

CONTENTS

<i>Preface</i>	vii
CHAPTER 1 Gas Properties	1
1.1 Introduction	1
1.2 Perfect and Real Gases	1
1.3 Intermolecular Forces	2
1.4 Gas Internal Energy	6
1.5 Distribution of the Molecules on the Available Energy States	8
1.6 The Internal Energy of Polyatomic Molecules	10
1.7 The Specific Heats and their Ratio	12
1.8 The Molecular Velocity Distribution. Averaged Values	15
1.9 The Mean Free Path and the Transport Coefficients	16
1.10 Classical Dynamics of Binary Collisions	22
1.11 The Collision Integrals	32
1.12 Effusive Sources	36
1.13 Different Regimes of a Gas in Thermal Equilibrium	39
1.14 On the Possibility of a Macroscopic Description of the Gas Behaviour	40
1.14.1 Gas in equilibrium	40
1.14.2 Gas in non-equilibrium	43
References and Notes	46
CHAPTER 2 The Non-Equilibrium Equations and the Relaxation of the Internal Degrees of Freedom	48
2.1 Introduction	48

2.2	The Boltzmann Transport Equation	48
2.3	The Wang Chang–Uhlenbeck and the Master Equations	50
2.4	Energy Transfer During Collisions	53
2.5	The Vibrational Energy Relaxation	57
2.6	The Rotational Energy Relaxation	64
	References and Notes	68
CHAPTER 3 The Fundamental Equations of Gas Dynamics		70
3.1	Introduction	70
3.2	Notes on the Fluid Motion	71
3.3	Kinematics of a Fluid Element	74
3.4	The Forces Acting on Fluids	77
3.5	More on the Forces on a Fluid Element	80
3.6	The Stress–Strain Relationship for a Viscous Fluid	83
3.7	The Navier–Stokes Equations	87
3.8	The Reynolds Number	89
3.9	The Fundamental Equations of Fluid Dynamics	90
3.10	The Bernoulli Theorem for Compressible Fluids	95
3.11	The Propagation of Small Disturbances through a Compressible Fluid	97
3.12	The Gas Dynamic Equation	100
3.13	The Boundary Layer	103
3.14	The Crocco Theorem	106
	References and Notes	109
CHAPTER 4 Isoentropic Flow. Characteristic Lines		110
4.1	Introduction	110
4.2	Isoentropic and Stationary Flow of a Perfect Gas	110

4.3	Temperature and Stagnation Pressure	116
4.4	The Flux Density	118
4.5	Propagation of Small Disturbances in a Gas in Equilibrium. Characteristic Lines	120
4.6	The Propagation of Finite Amplitude Disturbances. Characteristic Lines	122
4.7	Compression and Rarefaction Waves	125
4.8	Generation of Compression and Rarefaction Waves in a Gas Inside a Tube	129
4.9	Evolution of the Distribution of the Finite Disturbances	133
4.9.1	Compression waves	133
4.9.2	Rarefaction waves	135
	References and Notes	137

CHAPTER 5 The Method of Characteristics 138

5.1	Introduction	138
5.2	The Differential Equations of the Characteristics	139
5.3	Applications	143
5.4	Alternative Form of the Compatibility Equations	152
5.5	Properties of the Characteristic Lines. Weak Discontinuities	155
5.6	The Equations of the Planar Isoentropic Flow in the Hodograph Plane	156
5.7	Weakly Perturbed Two-Dimensional Flow. Mach Lines	162
5.8	The Flow Near a Curved Wall	167
5.8.1	Flow near a concave wall	168
5.8.2	Flow near a convex wall	171
5.9	Reflection of Rarefaction and Compression Waves	176
5.9.1	Reflection from a frictionless rigid wall	176
5.9.2	Reflection from a constant pressure free boundary	179

5.10	Intersection of Rarefaction and Compression Waves	182
	References and Notes	185
CHAPTER 6	The Shock Waves	186
6.1	Introduction	186
6.2	Discontinuities in the Flow Fields	187
6.3	Normal Shock. Shock Adiabatic	189
6.4	Application to a Perfect Gas	191
6.5	The Flow Variables Downstream of the Shock as Functions of the Upstream Mach Number	193
6.6	The Oblique Shock	198
6.7	The Relationship Between the Deflection and Shock Angles	202
6.8	The Detached Shock	206
6.9	Shock Polars	209
6.9.1	Hodograph shock polar	209
6.9.2	Pressure-deflection shock polar	212
6.10	Shock Reflection	214
6.10.1	Regular shock reflection from a planar rigid wall	214
6.10.2	Mach reflection (M.R.) of an oblique shock	216
6.10.3	Reflection of the shock from the free boundary between a moving and stagnating gas	219
6.11	Shock Interactions	220
	References and Notes	222
CHAPTER 7	The Flow in Nozzles and Jets	224
7.1	Introduction	224
7.2	Stationary and Isoentropic Flow in Variable Section Ducts	224
7.3	Expressions of the Nozzle Flow Rate	229

7.4	Effects of the Discharge Pressure Reduction	233
7.5	Flow Regimes of a de Laval Nozzle. The Emitted Jet	237
7.6	Flow Regimes of a Converging Nozzle. The Emitted Jet	246
	References and Notes	250

CHAPTER 8 The Supersonic Free Jet 251

8.1	Introduction	251
8.2	The Axisymmetric Under-expanded Jet Emitted from Converging Nozzle	251
8.3	The Jet Dimensions	255
8.4	Variations of the Variables in the Continuous Regime	258
8.5	Non-Equilibrium Cooling of a Monatomic Gas	261
8.6	Non-Equilibrium Cooling of a Polyatomic Gas	265
8.7	The Sudden Freeze Approximation	269
8.8	Influence of the Relaxation of an Internal Degree of Freedom on the Flow Variables	273
	References and Notes	278

CHAPTER 9 Application of the Boltzmann Equation to a Jet
of Monatomic Gas 279

9.1	Introduction	279
9.2	Fundamental Hypotheses and the Method of Moments	279
9.3	Calculation of the Collisional Term	283
9.4	The Moment Equations in Reduced Forms	287
9.5	Some Considerations about the Obtained Equations	290
9.6	Calculation of the Parallel Speed Ratio	292

9.7	Comparison with the Experimental Data	295
	References and Notes	298
CHAPTER 10 Characterisation of a Particle Source and Extraction of the Molecular Beam		299
10.1	Introduction	299
10.2	Characterisation of a Particle Source	299
10.3	The Virtual Source and the Non-Maxwellian Distribution of v_{\perp}	303
10.4	Extraction of a Molecular Beam by a Skimmer	308
	References	317
CHAPTER 11 The Condensation in a Supersonic Free Jet		318
11.1	Introduction	318
11.2	The Gas Expansion in the p - T Phase Diagram	319
11.3	The Dimers Formation Mechanism	320
11.4	The Dimers Formation Rate	322
	References	327
CHAPTER 12 Some Different Topics		328
12.1	Introduction	328
12.2	The Energetic Balance in a Free Supersonic Jet	328
12.2.1	Pure monatomic gas	328
12.2.2	Pure biatomic gas	329
12.2.3	Pure polyatomic gas	330
12.2.4	Mixture of two monatomic gases	330

12.2.5	Mixture of a monatomic gas (carrier) with a biatomic gas (sample)	330
12.3	Binary Mixture	331
12.3.1	Mixture in equilibrium	331
12.3.2	Free jet of a binary mixture	332
12.4	Expressions of the Molecular Beam Intensity	337
	References	342
Appendix A.1	Different Forms of Eq. (1.2.2)	343
Appendix A.2	Intermolecular Potential Energy	344
Appendix A.3	Molecular Energy Levels	345
Appendix B.1	Deduction of Eqs. (2.5.8;9;10)	348
Appendix C.1	Deduction of Eqs. (3.9.10;13)	349
Appendix C.2	Alternative Deduction of the Bernoulli Equation	352
Appendix D.1	Use of the Prandtl–Meyer Function in the Method of Characteristics	353
Appendix D.2	Planar Flow Classification	354
Appendix D.3	Characteristic Lines and Weak Discontinuities	356
Appendix E.1	Spherical Symmetry Source	360
Appendix E.2	A New Determination of the Flow Field	362

Appendix E.3	Deduction of Eqs. (8.5.1;2)	366
Appendix F.1	Deduction of Eqs. (9.2.9;10;11;12)	368
Appendix F.2	Deduction of Eqs. (9.3.5;6)	371
Appendix F.3	Deduction of Eq. (9.3.14)	374
Appendix G.1	Calculation of the Integral I_1 and I_2 in Eqs. (12.4.7;14).	375
Index		379