McGRAW HILL INTERNATIONAL EDITION

CONTENTS

Preface to the Fourth Edition xiv
Preface to the Third Edition xvii
Preface to the Second Edition xix
Preface to the First Edition xxi
List of Symbols xxiii

Chapter 1
Introduction 1

Chapter 2
Conservation Principles 5

The Control Volume 5
Principle of Conservation of Mass 5
The Momentum Theorem 6
Principle of Conservation of Energy 7

Chapter 3
Fluid Stresses and Flux Laws 9

Viscous Fluid Stresses 9
Fourier's Law of Heat Conduction 11
Fick's Law of Diffusion 13
Dimensionless Groups of Transport Properties 15
Turbulent-Flow Transport Coefficients 15
References 16

Chapter 4
Differential Equations for the Laminar Boundary Layer 17

The Concept of the Boundary Layer 17
The Continuity Equations 19
The Momentum Equations 22
The Mass-Diffusion Equations 25
The Energy Equations 29
Problems 38
References 39

Chapter 5
Integral Equations for the Boundary Layer 40

The Momentum Integral Equation 40
The Displacement and Momentum Thicknesses 43
Alternative Forms of the Momentum Integral Equation 45
The Energy Integral Equation 46
The Enthalpy and Conduction Thicknesses 48
Alternative Forms of the Energy Integral Equation 49
Problems 51
Reference 51

Chapter 6
Differential Equations for the Turbulent Boundary Layer 52

Momentum and Thermodynamic Variables 52
Newtonian Stress and Fourier Heat-Flux Models 53
Instantaneous Equations of Turbulence 54
Reynolds Decomposition 55
Time-Averaging and Turbulence Statistics 57
Reynolds-Averaged Transport Equations of Turbulence 58
Problems 66
References 66

Chapter 7
Laminar Internal Flows: Momentum Transfer 67

Fully Developed Laminar Flow in Circular Tubes 67

Fully Developed Laminar Flow in Other Cross-Sectional Shape Tubes 71

The Laminar Hydrodynamic Entry Length 74

Problems 76

TEXSTAN Problems 78

References 79

Chapter 8
Laminar Internal Flows: Heat Transfer 80

The Energy Differential Equations for Flow through a Circular Tube 81

The Circular Tube with Fully Developed Velocity and Temperature Profiles 82

The Concentric Circular-Tube Annulus with Fully Developed Velocity and Temperature Profiles, Asymmetric Heating 92

Solutions for Tubes of Noncircular Cross Section with Fully Developed Velocity and Temperature Profiles 95

Circular-Tube Thermal-Entry-Length Solutions 97

Thermal-Entry-Length Solutions for the Rectangular Tube and Annulus 105

The Effect of Axial Variation of the Surface Temperature with Hydrodynamically Fully Developed Flow 109

The Effect of Axial Variation of Heat Flux 115

Combined Hydrodynamic and Thermal Entry Length 117

Problems 120

TEXSTAN Problems 125

References 128

Chapter 9
Laminar External Boundary Layers: Momentum Transfer 130

Similarity Solutions: The Laminar Incompressible Boundary Layer with Constant Properties and Constant Free-Stream Velocity 131

Similarity Solutions for the Laminar Incompressible Boundary Layer for $u_\infty = Cx^m$ 137

Similarity Solutions for the Laminar Incompressible Boundary Layer for $v_s \neq 0$ 139

Nonsimilar Momentum Boundary Layers 141

An Approximate Laminar Boundary-Layer Solution for Constant Free-Stream Velocity Developed from the Momentum Integral Equation 141

An Approximate Laminar Boundary-Layer Solution for Arbitrarily Varying Free-Stream Velocity over a Body of Revolution 143

Problems 145

TEXSTAN Problems 146

References 147

Chapter 10
Laminar External Boundary Layers: Heat Transfer 148

Constant Free-Stream Velocity Flow along a Constant-Temperature Semi-Infinite Plate 149

Flow with $u_\infty = Cx^m$ along a Constant-Temperature Semi-Infinite Plate 154

Flow along a Constant-Temperature Semi-Infinite Plate with Injection or Suction 157

Nonsimilar Thermal Boundary Layers 159

Constant Free-Stream Velocity Flow along a Semi-Infinite Plate with Unheated Starting Length 159

Constant Free-Stream Velocity Flow along a Semi-Infinite Plate with Arbitrarily Specified Surface Temperature 162

Constant Free-Stream Velocity Flow along a Semi-Infinite Plate with Arbitrarily Specified Surface Heat Flux 165

Flow Over a Constant-Temperature Body of Arbitrary Shape 166

Flow Over a Body of Arbitrary Shape and Arbitrarily Specified Surface Temperature 170

Flow Over Bodies with Boundary-Layer Separation 171

Problems 172

TEXSTAN Problems 176

References 177

Chapter 11

Turbulent External Boundary Layers: Momentum Transfer 178

Transition of a Laminar Boundary Layer to a Turbulent Boundary Layer 178

The Qualitative Structure of the Turbulent Boundary Layer 180

The Concepts of Eddy Diffusivity and Eddy Viscosity 182

The Prandtl Mixing-Length Theory 183

Wall Coordinates 186

The Law of the Wall for the Case of $p^+ = 0.0$ and $v_s^+ = 0.0$ 187

An Approximate Solution for the Turbulent Momentum Boundary Layer 191

A Continuous Law of the Wall: The Van Driest Model 194

Summary of a Complete Mixing-Length Theory 196

A Model Based on the Turbulence Kinetic Energy Equation 201

The k–ε Model 206

Equilibrium Turbulent Boundary Layers 208

The Transpired Turbulent Boundary Layer 212

The Effects of Surface Roughness 215

The Effects of Axial Curvature 219

The Effects of Free-Stream Turbulence 221

Problems 223

TEXSTAN Problems 226

References 227

Chapter 12

Turbulent External Boundary Layers: Heat Transfer 229

The Concepts of Eddy Diffusivity for Heat Transfer, Eddy Conductivity, and Turbulent Prandtl Number 229

The Reynolds Analogy 231

Turbulent Prandtl Number 233

A Conduction Model for Turbulent Prandtl Number 239

Complete Solution of the Energy Equation 242

A Law of the Wall for the Thermal Boundary Layer 242

Effect of Pressure Gradient on Temperature Profiles 247

A Heat-Transfer Solution for Constant Free-Stream Velocity and Surface Temperature 248

Constant Free-Stream Velocity Flow along a Semi-Infinite Plate with Unheated Starting Length 251

Constant Free-Stream Velocity Flow along a Semi-Infinite Plate with Arbitrarily Specified Surface Temperature 254

Constant Free-Stream Velocity Flow along a Semi-Infinite Plate with Arbitrarily Specified Heat Flux 255

An Approximate Solution for Varying Free-Stream Velocity 256

Strongly Accelerated Boundary Layers 259

The Transpired Turbulent Boundary Layer 260

Full-Coverage Film Cooling 265

Film Cooling 267

The Effects of Surface Roughness 268
The Effects of Axial Curvature 271
The Effects of Free-Stream Turbulence 273
Problems 275
TEXSTAN Problems 279
References 280

Chapter 13
Turbulent Internal Flows: Momentum Transfer 282

Fully Developed Flow in a Circular Tube 282
Tubes of Noncircular Cross Section 287
Effects of Surface Roughness 287
Problems 289
TEXSTAN Problems 290
References 290

Chapter 14
Turbulent Internal Flows: Heat Transfer 292

Circular Tube with Fully Developed Velocity and Temperature Profiles, Constant Heat Rate, Prandtl Numbers 0.6–6.0 294
Circular Tube with Fully Developed Flow, Higher Prandtl Numbers 297
Very Low-Prandtl-Number Heat Transfer, Liquid Metals 299
Circular Tube, Fully Developed Profiles, Constant Surface Temperature 302
Effect of Peripheral Heat-Flux Variation 304
Fully Developed Turbulent Flow between Parallel Planes and in Concentric Circular-Tube Annuli 305
Fully Developed Turbulent Flow in Other Tube Geometries 309
Experimental Correlations for Flow in Tubes 311
Thermal-Entry Length for Turbulent Flow in a Circular Tube 312
Thermal-Entry Length for Turbulent Flow between Parallel Planes 317
The Effects of Axial Variations of Surface Temperature and Heat Flux 319
Combined Hydrodynamic- and Thermal-Entry Length 319
The Influence of Surface Roughness 322
Problems 323
TEXSTAN Problems 326
References 328

Chapter 15
Influence of Temperature-Dependent Fluid Properties 330

Laminar Flow in Tubes: Liquids 332
Laminar Flow in Tubes: Gases 334
Turbulent Flow in Tubes: Liquids 334
Turbulent Flow in Tubes: Gases 335
The Laminar External Boundary Layer: Gases 336
The Laminar External Boundary Layer: Liquids 340
The Turbulent External Boundary Layer: Liquids 340
The Turbulent External Boundary Layer: Gases 341
Problems 342
References 342

Chapter 16
Convective Heat Transfer at High Velocities 344

The Stagnation Enthalpy Equation 346
The High-Velocity Thermal Boundary Layer for a Fluid with $Pr = 1$ 349
The Laminar Constant-Property Boundary Layer for $Pr \neq 1$ 351
The Laminar Boundary Layer for a Gas with Variable Properties 355

The Use of Reference Properties for High-Velocity Laminar Boundary-Layer Calculations 358

The Turbulent Boundary Layer for a Gas with Variable Properties 360

Reference Properties for High-Velocity Turbulent Boundary-Layer Calculations 363

Mach Number and Large-Temperature-Difference Corrections for Variable Free-Stream Velocity and Variable Temperature Differences 363

Problems 364

References 366

Chapter 17

Convective Heat Transfer with Body Forces 367

Boundary-Layer Equations for Free Convection 368

Scaling and Flow Regimes in Free Convection 370

Similarity Solutions: Laminar Flow on a Constant-Temperature, Vertical, and Semi-Infinite Flat Plate 374

Similarity Solutions with Variable Surface Temperature 378

Similarity Solutions with Wall Suction or Blowing 380

Approximate Integral Solution: Laminar Flow on a Constant-Temperature, Vertical, and Semi-Infinite Flat Plate 381

The Effect of Variable Properties 382

Turbulent Flow on a Vertical and Semi-Infinite Flat Plate 383

Heat-Transfer Solutions for Other Geometries 386

Mixed Free and Forced Convection 389

Natural Convection in Enclosures 390

Problems 394

References 396

Chapter 18

Convective Mass Transfer: Basic Definitions and Formulation of a Simplified Theory 399

Definitions 400

The Differential Equations of the Concentration Boundary Layer 401

Simplified Equations for the Concentration Boundary Layer 404

Boundary Conditions 406

Definition of the Mass-Transfer Conductance and Driving Force 409

Problems 411

References 412

Chapter 19

Convective Mass Transfer: Evaluation of the Mass-Transfer Conductance from the Conserved-Property ($\mathcal{P}$) Equation 413

The Prediction of the Mass-Transfer Conductance g^* for Low Mass-Transfer Rates 414

The Laminar Constant-Property Boundary Layer for Low Mass-Transfer Rates 414

The Turbulent Constant-Property Boundary Layer for Low Mass-Transfer Rates 416

The Prediction of the Mass-Transfer Conductance g for High Mass-Transfer Rates 418

High Mass-Transfer-Rate Convection in a Laminar Couette Flow 418

The Laminar Constant-Property Boundary Layer, Similarity Solutions for High Mass-Transfer Rates 420

The Laminar Boundary Layer for High Mass-Transfer Rates: Some Variable-Property Solutions 424

The Laminar Constant-Property Boundary Layer with Arbitrary Varying Free-Stream Velocity and High Mass-Transfer Rates 425

The Turbulent Constant-Property Boundary Layer with Constant Free-Stream Velocity and High Mass-Transfer Rates 426

The Turbulent Boundary Layer: Some Variable-Property Solutions 427

Problems 427

References 428

Chapter 20

Convective Mass Transfer: Examples for Application of the Simplified Method 429

General Problem Solution Procedure 429

Thermodynamics of the Air–Water-Vapor System 430

Analysis of the Wet-Bulb Psychrometer 433

Drying 437

Evaporative Cooling 438

Naphthalene Sublimation from a Flat Plate 439

Burning of a Volatile Fuel in Air 442

Simple Graphite Burning in Air 444

Graphite Ablation with More than One Reaction 446

The High-Temperature Boundary Layer with Dissociation 448

Transpiration Cooling by Gas Injection 449

Problems 452

References 456

Appendix A Property Values 457

Appendix B Dimensions and Conversion to SI 471

Appendix C Some Tables of Functions Useful in Boundary-Layer Analysis 475

Appendix D Operations Implied by the ∇ Operator 477

Appendix E Detailed Derivation of the Simplified Mass-Diffusion and Energy Equation ($\mathcal{P}$ Equation) for Convective Mass Transfer Problems and the Corresponding Boundary Conditions 481

Appendix F The TEXSTAN Boundary-Layer Code 496

Appendix G Blasius Flow—A Sample Data Set for TEXSTAN 510

Appendix H TEXSTAN Data Sets 522

Index 531