF SHOCK-FREE FLOW	278
11.6*	THE HODOGRAPH TRANSFORMATION OF THE EQUATIONS	280

CHAPTER 12. THE METHOD OF CHARACTERISTICS

12.1	INTRODUCTION	284
12.2	HYPERBOLIC EQUATIONS	285
12.3	THE COMPATIBILITY RELATION	285
12.4	THE COMPUTATION METHOD	288
12.5	INTERIOR AND BOUNDARY POINTS	291
12.6*	AXIALLY SYMMETRIC FLOW	292
12.7*	NONISENTROPIC FLOW	295
12.8	THEOREMS ABOUT PLANE FLOW	296
12.9	COMPUTATION WITH WEAK, FINITE WAVES	298
12.10	INTERACTION OF WAVES	299
12.11	DESIGN OF SUPERSONIC NOZZLES	301
12.12	COMPARISON OF CHARACTERISTICS AND WAVES	304

CHAPTER 13. EFFECTS OF VISCOSITY AND CONDUCTIVITY

1301	INTRODUCTION	305
1302	COUETTE FLOW	306
1303	SHIPPY'S TEMPERATURE	310
1304	VELOCITY DISTRIBUTION IN COUETTE FLOW	311
1305	BLAZEN'S PROBLEM. THE DIFFUSION OF VORTICITY	313
1306	THE BOUNDARY-LAYER CONCEPT	316
1307	PRANDTL'S EQUATIONS FOR A FLAT PLATE	319
1308	CHARACTERISTIC RESULTS FROM THE BOUNDARY-LAYER EQUATION	320
1309	THE DISPLACEMENT EFFECT OF THE BOUNDARY LAYER. MOMENTUM AND ENERGY INTEGRALS	323
1310	CHANGE OF VARIABLES	325
1311	BOUNDARY LAYERS ON PROFILES OTHER THAN A FLAT PLATE	326
1312	FLOW THROUGH A SHOCK WAVE	329
1313*	THE NAVIER-STOKES EQUATIONS	332
1314	THE TURBULENT BOUNDARY LAYER	338
1315	BOUNDARY-LAYER EFFECTS ON THE EXTERNAL FLOW FIELD	340
1316	SHOCK-WAVE BOUNDARY-LAYER INTERACTION	342
1317	TURBULENCE	346
1318	COUETTE FLOW OF A DISSOCIATING GAS	348

CHAPTER 14. CONCEPTS FROM GASKINETICS

1401	INTRODUCTION	353
1402	PROBABILITY CONCEPTS	355
1403	DISTRIBUTION FUNCTIONS	359
1404	THE VIRIAL THEOREM OF CLAUSIUS	361
1405	THE EQUATION OF STATE OF A PERFECT GAS	362
1406	THE MAXWELL-BOLTZMANN DISTRIBUTION	363
1407*	THE SPECIFIC HEATS OF GASES	366
1408	MOLECULAR COLLISIONS. MEAN FREE PATH AND RELAXATION TIMES	369
1409	SHEAR VISCOSITY AND HEAT CONDUCTION	372
1410	COUETTE FLOW OF A HIGHLY RAREFIED GAS	373
1411	THE CONCEPTS OF SLIP AND ACCOMMODATION	376
1412	RELAXATION EFFECTS OF THE INTERNAL DEGREES OF FREEDOM	378
1413	THE LIMIT OF CONTINUUM THEORY	380

EXERCISES	383
-----------	-----

SELECTED REFERENCES	403
---------------------	-----

TABLES

I. CRITICAL DATA AND CHARACTERISTIC TEMPERATURES FOR SEVERAL CASES	405
II. FLOW PARAMETERS VERSUS M FOR SUBSONIC FLOW	406
III. FLOW PARAMETERS VERSUS M FOR SUPERSONIC FLOW	409
IV. PARAMETERS FOR SHOCK FLOW	418
V. MACH NUMBER AND MACH ANGLE VERSUS PRANDTL-MEYER FUNCTION	425

CHARTS

1. OBLIQUE SHOCK CHART	428
2. OBLIQUE SHOCK CHART	430