

is in *Who's Who in America*. He is an Honorary Fellow of the American Institute of Aeronautics and Astronautics (AIAA). He is also a fellow of the Royal Aeronautical Society, London. He is a member of Tau Beta Pi, Sigma Tau, Phi Kappa Phi, Phi Eta Sigma, The American Society for Engineering Education, the History of Science Society, and the Society for the History of Technology. In 1988, he was elected as Vice President of the AIAA for Education. In 1989, he was awarded the John Leland Atwood Award jointly by the American Society for Engineering Education and the American Institute of Aeronautics and Astronautics "for the lasting influence of his recent contributions to aerospace engineering education." In 1995, he was awarded the AIAA Pendray Aerospace Literature Award "for writing undergraduate and graduate textbooks in aerospace engineering which have received worldwide acclaim for their readability and clarity of presentation, including historical content." In 1996, he was elected Vice President of the AIAA for Publications. He has recently been honored by the AIAA with its 2000 von Karman Lectureship in Astronautics.

From 1987 to the present, Dr. Anderson has been the senior consulting editor on the McGraw-Hill Series in Aeronautical and Astronautical Engineering.

CONTENTS

Preface to the Sixth Edition XV

PART 1 Fundamental Principles 1

Chapter 1

Aerodynamics: Some Introductory Thoughts 3

- 1.1 Importance of Aerodynamics: Historical Examples 5
- 1.2 Aerodynamics: Classification and Practical Objectives 11
- 1.3 Road Map for This Chapter 15
- 1.4 Some Fundamental Aerodynamic Variables 15
 - 1.4.1 Units 18
- 1.5 Aerodynamic Forces and Moments 19
- 1.6 Center of Pressure 32
- 1.7 Dimensional Analysis: The Buckingham Pi Theorem 34
- 1.8 Flow Similarity 41
- 1.9 Fluid Statics: Buoyancy Force 52
- 1.10 Types of Flow 62
 - 1.10.1 Continuum Versus Free Molecule Flow 62
 - 1.10.2 Inviscid Versus Viscous Flow 62
 - 1.10.3 Incompressible Versus Compressible Flows 64
 - 1.10.4 Mach Number Regimes 64
- 1.11 Viscous Flow: Introduction to Boundary Layers 68
- 1.12 Applied Aerodynamics: The Aerodynamic Coefficients—Their Magnitudes and Variations 75

- 1.13 Historical Note: The Illusive Center of Pressure 89
- 1.14 Historical Note: Aerodynamic Coefficients 93
- 1.15 Summary 97
- 1.16 Integrated Work Challenge: Forward-Facing Axial Aerodynamic Force on an Airfoil—Can It Happen and, If So, How? 98
- 1.17 Problems 101

Chapter 2

Aerodynamics: Some Fundamental Principles and Equations 105

- 2.1 Introduction and Road Map 106
- 2.2 Review of Vector Relations 107
 - 2.2.1 Some Vector Algebra 108
 - 2.2.2 Typical Orthogonal Coordinate Systems 109
 - 2.2.3 Scalar and Vector Fields 112
 - 2.2.4 Scalar and Vector Products 112
 - 2.2.5 Gradient of a Scalar Field 113
 - 2.2.6 Divergence of a Vector Field 115
 - 2.2.7 Curl of a Vector Field 116
 - 2.2.8 Line Integrals 116
 - 2.2.9 Surface Integrals 117
 - 2.2.10 Volume Integrals 118
 - 2.2.11 Relations Between Line, Surface, and Volume Integrals 119
 - 2.2.12 Summary 119
- 2.3 Models of the Fluid: Control Volumes and Fluid Elements 119
 - 2.3.1 Finite Control Volume Approach 120
 - 2.3.2 Infinitesimal Fluid Element Approach 121
 - 2.3.3 Molecular Approach 121

- 2.3.4 *Physical Meaning of the Divergence of Velocity* 122
- 2.3.5 *Specification of the Flow Field* 123
- 2.4 Continuity Equation 127
- 2.5 Momentum Equation 132
- 2.6 An Application of the Momentum Equation: Drag of a Two-Dimensional Body 137
 - 2.6.1 *Comment* 146
- 2.7 Energy Equation 146
- 2.8 Interim Summary 151
- 2.9 Substantial Derivative 152
- 2.10 Fundamental Equations in Terms of the Substantial Derivative 158
- 2.11 Pathlines, Streamlines, and Streaklines of a Flow 160
- 2.12 Angular Velocity, Vorticity, and Strain 165
- 2.13 Circulation 176
- 2.14 Stream Function 179
- 2.15 Velocity Potential 183
- 2.16 Relationship Between the Stream Function and Velocity Potential 186
- 2.17 How Do We Solve the Equations? 187
 - 2.17.1 *Theoretical (Analytical) Solutions* 187
 - 2.17.2 *Numerical Solutions—Computational Fluid Dynamics (CFD)* 189
 - 2.17.3 *The Bigger Picture* 196
- 2.18 Summary 196
- 2.19 Problems 200

PART 2 Inviscid, Incompressible Flow 203

Chapter 3

Fundamentals of Inviscid, Incompressible Flow 205

- 3.1 Introduction and Road Map 206
- 3.2 Bernoulli's Equation 209
- 3.3 Incompressible Flow in a Duct: The Venturi and Low-Speed Wind Tunnel 213

- 3.4 Pitot Tube: Measurement of Airspeed 226
- 3.5 Pressure Coefficient 235
- 3.6 Condition on Velocity for Incompressible Flow 237
- 3.7 Governing Equation for Irrotational, Incompressible Flow: Laplace's Equation 238
 - 3.7.1 *Infinity Boundary Conditions* 241
 - 3.7.2 *Wall Boundary Conditions* 241
- 3.8 Interim Summary 242
- 3.9 Uniform Flow: Our First Elementary Flow 243
- 3.10 Source Flow: Our Second Elementary Flow 245
- 3.11 Combination of a Uniform Flow with a Source and Sink 249
- 3.12 Doublet Flow: Our Third Elementary Flow 253
- 3.13 Nonlifting Flow over a Circular Cylinder 255
- 3.14 Vortex Flow: Our Fourth Elementary Flow 264
- 3.15 Lifting Flow over a Cylinder 268
- 3.16 The Kutta-Joukowski Theorem and the Generation of Lift 282
- 3.17 Nonlifting Flows over Arbitrary Bodies: The Numerical Source Panel Method 284
- 3.18 Applied Aerodynamics: The Flow over a Circular Cylinder—The Real Case 294
- 3.19 Historical Note: Bernoulli and Euler—The Origins of Theoretical Fluid Dynamics 302
- 3.20 Historical Note: d'Alembert and His Paradox 307
- 3.21 Summary 308
- 3.22 Integrated Work Challenge: Relation Between Aerodynamic Drag and the Loss of Total Pressure in the Flow Field 311
- 3.23 Integrated Work Challenge: Conceptual Design of a Subsonic Wind Tunnel 314
- 3.24 Problems 318

Chapter 4

Incompressible Flow over Airfoils 321

- 4.1 Introduction 323
- 4.2 Airfoil Nomenclature 326
- 4.3 Airfoil Characteristics 328
- 4.4 Philosophy of Theoretical Solutions for Low-Speed Flow over Airfoils: The Vortex Sheet 333
- 4.5 The Kutta Condition 338
 - 4.5.1 *Without Friction Could We Have Lift?* 342
- 4.6 Kelvin's Circulation Theorem and the Starting Vortex 342
- 4.7 Classical Thin Airfoil Theory: The Symmetric Airfoil 346
- 4.8 The Cambered Airfoil 356
- 4.9 The Aerodynamic Center: Additional Considerations 365
- 4.10 Lifting Flows over Arbitrary Bodies: The Vortex Panel Numerical Method 369
- 4.11 Modern Low-Speed Airfoils 375
- 4.12 Viscous Flow: Airfoil Drag 379
 - 4.12.1 *Estimating Skin-Friction Drag: Laminar Flow* 380
 - 4.12.2 *Estimating Skin-Friction Drag: Turbulent Flow* 382
 - 4.12.3 *Transition* 384
 - 4.12.4 *Flow Separation* 389
 - 4.12.5 *Comment* 394
- 4.13 Applied Aerodynamics: The Flow over an Airfoil—The Real Case 395
- 4.14 Historical Note: Early Airplane Design and the Role of Airfoil Thickness 406
- 4.15 Historical Note: Kutta, Joukowski, and the Circulation Theory of Lift 411
- 4.16 Summary 413
- 4.17 Integrated Work Challenge: Wall Effects on Measurements Made in Subsonic Wind Tunnels 415
- 4.18 Problems 419

Chapter 5

Incompressible Flow over Finite Wings 423

- 5.1 Introduction: Downwash and Induced Drag 427
- 5.2 The Vortex Filament, the Biot-Savart Law, and Helmholtz's Theorems 432
- 5.3 Prandtl's Classical Lifting-Line Theory 436
 - 5.3.1 *Elliptical Lift Distribution* 442
 - 5.3.2 *General Lift Distribution* 447
 - 5.3.3 *Effect of Aspect Ratio* 450
 - 5.3.4 *Physical Significance* 456
- 5.4 A Numerical Nonlinear Lifting-Line Method 465
- 5.5 The Lifting-Surface Theory and the Vortex Lattice Numerical Method 469
- 5.6 Applied Aerodynamics: The Delta Wing 476
- 5.7 Historical Note: Lanchester and Prandtl—The Early Development of Finite-Wing Theory 488
- 5.8 Historical Note: Prandtl—The Man 492
- 5.9 Summary 495
- 5.10 Problems 496

Chapter 6

Three-Dimensional Incompressible Flow 499

- 6.1 Introduction 499
- 6.2 Three-Dimensional Source 500
- 6.3 Three-Dimensional Doublet 502
- 6.4 Flow over a Sphere 504
 - 6.4.1 *Comment on the Three-Dimensional Relieving Effect* 506
- 6.5 General Three-Dimensional Flows: Panel Techniques 507
- 6.6 Applied Aerodynamics: The Flow over a Sphere—The Real Case 509

- 6.7 Applied Aerodynamics: Airplane Lift and Drag 512**
 - 6.7.1 Airplane Lift 512
 - 6.7.2 Airplane Drag 514
 - 6.7.3 Application of Computational Fluid Dynamics for the Calculation of Lift and Drag 519
- 6.8 Summary 523**
- 6.9 Problems 524**

PART 3

Inviscid, Compressible Flow 525

Chapter 7

Compressible Flow: Some Preliminary Aspects 527

- 7.1 Introduction 528**
- 7.2 A Brief Review of Thermodynamics 530**
 - 7.2.1 Perfect Gas 530
 - 7.2.2 Internal Energy and Enthalpy 530
 - 7.2.3 First Law of Thermodynamics 535
 - 7.2.4 Entropy and the Second Law of Thermodynamics 536
 - 7.2.5 Isentropic Relations 538
- 7.3 Definition of Compressibility 542**
- 7.4 Governing Equations for Inviscid, Compressible Flow 543**
- 7.5 Definition of Total (Stagnation) Conditions 545**
- 7.6 Some Aspects of Supersonic Flow: Shock Waves 552**
- 7.7 Summary 556**
- 7.8 Problems 558**

Chapter 8

Normal Shock Waves and Related Topics 561

- 8.1 Introduction 562**
- 8.2 The Basic Normal Shock Equations 563**

- 8.3 Speed of Sound 567**
 - 8.3.1 Comments 575
- 8.4 Special Forms of the Energy Equation 576**
- 8.5 When Is a Flow Compressible? 584**
- 8.6 Calculation of Normal Shock-Wave Properties 587**
 - 8.6.1 Comment on the Use of Tables to Solve Compressible Flow Problems 602
- 8.7 Measurement of Velocity in a Compressible Flow 603**
 - 8.7.1 Subsonic Compressible Flow 603
 - 8.7.2 Supersonic Flow 604
- 8.8 Summary 608**
- 8.9 Problems 611**

Chapter 9

Oblique Shock and Expansion Waves 613

- 9.1 Introduction 614**
- 9.2 Oblique Shock Relations 620**
- 9.3 Supersonic Flow over Wedges and Cones 634**
 - 9.3.1 A Comment on Supersonic Lift and Drag Coefficients 637
- 9.4 Shock Interactions and Reflections 638**
- 9.5 Detached Shock Wave in Front of a Blunt Body 644**
 - 9.5.1 Comment on the Flow Field Behind a Curved Shock Wave: Entropy Gradients and Vorticity 648
- 9.6 Prandtl-Meyer Expansion Waves 648**
- 9.7 Shock-Expansion Theory: Applications to Supersonic Airfoils 660**
- 9.8 A Comment on Lift and Drag Coefficients 664**
- 9.9 The X-15 and Its Wedge Tail 664**
- 9.10 Viscous Flow: Shock-Wave/ Boundary-Layer Interaction 669**
- 9.11 Historical Note: Ernst Mach—A Biographical Sketch 671**

- 9.12 Summary 674**
- 9.13 Integrated Work Challenge: Relation Between Supersonic Wave Drag and Entropy Increase—Is There a Relation? 675**
- 9.14 Integrated Work Challenge: The Sonic Boom 678**
- 9.15 Problems 681**

Chapter 10

Compressible Flow Through Nozzles, Diffusers, and Wind Tunnels 689

- 10.1 Introduction 690**
- 10.2 Governing Equations for Quasi-One-Dimensional Flow 692**
- 10.3 Nozzle Flows 701**
 - 10.3.1 More on Mass Flow 715
- 10.4 Diffusers 716**
- 10.5 Supersonic Wind Tunnels 718**
- 10.6 Viscous Flow: Shock-Wave/ Boundary-Layer Interaction Inside Nozzles 724**
- 10.7 Summary 726**
- 10.8 Integrated Work Challenge: Conceptual Design of a Supersonic Wind Tunnel 727**
- 10.9 Problems 736**

Chapter 11

Subsonic Compressible Flow over Airfoils: Linear Theory 739

- 11.1 Introduction 740**
- 11.2 The Velocity Potential Equation 742**
- 11.3 The Linearized Velocity Potential Equation 745**
- 11.4 Prandtl-Glauert Compressibility Correction 750**
- 11.5 Improved Compressibility Corrections 755**

- 11.6 Critical Mach Number 756**
 - 11.6.1 A Comment on the Location of Minimum Pressure (Maximum Velocity) 765
- 11.7 Drag-Divergence Mach Number: The Sound Barrier 765**
- 11.8 The Area Rule 773**
- 11.9 The Supercritical Airfoil 775**
- 11.10 CFD Applications: Transonic Airfoils and Wings 777**
- 11.11 Applied Aerodynamics: The Blended Wing Body 782**
- 11.12 Historical Note: High-Speed Airfoils—Early Research and Development 788**
- 11.13 Historical Note: The Origin of the Swept-Wing Concept 792**
- 11.14 Historical Note: Richard T. Whitcomb—Architect of the Area Rule and the Supercritical Wing 801**
- 11.15 Summary 802**
- 11.16 Integrated Work Challenge: Transonic Testing by the Wing-Flow Method 804**
- 11.17 Problems 808**

Chapter 12

Linearized Supersonic Flow 811

- 12.1 Introduction 812**
- 12.2 Derivation of the Linearized Supersonic Pressure Coefficient Formula 812**
- 12.3 Application to Supersonic Airfoils 816**
- 12.4 Viscous Flow: Supersonic Airfoil Drag 822**
- 12.5 Summary 825**
- 12.6 Problems 826**

Chapter 13

Introduction to Numerical Techniques for Nonlinear Supersonic Flow 829

- 13.1 Introduction: Philosophy of Computational Fluid Dynamics 830**

- 13.2** Elements of the Method of Characteristics 832
 - 13.2.1 *Internal Points* 838
 - 13.2.2 *Wall Points* 839
- 13.3** Supersonic Nozzle Design 840
- 13.4** Elements of Finite-Difference Methods 843
 - 13.4.1 *Predictor Step* 849
 - 13.4.2 *Corrector Step* 849
- 13.5** The Time-Dependent Technique: Application to Supersonic Blunt Bodies 850
 - 13.5.1 *Predictor Step* 854
 - 13.5.2 *Corrector Step* 854
- 13.6** Flow over Cones 858
 - 13.6.1 *Physical Aspects of Conical Flow* 859
 - 13.6.2 *Quantitative Formulation* 860
 - 13.6.3 *Numerical Procedure* 865
 - 13.6.4 *Physical Aspects of Supersonic Flow over Cones* 866
- 13.7** Summary 869
- 13.8** Problem 870

Chapter 14

Elements of Hypersonic Flow 871

- 14.1** Introduction 872
- 14.2** Qualitative Aspects of Hypersonic Flow 873
- 14.3** Newtonian Theory 877
- 14.4** The Lift and Drag of Wings at Hypersonic Speeds: Newtonian Results for a Flat Plate at Angle of Attack 881
 - 14.4.1 *Accuracy Considerations* 888
- 14.5** Hypersonic Shock-Wave Relations and Another Look at Newtonian Theory 892
- 14.6** Mach Number Independence 896
- 14.7** Hypersonics and Computational Fluid Dynamics 898

- 14.8** Hypersonic Viscous Flow: Aerodynamic Heating 901
 - 14.8.1 *Aerodynamic Heating and Hypersonic Flow—The Connection* 901
 - 14.8.2 *Blunt Versus Slender Bodies in Hypersonic Flow* 903
 - 14.8.3 *Aerodynamic Heating to a Blunt Body* 906
- 14.9** Applied Hypersonic Aerodynamics: Hypersonic Waveriders 908
 - 14.9.1 *Viscous-Optimized Waveriders* 914
- 14.10** Summary 921
- 14.11** Problems 922

PART 4

Viscous Flow 923

Chapter 15

Introduction to the Fundamental Principles and Equations of Viscous Flow 925

- 15.1** Introduction 926
- 15.2** Qualitative Aspects of Viscous Flow 927
- 15.3** Viscosity and Thermal Conduction 935
- 15.4** The Navier-Stokes Equations 940
- 15.5** The Viscous Flow Energy Equation 944
- 15.6** Similarity Parameters 948
- 15.7** Solutions of Viscous Flows: A Preliminary Discussion 952
- 15.8** Summary 955
- 15.9** Problems 957

Chapter 16

A Special Case: Couette Flow 959

- 16.1** Introduction 959
- 16.2** Couette Flow: General Discussion 960
- 16.3** Incompressible (Constant Property) Couette Flow 964
 - 16.3.1 *Negligible Viscous Dissipation* 970

- 16.3.2 *Equal Wall Temperatures* 971
- 16.3.3 *Adiabatic Wall Conditions (Adiabatic Wall Temperature)* 973
- 16.3.4 *Recovery Factor* 976
- 16.3.5 *Reynolds Analogy* 977
- 16.3.6 *Interim Summary* 978
- 16.4** Compressible Couette Flow 980
 - 16.4.1 *Shooting Method* 982
 - 16.4.2 *Time-Dependent Finite-Difference Method* 984
 - 16.4.3 *Results for Compressible Couette Flow* 988
 - 16.4.4 *Some Analytical Considerations* 990
- 16.5** Summary 995

Chapter 17

Introduction to Boundary Layers 997

- 17.1** Introduction 998
- 17.2** Boundary-Layer Properties 1000
- 17.3** The Boundary-Layer Equations 1006
- 17.4** How Do We Solve the Boundary-Layer Equations? 1009
- 17.5** Summary 1011

Chapter 18

Laminar Boundary Layers 1013

- 18.1** Introduction 1013
- 18.2** Incompressible Flow over a Flat Plate: The Blasius Solution 1014
- 18.3** Compressible Flow over a Flat Plate 1021
 - 18.3.1 *A Comment on Drag Variation with Velocity* 1032
- 18.4** The Reference Temperature Method 1033
 - 18.4.1 *Recent Advances: The Meador-Smart Reference Temperature Method* 1036
- 18.5** Stagnation Point Aerodynamic Heating 1037

- 18.6** Boundary Layers over Arbitrary Bodies: Finite-Difference Solution 1043
 - 18.6.1 *Finite-Difference Method* 1044
- 18.7** Summary 1049
- 18.8** Problems 1050

Chapter 19

Turbulent Boundary Layers 1051

- 19.1** Introduction 1052
- 19.2** Results for Turbulent Boundary Layers on a Flat Plate 1052
 - 19.2.1 *Reference Temperature Method for Turbulent Flow* 1054
 - 19.2.2 *The Meador-Smart Reference Temperature Method for Turbulent Flow* 1056
 - 19.2.3 *Prediction of Airfoil Drag* 1057
- 19.3** Turbulence Modeling 1057
 - 19.3.1 *The Baldwin-Lomax Model* 1058
- 19.4** Final Comments 1060
- 19.5** Summary 1061
- 19.6** Problems 1062

Chapter 20

Navier-Stokes Solutions: Some Examples 1063

- 20.1** Introduction 1064
- 20.2** The Approach 1064
- 20.3** Examples of Some Solutions 1065
 - 20.3.1 *Flow over a Rearward-Facing Step* 1065
 - 20.3.2 *Flow over an Airfoil* 1065
 - 20.3.3 *Flow over a Complete Airplane* 1068
 - 20.3.4 *Shock-Wave/Boundary-Layer Interaction* 1069
 - 20.3.5 *Flow over an Airfoil with a Protuberance* 1070
- 20.4** The Issue of Accuracy for the Prediction of Skin Friction Drag 1072
- 20.5** Summary 1077

Appendix A	Appendix E
Isentropic Flow Properties 1079	Standard Atmosphere, English Engineering Units 1103
Appendix B	References 1111
Normal Shock Properties 1085	Index 1117
Appendix C	
Prandtl-Meyer Function and Mach Angle 1089	
Appendix D	
Standard Atmosphere, SI Units 1093	

PREFACE TO THE SIXTH EDITION

This book follows in the same tradition as the previous editions: it is for students—to be read, understood, and enjoyed. It is consciously written in a clear, informal, and direct style to *talk* to the reader and gain his or her immediate interest in the challenging and yet beautiful discipline of aerodynamics. The explanation of each topic is carefully constructed to make sense to the reader. Moreover, the structure of each chapter is highly organized in order to keep the reader aware of where we are, where we were, and where we are going. Too frequently the student of aerodynamics loses sight of what is trying to be accomplished; to avoid this, I attempt to keep the reader informed of my intent at all times. For example, preview boxes are introduced at the beginning of each chapter. These short sections, literally set in boxes, inform the reader in plain language what to expect from each chapter and why the material is important and exciting. They are primarily motivational; they help to encourage the reader to actually enjoy reading the chapter, therefore enhancing the educational process. In addition, each chapter contains a road map—a block diagram designed to keep the reader well aware of the proper flow of ideas and concepts. The use of preview boxes and chapter road maps are unique features of this book. Also, to help organize the reader's thoughts, there are special summary sections at the end of most chapters.

The material in this book is at the level of college juniors and seniors in aerospace or mechanical engineering. It assumes no prior knowledge of fluid dynamics in general, or aerodynamics in particular. It does assume a familiarity with differential and integral calculus, as well as the usual physics background common to most students of science and engineering. Also, the language of vector analysis is used liberally; a compact review of the necessary elements of vector algebra and vector calculus is given in Chapter 2 in such a fashion that it can either educate or refresh the reader, whatever may be the case for each individual.

This book is designed for a one-year course in aerodynamics. Chapters 1 to 6 constitute a solid semester emphasizing inviscid, incompressible flow. Chapters 7 to 14 occupy a second semester dealing with inviscid, compressible flow. Finally, Chapters 15 to 20 introduce some basic elements of viscous flow, mainly to serve as a contrast to and comparison with the inviscid flows treated throughout the bulk of the text. Specific sections on viscous flow, however, have been added much earlier in the book in order to give the reader some idea of how the inviscid results are tempered by the influence of friction. This is done by adding self-contained viscous flow sections at the end of various chapters, written and placed in such a way that they do not interfere with the flow of the inviscid flow discussion, but are there to complement the discussion. For example, at the end of Chapter 4 on