

- Preface p. iii
- 1 Introduction p. 1
- 1.1 Motivation and Contents p. 1
- 1.2 Preliminaries p. 2
- 1.3 Polymer Matrices for Composites p. 4
- 1.3.1 Polymer Resins p. 7
- 1.3.2 Comparison Between Thermoplastic and Thermoset Polymers p. 9
- 1.3.3 Additives and Inert Fillers p. 11
- 1.4 Fibers p. 11
- 1.4.1 Fiber-Matrix Interface p. 12
- 1.5 Classification p. 13
- 1.5.1 Short Fiber Composites p. 13
- 1.5.2 Advanced Composites p. 15
- 1.6 General Approach to Modeling p. 16
- 1.7 Organization of the Book p. 18
- 1.8 Exercises p. 18
- 1.8.1 Questions p. 18
- 1.8.2 Fill in the Blanks p. 19
- 2 Overview of Manufacturing Processes p. 23
- 2.1 Background p. 23
- 2.2 Classification Based on Dominant Flow Process p. 24
- 2.3 Short Fiber Suspension Manufacturing Methods p. 25
- 2.3.1 Injection Molding p. 25
- 2.3.2 Extrusion p. 32
- 2.3.3 Compression Molding p. 34
- 2.4 Advanced Thermoplastic Manufacturing Methods p. 37
- 2.4.1 Sheet Forming p. 38
- 2.4.2 Thermoplastic Pultrusion p. 41
- 2.4.3 Thermoplastic Tape Lay-Up Process p. 44
- 2.5 Advanced Thermoset Composite Manufacturing Methods p. 46
- 2.5.1 Autoclave Processing p. 46
- 2.5.2 Liquid Composite Molding p. 49
- 2.5.3 Filament Winding p. 52
- 2.6 Exercises p. 54
- 2.6.1 Questions p. 54
- 2.6.2 Fill in the Blanks p. 58
- 3 Transport Equations for Composite Processing p. 63
- 3.1 Introduction to Process Models p. 63
- 3.2 Conservation of Mass (Continuity Equation) p. 64
- 3.2.1 Conservation of Mass p. 65
- 3.2.2 Mass Conservation for Resin with Presence of Fiber p. 69
- 3.3 Conservation of Momentum (Equation of Motion) p. 70
- 3.4 Stress-Strain Rate Relationship p. 75
- 3.4.1 Kinematics of Fluid p. 75
- 3.4.2 Newtonian Fluids p. 80
- 3.5 Examples on Use of Conservation Equations to Solve Viscous Flow Problems p. 84

- 3.5.1 Boundary Conditions p. 84
- 3.5.2 Solution Procedure p. 87
- 3.6 Conservation of Energy p. 95
- 3.6.1 Heat Flux-Temperature Gradient Relationship p. 101
- 3.6.2 Thermal Boundary Conditions p. 103
- 3.7 Exercises p. 107
- 3.7.1 Questions p. 107
- 3.7.2 Problems p. 108
- 4 Constitutive Laws and Their Characterization p. 111
- 4.1 Introduction p. 111
- 4.2 Resin Viscosity p. 112
- 4.2.1 Shear Rate Dependence p. 114
- 4.2.2 Temperature and Cure Dependence p. 118
- 4.3 Viscosity of Aligned Fiber Thermoplastic Laminates p. 121
- 4.4 Suspension Viscosity p. 129
- 4.4.1 Regimes of Fiber Suspension p. 129
- 4.4.2 Constitutive Equations p. 136
- 4.5 Reaction Kinetics p. 137
- 4.5.1 Techniques to Monitor Cure: Macroscopic Characterization p. 141
- 4.5.2 Technique to Monitor Cure: Microscopic Characterization p. 143
- 4.5.3 Effect of Reinforcements on Cure Kinetics p. 144
- 4.6 Crystallization Kinetics p. 146
- 4.6.1 Introduction p. 146
- 4.6.2 Solidification and Crystallization p. 146
- 4.6.3 Background p. 147
- 4.6.4 Crystalline Structure p. 148
- 4.6.5 Spherulitic Growth p. 149
- 4.6.6 Macroscopic Crystallization p. 150
- 4.7 Permeability p. 151
- 4.7.1 Permeability and Preform Parameters p. 155
- 4.7.2 Analytic and Numerical Characterization of Permeability p. 156
- 4.7.3 Experimental Characterization of Permeability p. 157
- 4.8 Fiber Stress p. 161
- 4.9 Exercises p. 164
- 4.9.1 Questions p. 164
- 4.9.2 Fill in the Blanks p. 167
- 4.9.3 Problems p. 169
- 5 Model Simplifications and Solution p. 173
- 5.1 Introduction p. 173
- 5.1.1 Usefulness of Models p. 174
- 5.2 Formulation of Models p. 175
- 5.2.1 Problem Definition p. 175
- 5.2.2 Building the Mathematical Model p. 177
- 5.2.3 Solution of the Equations p. 177
- 5.2.4 Model Assessment p. 178
- 5.2.5 Revisions of the Model p. 179

- 5.3 Model and Geometry Simplifications p. 180
- 5.4 Dimensionless Analysis and Dimensionless Numbers p. 183
- 5.4.1 Dimensionless Numbers Used in Composites Processing p. 190
- 5.5 Customary Assumptions in Polymer Composite Processing p. 198
- 5.5.1 Quasi-Steady State p. 198
- 5.5.2 Fully Developed Region and Entrance Effects p. 199
- 5.5.3 Lubrication Approximation p. 200
- 5.5.4 Thin Shell Approximation p. 201
- 5.6 Boundary Conditions for Flow Analysis p. 201
- 5.6.1 In Contact with the Solid Surface p. 201
- 5.6.2 In Contact with Other Fluid Surfaces p. 202
- 5.6.3 Free Surfaces p. 202
- 5.6.4 No Flow out of the Solid Surface p. 202
- 5.6.5 Specified Conditions p. 203
- 5.6.6 Periodic Boundary Condition p. 203
- 5.6.7 Temperature Boundary Conditions p. 203
- 5.7 Convection of Variables p. 205
- 5.8 Process Models from Simplified Geometries p. 206
- 5.8.1 Model Construction Based on Simple Geometries p. 209
- 5.9 Mathematical Tools for Simplification p. 211
- 5.9.1 Transformation of Coordinates p. 211
- 5.9.2 Superposition p. 213
- 5.9.3 Decoupling of Equations p. 215
- 5.10 Solution Methods p. 216
- 5.10.1 Closed Form Solutions p. 217
- 5.11 Numerical Methods p. 219
- 5.12 Validation p. 221
- 5.12.1 Various Approaches for Validation p. 221
- 5.13 Exercises p. 223
- 5.13.1 Questions p. 223
- 5.13.2 Problems p. 225
- 6 Short Fiber Composites p. 227
- 6.1 Introduction p. 227
- 6.2 Compression Molding p. 229
- 6.2.1 Basic Processing Steps [1] p. 229
- 6.2.2 Applications [1] p. 230
- 6.2.3 Flow Modeling p. 231
- 6.2.4 Thin Cavity Models p. 231
- 6.2.5 Hele-Shaw Model p. 234
- 6.2.6 Lubricated Squeeze Flow Model p. 238
- 6.2.7 Hele-Shaw Model with a Partial Slip Boundary Condition [2] p. 243
- 6.2.8 Heat Transfer and Cure p. 248
- 6.2.9 Cure p. 251
- 6.2.10 Coupling of Heat Transfer with Cure p. 252
- 6.2.11 Fiber Orientation p. 254
- 6.3 Extrusion p. 255

- 6.3.1 Flow Modeling p. 257
- 6.3.2 Calculation of Power Requirements [3] p. 260
- 6.3.3 Variable Channel Length [3] p. 262
- 6.3.4 Newtonian Adiabatic Analysis [3] p. 263
- 6.4 Injection Molding p. 265
- 6.4.1 Process Description p. 265
- 6.4.2 Materials p. 267
- 6.4.3 Applications p. 267
- 6.4.4 Critical Issues p. 268
- 6.4.5 Model Formulation for Injection Molding p. 269
- 6.4.6 Fiber Orientation p. 280
- 6.5 Exercises p. 285
- 6.5.1 Questions p. 285
- 6.5.2 Fill in the Blanks p. 287
- 6.5.3 Problems p. 289
- 7 Advanced Thermoplastic Composite Manufacturing Processes p. 291
- 7.1 Introduction p. 291
- 7.2 Composite Sheet Forming Processes p. 292
- 7.2.1 Diaphragm Forming p. 293
- 7.2.2 Matched Die Forming p. 293
- 7.2.3 Stretch and Roll Forming p. 295
- 7.2.4 Deformation Mechanisms p. 296
- 7.3 Pultrusion p. 299
- 7.3.1 Thermoset Versus Thermoplastics Pultrusion p. 300
- 7.3.2 Cell Model [4] p. 300
- 7.4 Thermal Model p. 308
- 7.4.1 Transient Heat Transfer Equation p. 308
- 7.4.2 Viscous Dissipation p. 310
- 7.5 On-line Consolidation of Thermoplastics p. 311
- 7.5.1 Introduction to Consolidation Model p. 314
- 7.5.2 Importance of Process Modeling p. 314
- 7.5.3 Consolidation Process Model p. 316
- 7.5.4 Model Assumptions and Simplifications p. 316
- 7.5.5 Governing Equations p. 317
- 7.5.6 Boundary Conditions p. 322
- 7.5.7 Rheology of the Composite p. 323
- 7.5.8 Model Solutions p. 324
- 7.5.9 Inverse Problem of Force Control p. 331
- 7.5.10 Extended Consolidation Model p. 331
- 7.6 Exercises p. 333
- 7.6.1 Questions p. 333
- 7.6.2 Fill in the Blanks p. 334
- 7.6.3 Problems p. 337
- 8 Processing Advanced Thermoset Fiber Composites p. 339
- 8.1 Introduction p. 339
- 8.2 Autoclave Molding p. 340

- 8.2.1 Part Preparation p. 341
- 8.2.2 Material and Process Parameters p. 341
- 8.2.3 Processing Steps p. 348
- 8.2.4 Critical Issues p. 348
- 8.2.5 Flow Model for Autoclave Processing p. 349
- 8.3 Liquid Composite Molding p. 356
- 8.3.1 Similarities and Differences Between Various LCM Processes p. 356
- 8.3.2 Important Components of LCM Processes p. 361
- 8.3.3 Modeling the Process Issues in LCM p. 367
- 8.3.4 Process Models p. 375
- 8.3.5 Resin Flow p. 376
- 8.3.6 Heat Transfer and Cure p. 382
- 8.3.7 Numerical Simulation of Resin Flow in LCM Processes p. 390
- 8.4 Filament Winding of Thermosetting Matrix Composites p. 393
- 8.4.1 Introduction p. 393
- 8.4.2 Process Models p. 395
- 8.5 Summary and Outlook p. 402
- 8.6 Exercises p. 403
- 8.6.1 Questions p. 403
- 8.6.2 Fill in the Blanks p. 405
- 8.6.3 Problems p. 407
- Bibliography p. 409
- Index p. 433