

Hypersonic and High-Temperature Gas Dynamics

Third Edition

John D. Anderson, Jr.

National Air and Space Museum
Smithsonian Institution
Washington, DC

and

Professor Emeritus, Aerospace Engineering
University of Maryland
College Park, Maryland



AIAA EDUCATION SERIES

Joseph A. Schetz, Editor-in-Chief

Virginia Polytechnic Institute and State University
Blacksburg, Virginia



American Institute of Aeronautics and Astronautics, Inc.

CONTENTS

<i>Preface to the Third Edition</i>	<i>xv</i>
<i>Preface to the Second Edition</i>	<i>xvii</i>
<i>Preface to the First Edition</i>	<i>xix</i>
<i>Chapter 1 Some Preliminary Thoughts</i>	<i>1</i>
1.1 Hypersonic Flight—Some Historical Firsts	2
1.2 Hypersonic Flow—Why is it important?	7
1.3 Hypersonic Flow—What Is It?	15
1.4 Fundamental Sources of Aerodynamic Force and Aerodynamic Heating	25
1.5 Hypersonic Flight Paths: Velocity-Altitude Map	30
1.6 Summary and Outlook Problems	33 35
<i>Part 1: Inviscid Hypersonic Flow</i>	<i>37</i>
<i>Chapter 2 Hypersonic Shock and Expansion-Wave Relations</i>	<i>39</i>
2.1 Introduction	40
2.2 Basic Hypersonic Shock Relations	41
2.3 Hypersonic Shock Relations in Terms of the Hypersonic Similarity Parameter	46
2.4 Hypersonic Expansion-Wave Relations	48
2.5 Summary and Comments Problem	51 53
<i>Chapter 3 Local Surface Inclination Methods</i>	<i>55</i>
3.1 Introduction	56
3.2 Newtonian Flow	58
3.3 Modified Newtonian Law	65

3.4	Centrifugal Force Corrections to Newtonian Theory	67
3.5	Newtonian Theory—What It Really Means	74
3.6	Tangent-Wedge Tangent-Cone Methods	83
3.7	Shock-Expansion Method	87
3.8	Summary and Comments	90
	Problems	106

Chapter 4 Hypersonic Inviscid Flowfields: Approximate Methods 107

4.1	Introduction	108
4.2	Governing Equations	110
4.3	Mach-Number Independence	111
4.4	Hypersonic Small-Disturbance Equations	115
4.5	Hypersonic Similarity	122
4.6	Hypersonic Small-Disturbance Theory: Some Results	133
4.7	Comment on Hypersonic Small-Disturbance Theory	149
4.8	Hypersonic Equivalence Principle and Blast-Wave Theory	150
4.9	Thin Shock-Layer Theory	171
4.10	Summary and Comments	177
	Problems	180

Chapter 5 Hypersonic Inviscid Flowfields: Exact Methods 183

5.1	General Thoughts	185
5.2	Method of Characteristics	188
5.3	Time-Marching Finite Difference Method: Application to the Hypersonic Blunt-Body Problem	204
5.4	Correlations for Hypersonic Shock-Wave Shapes	228
5.5	Shock-Shock Interactions	232
5.6	Space-Marching Finite Difference Method: Additional Solutions of the Euler Equations	238
5.7	Comments on the State of the Art	253
5.8	Summary and Comments	255
	Problems	266

Part 2: Viscous Hypersonic Flow 267

Chapter 6 Viscous Flow: Basic Aspects, Boundary Layer Results, and Aerodynamic Heating 269

6.1	Introduction	270
6.2	Governing Equations for Viscous Flow: Navier–Stokes Equations	274
6.3	Similarity Parameters and Boundary Conditions	277
6.4	Boundary-Layer Equations for Hypersonic Flow	281
6.5	Hypersonic Boundary-Layer Theory: Self-Similar Solutions	286

6.6	Nonsimilar Hypersonic Boundary Layers	323
6.7	Hypersonic Transition	335
6.8	Hypersonic Turbulent Boundary Layer	345
6.9	Reference Temperature Method	350
6.10	Hypersonic Aerodynamic Heating: Some Comments and Approximate Results Applied to Hypersonic Vehicles	356
6.11	Entropy-Layer Effects on Aerodynamic Heating	363
6.12	Summary and Comments	365
	Problems	388
Chapter 7 Hypersonic Viscous Interactions		389
7.1	Introduction	390
7.2	Strong and Weak Viscous Interactions: Definition and Description	394
7.3	Role of $\bar{\chi}$ in Hypersonic Viscous Interaction	396
7.4	Other Viscous Interaction Results	404
7.5	Hypersonic Shock-Wave/Boundary-Layer Interactions	410
7.6	Summary and Comments	421
	Problems	428
Chapter 8 Computational-Fluid-Dynamic Solutions of Hypersonic Viscous Flows		429
8.1	Introduction	430
8.2	Viscous Shock-Layer Technique	432
8.3	Parabolized Navier–Stokes Solutions	438
8.4	Full Navier–Stokes Solutions	448
8.5	Summary and Comments	459
Part 3: High-Temperature Gas Dynamics		461
Chapter 9 High-Temperature Gas Dynamics: Some Introductory Considerations		463
9.1	Importance of High-Temperature Flows	463
9.2	Nature of High-Temperature Flows	472
9.3	Chemical Effects in Air: The Velocity-Altitude Map	473
9.4	Summary and Comments	476
Chapter 10 Some Aspects of the Thermodynamics of Chemically Reacting Gases (Classical Physical Chemistry)		477
10.1	Introduction: Definition of Real Gases and Perfect Gases	478
10.2	Various Forms of the Perfect-Gas Equation of State	480
10.3	Various Descriptions of the Composition of a Gas Mixture	486
10.4	Classification of Gases	488

10.5	First Law of Thermodynamics	492
10.6	Second Law of Thermodynamics	496
10.7	Calculation of Entropy	498
10.8	Gibbs Free Energy and the Entropy Produced by Chemical Nonequilibrium	500
10.9	Composition of Equilibrium Chemically Reacting Mixtures: The Equilibrium Constant	503
10.10	Heat of Reaction	511
10.11	Summary and Comments	512
	Problems	514

Chapter 11 Elements of Statistical Thermodynamics **517**

11.1	Introduction	518
11.2	Microscopic Description of Gases	520
11.3	Counting the Number of Microstates for a Given Macrostate	528
11.4	Most Probable Macrostate	531
11.5	Limiting Case: Boltzmann Distribution	533
11.6	Evaluation of Thermodynamic Properties in Terms of the Partition Function	535
11.7	Evaluation of the Partition Function in Terms of T and V	541
11.8	Practical Evaluation of Thermodynamic Properties for a Single Chemical Species	545
11.9	Calculation of the Equilibrium Constant	549
11.10	Chemical Equilibrium—Some Further Comments	554
11.11	Calculation of the Equilibrium Composition for High-Temperature Air	555
11.12	Thermodynamic Properties of an Equilibrium Chemically Reacting Gas	559
11.13	Equilibrium Properties of High-Temperature Air	565
11.14	Summary and Comments	576
	Problems	577

Chapter 12 Elements of Kinetic Theory **579**

12.1	Introduction	580
12.2	Perfect-Gas Equation of State (Revisited)	580
12.3	Collision Frequency and Mean Free Path	584
12.4	Velocity and Speed Distribution Functions: Mean Velocities	587
12.5	Summary and Comments	591
	Problems	593

Chapter 13 Chemical and Vibrational Nonequilibrium **595**

13.1	Introduction	596
13.2	Vibrational Nonequilibrium: The Vibrational Rate Equation	597

13.3	Chemical Nonequilibrium: The Chemical Rate Equation	604
13.4	Chemical Nonequilibrium in High-Temperature Air	609
13.5	Chemical Nonequilibrium in H ₂ -Air Mixtures	615
13.6	Summary and Comments	618
 Chapter 14 Inviscid High Temperature Equilibrium Flows		 619
14.1	Introduction	619
14.2	Governing Equations for Inviscid High-Temperature Equilibrium Flow	621
14.3	Equilibrium Normal and Oblique Shock-Wave Flows	624
14.4	Equilibrium Quasi-One-Dimensional Nozzle Flows	637
14.5	Frozen and Equilibrium Flows: The Distinction	644
14.6	Equilibrium and Frozen Specific Heats	647
14.7	Equilibrium Speed of Sound	650
14.8	Equilibrium Conical Flow	654
14.9	Equilibrium Blunt-Body Flows	659
14.10	Summary and Comments	664
	Problems	669
 Chapter 15 Inviscid High-Temperature Nonequilibrium Flows		 671
15.1	Introduction	671
15.2	Governing Equations for Inviscid, Nonequilibrium Flows	673
15.3	Nonequilibrium Normal and Oblique Shock-Wave Flows	679
15.4	Nonequilibrium Quasi-One-Dimensional Nozzle Flows	688
15.5	Nonequilibrium Blunt-Body Flows	696
15.6	Binary Scaling	705
15.7	Nonequilibrium Flow over Other Shapes: Nonequilibrium Method of Characteristics	708
15.8	Summary and Comments	714
	Problems	715
 Chapter 16 Kinetic Theory Revisited: Transport Properties in High-Temperature Gases		 717
16.1	Introduction	717
16.2	Definition of Transport Phenomena	718
16.3	Transport Coefficients	722
16.4	Mechanism of Diffusion	726
16.5	Energy Transport by Thermal Conduction and Diffusion: Total Thermal Conductivity	729
16.6	Transport Properties for High-Temperature Air	732
16.7	Summary and Comments	734

Chapter 17	<i>Viscous High-Temperature Flows</i>	735
17.1	Introduction	735
17.2	Governing Equations for Chemically Reacting Viscous Flow	736
17.3	Alternate Forms of the Energy Equation	739
17.4	Boundary-Layer Equations for a Chemically Reacting Gas	743
17.5	Boundary Conditions: Catalytic Walls	750
17.6	Boundary-Layer Solutions: Stagnation-Point Heat Transfer for a Dissociating Gas	754
17.7	Boundary-Layer Solutions: Nonsimilar Flows	764
17.8	Viscous-Shock-Layer Solutions to Chemically Reacting Flow	766
17.9	Parabolized Navier–Stokes Solutions to Chemically Reacting Flows	773
17.10	Full Navier–Stokes Solutions to Chemically Reacting Flows	776
17.11	Summary and Comments	781
	Problems	781
Chapter 18	<i>Introduction to Radiative Gas Dynamics</i>	783
18.1	Introduction	783
18.2	Definitions of Radiative Transfer in Gases	785
18.3	Radiative-Transfer Equation	787
18.4	Solutions of the Radiative-Transfer Equation: Transparent Gas	789
18.5	Solutions of the Radiative-Transfer Equation: Absorbing Gas	792
18.6	Solutions of the Radiative-Transfer Equation: Emitting and Absorbing Gas	794
18.7	Radiating Flowfields: Sample Results	797
18.8	Surface Radiative Cooling	805
18.9	Summary and Comments	806
	Problems	810
Appendix A	<i>Creating Hypersonic Flow in the Laboratory</i>	811
Appendix B	<i>Creating Hypersonic Flow in Flight</i>	829
Appendix C	<i>Hypersonic Aerodynamics on the Computer</i>	837
	<i>Postface</i>	847
	<i>References</i>	849
	<i>Index</i>	863
	<i>Supporting Materials</i>	871