

Contents

Introduction	XXI
---------------------------	-----

Part I. Fundamentals of Viscous Flows

1. Some Features of Viscous Flows	3
1.1 Real and Ideal Fluids	3
1.2 Viscosity	4
1.3 Reynolds Number	6
1.4 Laminar and Turbulent Flows	12
1.5 Asymptotic Behaviour at Large Reynolds Numbers	14
1.6 Comparison of Measurements Using the Inviscid Limiting Solution	14
1.7 Summary	26
2. Fundamentals of Boundary–Layer Theory	29
2.1 Boundary–Layer Concept	29
2.2 Laminar Boundary Layer on a Flat Plate at Zero Incidence ..	30
2.3 Turbulent Boundary Layer on a Flat Plate at Zero Incidence .	33
2.4 Fully Developed Turbulent Flow in a Pipe	36
2.5 Boundary Layer on an Airfoil	38
2.6 Separation of the Boundary Layer	39
2.7 Overview of the Following Material	48
3. Field Equations for Flows of Newtonian Fluids	51
3.1 Description of Flow Fields	51
3.2 Continuity Equation	52
3.3 Momentum Equation	52
3.4 General Stress State of Deformable Bodies	53
3.5 General State of Deformation of Flowing Fluids	57
3.6 Relation Between Stresses and Rate of Deformation	62
3.7 Stokes Hypothesis	65
3.8 Bulk Viscosity and Thermodynamic Pressure	66
3.9 Navier–Stokes Equations	68

3.10	Energy Equation	69
3.11	Equations of Motion for Arbitrary Coordinate Systems (Summary)	73
3.12	Equations of Motion for Cartesian Coordinates in Index Notation	76
3.13	Equations of Motion in Different Coordinate Systems	79
4.	General Properties of the Equations of Motion	83
4.1	Similarity Laws	83
4.2	Similarity Laws for Flow with Buoyancy Forces (Mixed Forced and Natural Convection)	86
4.3	Similarity Laws for Natural Convection	90
4.4	Vorticity Transport Equation	91
4.5	Limit of Very Small Reynolds Numbers	93
4.6	Limit of Very Large Reynolds Numbers	94
4.7	Mathematical Example of the Limit $Re \rightarrow \infty$	96
4.8	Non-Uniqueness of Solutions of the Navier–Stokes Equations.	99
5.	Exact Solutions of the Navier–Stokes Equations	101
5.1	Steady Plane Flows	101
5.1.1	Couette–Poiseuille Flows	101
5.1.2	Jeffery–Hamel Flows (Fully Developed Nozzle and Diffuser Flows)	104
5.1.3	Plane Stagnation–Point Flow	110
5.1.4	Flow Past a Parabolic Body	115
5.1.5	Flow Past a Circular Cylinder	115
5.2	Steady Axisymmetric Flows	116
5.2.1	Circular Pipe Flow (Hagen–Poiseuille Flow)	116
5.2.2	Flow Between Two Concentric Rotating Cylinders	117
5.2.3	Axisymmetric Stagnation–Point Flow	118
5.2.4	Flow at a Rotating Disk	119
5.2.5	Axisymmetric Free Jet	124
5.3	Unsteady Plane Flows	126
5.3.1	Flow at a Wall Suddenly Set into Motion (First Stokes Problem)	126
5.3.2	Flow at an Oscillating Wall (Second Stokes Problem)	129
5.3.3	Start–up of Couette Flow	130
5.3.4	Unsteady Asymptotic Suction	131
5.3.5	Unsteady Plane Stagnation–Point Flow	131
5.3.6	Oscillating Channel Flow	137
5.4	Unsteady Axisymmetric Flows	139
5.4.1	Vortex Decay	139
5.4.2	Unsteady Pipe Flow	139
5.5	Summary	141

Part II. Laminar Boundary Layers

6. Boundary–Layer Equations in Plane Flow; Plate Boundary Layer	145
6.1 Setting up the Boundary–Layer Equations	145
6.2 Wall Friction, Separation and Displacement	150
6.3 Dimensional Representation of the Boundary–Layer Equations	152
6.4 Friction Drag	155
6.5 Plate Boundary Layer	156
7. General Properties and Exact Solutions of the Boundary–Layer Equations for Plane Flows	165
7.1 Compatibility Condition at the Wall	166
7.2 Similar Solutions of the Boundary–Layer Equations	167
7.2.1 Derivation of the Ordinary Differential Equation	167
A Boundary Layers with Outer Flow	169
B Boundary Layers Without Outer Flow	172
7.2.2 Wedge Flows	172
7.2.3 Flow in a Convergent Channel	174
7.2.4 Mixing Layer	175
7.2.5 Moving Plate	177
7.2.6 Free Jet	177
7.2.7 Wall Jet	180
7.3 Coordinate Transformation	182
7.3.1 Görtler Transformation	182
7.3.2 v. Mises Transformation	183
7.3.3 Crocco Transformation	184
7.4 Series Expansion of the Solutions	184
7.4.1 Blasius Series	184
7.4.2 Görtler Series	186
7.5 Asymptotic Behaviour of Solutions Downstream	187
7.5.1 Wake Behind Bodies	187
7.5.2 Boundary Layer at a Moving Wall	190
7.6 Integral Relations of the Boundary Layer	191
7.6.1 Momentum–Integral Equation	191
7.6.2 Energy–Integral Equation	192
7.6.3 Moment–of–Momentum Integral Equations	194
8. Approximate Methods for Solving the Boundary–Layer Equations for Steady Plane Flows	195
8.1 Integral Methods	196

8.2	Stratford's Separation Criterion	202
8.3	Comparison of the Approximate Solutions with Exact Solutions	202
8.3.1	Retarded Stagnation-Point Flow	202
8.3.2	Divergent Channel (Diffuser)	204
8.3.3	Circular Cylinder Flow	205
8.3.4	Symmetric Flow past a Joukowski Airfoil	207
9.	Thermal Boundary Layers without Coupling of the Velocity Field to the Temperature Field	209
9.1	Boundary-Layer Equations for the Temperature Field	209
9.2	Forced Convection for Constant Properties	211
9.3	Effect of the Prandtl Number	215
9.4	Similar Solutions of the Thermal Boundary Layer	218
9.5	Integral Methods for Computing the Heat Transfer	223
9.6	Effect of Dissipation; Distribution of the Adiabatic Wall Temperature	226
10.	Thermal Boundary Layers with Coupling of the Velocity Field to the Temperature Field	231
10.1	Remark	231
10.2	Boundary-Layer Equations	231
10.3	Boundary Layers with Moderate Wall Heat Transfer (Without Gravitational Effects)	233
10.3.1	Perturbation Calculation	233
10.3.2	Property Ratio Method (Temperature Ratio Method) .	237
10.3.3	Reference Temperature Method	240
10.4	Compressible Boundary Layers (Without Gravitational Effects)	241
10.4.1	Physical Property Relations	241
10.4.2	Simple Solutions of the Energy Equation	244
10.4.3	Transformations of the Boundary-Layer Equations ...	246
10.4.4	Similar Solutions	249
10.4.5	Integral Methods	258
10.4.6	Boundary Layers in Hypersonic Flows	263
10.5	Natural Convection	265
10.5.1	Boundary-Layer Equations	265
10.5.2	Transformation of the Boundary-Layer Equations ...	270
10.5.3	Limit of Large Prandtl Numbers ($T_w = \text{const}$)	271
10.5.4	Similar Solutions	273
10.5.5	General Solutions	277
10.5.6	Variable Physical Properties	278
10.5.7	Effect of Dissipation	280

10.6 Indirect Natural Convection	281
10.7 Mixed Convection	284
11. Boundary–Layer Control (Suction/Blowing)	291
11.1 Different Kinds of Boundary–Layer Control	291
11.2 Continuous Suction and Blowing	295
11.2.1 Fundamentals	295
11.2.2 Massive Suction	297
11.2.3 Massive Blowing	299
11.2.4 Similar Solutions	302
11.2.5 General Solutions	307
1. Plate Flow with Uniform Suction or Blowing	307
2. Airfoil	309
11.2.6 Natural Convection with Blowing and Suction	310
11.3 Binary Boundary Layers	311
11.3.1 Overview	311
11.3.2 Basic Equations	312
11.3.3 Analogy Between Heat and Mass Transfer	316
11.3.4 Similar Solutions	317
12. Axisymmetric and Three–Dimensional Boundary Layers ..	321
12.1 Axisymmetric Boundary Layers	321
12.1.1 Boundary–Layer Equations	321
12.1.2 Mangler Transformation	323
12.1.3 Boundary Layers on Non–Rotating Bodies of Revolution	324
12.1.4 Boundary Layers on Rotating Bodies of Revolution ...	327
12.1.5 Free Jets and Wakes	331
12.2 Three–Dimensional Boundary Layers	335
12.2.1 Boundary–Layer Equations	335
12.2.2 Boundary Layer at a Cylinder	341
12.2.3 Boundary Layer at a Yawing Cylinder	342
12.2.4 Three–Dimensional Stagnation Point	344
12.2.5 Boundary Layers in Symmetry Planes	345
12.2.6 General Configurations	345
13. Unsteady Boundary Layers	349
13.1 Fundamentals	349
13.1.1 Remark	349
13.1.2 Boundary–Layer Equations	350
13.1.3 Similar and Semi–Similar Solutions	351
13.1.4 Solutions for Small Times (High Frequencies)	352
13.1.5 Separation of Unsteady Boundary Layers	353
13.1.6 Integral Relations and Integral Methods	354
13.2 Unsteady Motion of Bodies in a Fluid at Rest	355

13.2.1	Start-Up Processes	355
13.2.2	Oscillation of Bodies in a Fluid at Rest	362
13.3	Unsteady Boundary Layers in a Steady Basic Flow	365
13.3.1	Periodic Outer Flow	365
13.3.2	Steady Flow with a Weak Periodic Perturbation	367
13.3.3	Transition Between Two Slightly Different Steady Boundary Layers	369
13.4	Compressible Unsteady Boundary Layers	370
13.4.1	Remark	370
13.4.2	Boundary Layer Behind a Moving Normal Shock Wave	371
13.4.3	Flat Plate at Zero Incidence with Variable Free Stream Velocity and Wall Temperature	373
14.	Extensions to the Prandtl Boundary-Layer Theory	377
14.1	Remark	377
14.2	Higher Order Boundary-Layer Theory	379
14.3	Hypersonic Interaction	389
14.4	Triple-Deck Theory	392
14.5	Marginal Separation	403
14.6	Massive Separation	408

Part III. Laminar-Turbulent Transition

15.	Onset of Turbulence (Stability Theory)	415
15.1	Some Experimental Results	
	on the Laminar-Turbulent Transition	415
15.1.1	Transition in the Pipe Flow	415
15.1.2	Transition in the Boundary Layer	419
15.2	Fundamentals of Stability Theory	424
15.2.1	Remark	424
15.2.2	Fundamentals of Primary Stability Theory	425
15.2.3	Orr-Sommerfeld Equation	427
15.2.4	Curve of Neutral Stability and the Indifference Reynolds Number	434
	a Plate Boundary Layer	436
	b Effect of Pressure Gradient	445
	c Effect of Suction	457
	d Effect of Wall Heat Transfer	460
	e Effect of Compressibility	463
	f Effect of Wall Roughness	467
	g Further Effects	472
15.3	Instability of the Boundary Layer for Three-Dimensional Perturbations	473

15.3.1 Remark	473
15.3.2 Fundamentals of Secondary Stability Theory	476
15.3.3 Boundary Layers at Curved Walls	481
15.3.4 Boundary Layer at a Rotating Disk	485
15.3.5 Three-Dimensional Boundary Layers	487
15.4 Local Perturbations	493

Part IV. Turbulent Boundary Layers

16. Fundamentals of Turbulent Flows	499
16.1 Remark	499
16.2 Mean Motion and Fluctuations	501
16.3 Basic Equations for the Mean Motion of Turbulent Flows	504
16.3.1 Continuity Equation	504
16.3.2 Momentum Equations (Reynolds Equations)	505
16.3.3 Equation for the Kinetic Energy of the Turbulent Fluctuations (k -Equation)	507
16.3.4 Thermal Energy Equation	510
16.4 Closure Problem	511
16.5 Description of the Turbulent Fluctuations	512
16.5.1 Correlations	512
16.5.2 Spectra and Eddies	513
16.5.3 Turbulence of the Outer Flow	515
16.5.4 Edges of Turbulent Regions and Intermittence	515
16.6 Boundary-Layer Equations for Plane Flows	516
17. Internal Flows	519
17.1 Couette Flow	519
17.1.1 Two-Layer Structure of the Velocity Field and the Logarithmic Overlap Law	519
17.1.2 Universal Laws of the Wall	524
17.1.3 Friction Law	536
17.1.4 Turbulence Models	538
17.1.5 Heat Transfer	541
17.2 Fully Developed Internal Flows ($A = \text{const}$)	543
17.2.1 Channel Flow	543
17.2.2 Couette-Poiseuille Flows	544
17.2.3 Pipe Flow	549
17.3 Slender-Channel Theory	554
18. Turbulent Boundary Layers without Coupling of the Velocity Field to the Temperature Field	557
18.1 Turbulence Models	557

18.1.1 Remark	557
18.1.2 Algebraic Turbulence Models	559
18.1.3 Turbulent Energy Equation	560
18.1.4 Two-Equation Models	562
18.1.5 Reynolds Stress Models	565
18.1.6 Heat Transfer Models	568
18.1.7 Low-Reynolds-Number Models	570
18.1.8 Large-Eddy Simulation and Direct Numerical Simulation	571
18.2 Attached Boundary Layers	572
18.2.1 Layered Structure	572
18.2.2 Boundary-Layer Equations Using the Defect Formulation	574
18.2.3 Friction Law and Characteristic Quantities of the Boundary Layer	577
18.2.4 Equilibrium Boundary Layers	580
18.2.5 Boundary Layer on a Plate at Zero Incidence	582
18.3 Boundary Layers with Separation	589
18.3.1 Stratford Flow	589
18.3.2 Quasi-Equilibrium Boundary Layers	591
18.4 Computation of Boundary Layers Using Integral Methods	594
18.4.1 Direct Method	594
18.4.2 Inverse Method	597
18.5 Computation of Boundary Layers Using Field Methods	598
18.5.1 Attached Boundary Layers	598
18.5.2 Boundary Layers with Separation	601
18.5.3 Low-Reynolds-Number Turbulence Models	603
18.5.4 Additional Effects	604
18.6 Computation of Thermal Boundary Layers	607
18.6.1 Fundamentals	607
18.6.2 Computation of Thermal Boundary Layers Using Field Methods	609
19. Turbulent Boundary Layers with Coupling of the Velocity Field to the Temperature Field	611
19.1 Fundamental Equations	611
19.1.1 Time Averaging for Variable Density	611
19.1.2 Boundary-Layer Equations	613
19.2 Compressible Turbulent Boundary Layers	617
19.2.1 Temperature Field	617
19.2.2 Overlap Law	619
19.2.3 Skin-Friction Coefficient and Nusselt Number	621
19.2.4 Integral Methods for Adiabatic Walls	623

19.2.5	Field Methods	625
19.2.6	Shock–Boundary–Layer Interaction	625
19.3	Natural Convection	627
20.	Axisymmetric and Three–Dimensional	
	Turbulent Boundary Layers	631
20.1	Axisymmetric Boundary Layers	631
20.1.1	Boundary–Layer Equations	631
20.1.2	Boundary Layers without Body Rotation	632
20.1.3	Boundary Layers with Body Rotation	635
20.2	Three–Dimensional Boundary Layers	637
20.2.1	Boundary–Layer Equations	637
20.2.2	Computation Methods	641
20.2.3	Examples	643
21.	Unsteady Turbulent Boundary Layers	645
21.1	Averaging and Boundary–Layer Equations	645
21.2	Computation Methods	648
21.3	Examples	649
22.	Turbulent Free Shear Flows	653
22.1	Remark	653
22.2	Equations for Plane Free Shear Layers	655
22.3	Plane Free Jet	659
22.3.1	Global Balances	659
22.3.2	Far Field	660
22.3.3	Near Field	665
22.3.4	Wall Effects	665
22.4	Mixing Layer	667
22.5	Plane Wake	669
22.6	Axisymmetric Free Shear Flows	671
22.6.1	Basic Equations	671
22.6.2	Free Jet	672
22.6.3	Wake	673
22.7	Buoyant Jets	675
22.7.1	Plane Buoyant Jet	675
22.7.2	Axisymmetric Buoyant Jet	676
22.8	Plane Wall Jet	677

Part V. Numerical Methods in Boundary–Layer Theory

23. Numerical Integration of the Boundary–Layer Equations	683
23.1 Laminar Boundary Layers	683
23.1.1 Remark	683
23.1.2 Note on Boundary–Layer Transformations	684
23.1.3 Explicit and Implicit Discretisation	685
23.1.4 Solution of the Implicit Difference Equations	689
23.1.5 Integration of the Continuity Equation	691
23.1.6 Boundary–Layer Edge and Wall Shear Stress	691
23.1.7 Integration of the Transformed Boundary–Layer Equations Using the Box Scheme	692
23.2 Turbulent Boundary Layers	695
23.2.1 Method of Wall Functions	695
23.2.2 Low–Reynolds–Number Turbulence Models	700
23.3 Unsteady Boundary Layers	701
23.4 Steady Three–Dimensional Boundary Layers	703
List of Frequently Used Symbols	709
References and Index of Authors	717
Index	799

Boundary-Layer Theory

Schlichting (Deceased), H.; Gersten, K.

2017, XXVIII, 805 p. 288 illus., Hardcover

ISBN: 978-3-662-52917-1