Contents

Chapter 1 INTRODUCTION 1

References 5

Chapter 2 MOLECULAR DIFFUSION 6

Flux Definitions 6

STEADY-STATE MOLECULAR DIFFUSION 12

Steady-State Equimolal Counterdiffusion in Gases 13
Steady-State Unimolal Unidirectional Diffusion in Gases 14
Molecular Diffusion in Liquids 17
Molal and Volumetric Diffusivities 18
Steady-State Diffusion from a Sphere 18

UNSTEADY-STATE MOLECULAR DIFFUSION 21

Unsteady-State Diffusion in a Sphere 21

Unsteady-State Diffusion in a Slab 28
Diffusion Through Two Opposite Surfaces of a Slab 29
Diffusion Through a Single Surface of a Slab 35

Unsteady-State Diffusion in a Cylinder 36

Nomenclature 42

Problems 44

References 48

Chapter 3 MOLECULAR DIFFUSIVITIES 49

DIFFUSIVITIES IN GASES 49

DIFFUSIVITIES IN LIQUIDS 54

Nonelectrolytes 54
Dilute Solutions 54
Concentrated Solutions 61
Electrolytes 67
Dilute Solutions 68
Concentrated Solutions 69

DIFFUSIVITIES IN SOLIDS 77

Nomenclature 77

Problems 79

References 80

Chapter 4 MASS TRANSFER COEFFICIENTS 83

Equilibrium 83
Individual Mass Transfer Coefficients 91
Overall Mass Transfer Coefficients 91

MECHANISMS OF MASS TRANSFER 94

The Two-Film Theory 94
The Penetration Theory 96
The Theory of Penetration with Random
Surface Renewal 98
The Film-Penetration Theory 99
The Mass-Flow or Convective-Transfer Theory 101

Nomenclature 102

Problems 104

References 107

Chapter 5 MASS TRANSFER IN LAMINAR FLOW 109

MASS TRANSFER IN THE LAMINAR BOUNDARY LAYER ON A FLAT PLATE 110

MASS TRANSFER IN LAMINAR NATURAL CONVECTION ON A VERTICAL PLATE 120

MASS TRANSFER BETWEEN TWO IMMISCIBLE CO-CURRENT STREAMS IN LAMINAR FLOW 127

MASS TRANSFER IN A FALLING LIQUID FILM IN LAMINAR FLOW 130

Mass Transfer Between an Inclined Plate and a Falling Liquid Film 130
Mass Transfer Between a Gas Phase and a Falling Liquid Film 138

MASS TRANSFER IN LAMINAR FLOW THROUGH A TUBE 142

Developing Velocity and Concentration Distributions 149
Uniform Wall Concentration 149
Uniform Mass Flux at the Wall 150
Uniform Plug Velocity Distribution and Developing Concentration Distribution 150
Uniform Wall Concentration 150
Fully Developed Parabolic Velocity Distribution and Developing Concentration Distribution 159
Uniform Wall Concentration 159
Uniform Mass Flux at the Wall 167
Fully Developed Velocity and Concentration Distributions 168
Uniform Wall Concentration 168
Uniform Mass Flux at the Wall 169
Assuming a Cubic Polynomial Concentration Distribution 170
Dispersion in Tube Flow 175

MASS TRANSFER IN LAMINAR FLOW BETWEEN FLAT PARALLEL PLATES 176

MASS TRANSFER IN LAMINAR FLOW THROUGH CONCENTRIC ANNULI 180

TRANSFER WITH A HIGH MASS FLUX 181

The Driving Force B 189
Corrections from Film Theory 190
Corrections from Laminar Boundary Layer Theory 192
Corrections from Penetration Theory 194

Corrections for Variation in Physical Properties 194
Conclusions Concerning Transfer with a
High Mass Flux 199

Nomenclature 208

Problems 213

References 216

Chapter 6 MASS TRANSFER IN TURBULENT FLOW 221

MASS TRANSFER IN THE TURBULENT BOUNDARY LAYER ON A FLAT PLATE 221

MASS TRANSFER IN TURBULENT NATURAL CONVECTION ON A VERTICAL PLATE 225

MASS TRANSFER IN A FALLING LIQUID FILM IN TURBULENT FLOW 228

Mass Transfer Between an Inclined Plate and
a Falling Liquid Film 229

ANALOGIES BETWEEN MOMENTUM AND MASS TRANSFER 231

The Universal Velocity Distribution in
Smooth Tubes 232
The Distribution of Resistance to Mass Transfer
in Turbulent Flow 238
Analogy Assuming only a Turbulent Core 239
Analogy Assuming a Laminar Sublayer and
a Turbulent Core 241
Analogy Assuming a Laminar Sublayer, a Buffer Zone,
and a Turbulent Core 243
Analogy Assuming an Eddying Sublayer, a Buffer Zone,
and a Turbulent Core 247
Analogy Assuming no Discrete Fluid Layers near
the Wall 254
Analogies in Terms of j Factors 264
j Factors for Tubes 265
j Factors for a Flat Plate 271
j Factors for Single Cylinders 273
j Factors for Single Spheres 273
j Factors for Single Oblate Spheroids 284

j Factors Generalized for all Shapes 285
j Factors for Packed and Fluidized Beds 286
Mass Transfer in Noncircular Conduits 289
INTERFACIAL TURBULENCE 289
TRANSFER WITH A HIGH MASS FLUX 291
Nomenclature 295
Problems 300
References 302

Chapter 7 DESIGN OF CONTINUOUS COLUMNS FROM RATE EQUATIONS 308

Capacity and Flooding 309
THE OPERATING LINE 310
Binary Distillation with Reflux 312
Minimum Reflux Ratio 316
Total Reflux 317
Side Streams and Multiple Feeds 317
Open Steam 319
The Leaking Condenser 322
Gas Absorption, Stripping or Desorption, and Liquid Extraction with Reflux 326
The Line Ratio Principle on Triangular Diagrams 329
Material Balances on a Continuous Column Using Reflux 333
Evaluation of Terminal Stream Flow Rates 336
Minimum Reflux Ratio 337
Total Reflux 339
Side Streams and Multiple Feeds 340
The Futility of Raffinate-Type Reflux 344
TRANSFER UNITS IN EQUIMOLAL COUNTERDIFFUSION 344
TRANSFER UNITS IN UNIMOLAL UNIDIRECTIONAL DIFFUSION 346
Approximate Expressions for NTU in Unimolal Unidirectional Diffusion 349
EVALUATION OF THE NUMBER OF TRANSFER UNITS 350

THE RELATIONSHIP BETWEEN OVERALL AND INDIVIDUAL HEIGHTS OF TRANSFER UNITS 352

Nomenclature 374

Problems 379

References 382

Chapter 8 DESIGN OF STAGEWISE COLUMNS FROM RATE EQUATIONS 384

THE PSEUDO-EQUILIBRIUM CURVE 385

ESTIMATION OF INTERFACIAL AREA DURING DROPLET FORMATION 388

ESTIMATION OF INTERFACIAL AREA DURING DROPLET RISE 391

ESTIMATION OF INTERFACIAL AREA DURING DROPLET COALESCENCE 397

ESTIMATION OF THE OVERALL TRANSFER COEFFICIENT DURING DROPLET FORMATION 398

Relationships for the Individual Disperse Phase Coefficient 398
Relationships for the Individual Continuous Phase Coefficient 401

ESTIMATION OF THE OVERALL TRANSFER COEFFICIENT DURING DURING DROPLET RISE 402

Relationships for the Individual Disperse Phase Coefficient 402
Relationships for the Individual Continuous Phase Coefficient 406

ESTIMATION OF THE OVERALL TRANSFER COEFFICIENT DURING DROPLET COALESCENCE 408

Relationships for the Individual Disperse Phase Coefficient 408
Relationships for the Individual Continuous Phase Coefficient 408

EFFECTS OF SURFACE ACTIVE CONTAMINATION 409

A COMPUTER PROGRAM FOR THE PROVISIONAL DESIGN PROCEDURE 411

COMPARISONS BETWEEN PREDICTIONS AND PUBLISHED DATA 412

CONCLUSIONS 426

Nomenclature 426

Problems 430

References 431

Chapter 9 DESIGN OF COOLING TOWERS FROM RATE EQUATIONS 435

Definitions 436
The Wet-Bulb Temperature 438
The Adiabatic Saturation Temperature 441
Relation between the Wet-Bulb and Adiabatic Saturation Temperatures 441
The Psychrometric Chart 442
The Operating Line 446
Transfer Unit Expressions for Simultaneous Heat and Mass Transfer 448
Evaluation of Number of Transfer Units 450
The Axial Temperature-Enthalpy Profile for the Air-Water Vapor Mixture 452
Experimental Evaluation of Individual Rate Coefficients 453
The Minimum Air-to-Water Ratio 454
Cocurrent Flow 464
Dehumidification 467
Humidification and Gas Cooling with Liquid at the Adiabatic Saturation Temperature 470

Nomenclature 474

Problems 477

References 480

APPENDIX 481

AUTHOR INDEX 491

SUBJECT INDEX 499