Contents

PREFACE xiii
Gilles AUSIAS and Francisco CHINESTA

CHAPTER 1. INTRODUCTION TO SUSPENSION RHEOLOGY 1
Nhan PHAN-THIEN

1.1. Introduction. 1
1.2. General bulk suspension properties. 3
1.2.1. Bulk stress and stresslet 3
1.2.2. Bulk dissipation. 5
1.3. Dilute suspension of rigid spheres 6
1.3.1. Stresslet. 6
1.3.2. An exact poly-dispersed model. 8
1.4. Dilute suspension of spherical droplets 9
1.5. Dilute suspension of rigid spheroids 10
1.5.1. Jeffery's solution and stress rule 10
1.5.2. Jeffery's orbit 11
1.6. Bibliography 15

CHAPTER 2. RHEOLOGICAL CHARACTERIZATION OF FIBER SUSPENSIONS AND NANOCOMPOSITES 19
Pierre J. CARREAU and Bruno VERGNES

2.1. General considerations 19
2.1.1. Basic concepts. 19
2.1.2. Difficulties encountered in rheometry. 21
2.1.3. Homogenization and other problems 23
2.2. Suspensions of fibers 24
2.2.1. Suspensions of glass fibers in a Newtonian matrix and in Boger fluids 24

2.2.2. Suspensions of glass fibers in polypropylene 27
2.2.3. Suspensions of flexible fibers in polymers 30
2.3. Nanocomposites 33
2.3.1. Suspensions of nanoclay particles 33
2.3.2. Suspensions of carbon nanotubes 46
2.4. Concluding remarks 53
2.5. Bibliography 54

CHAPTER 3. RHEOLOGY OF CARBON NANOPARTICLE SUSPENSIONS AND NANOCOMPOSITES 59

Philippe CASSAGNAU

3.1. Introduction 59
3.2. Diffusivity of nanoparticles 61
3.3. Fractal particles: carbon black 63
3.4. Aggregated particles: graphite oxide derivatives and carbon nanotubes 66
3.5. Analogy between shear modulus of nanocomposites and shear viscosity of suspensions 71
3.6. Conclusion 72
3.7. Bibliography 73

CHAPTER 4. RHEOLOGICAL MODELING OF NON-DILUTE ROD SUSPENSIONS 77

Julien FÉREC and Gilles AUSIAS

4.1. Introduction 77
4.2. Intrinsic properties of fibers 78
4.2.1. Concentration regimes 79
4.2.2. Flexibility 79
4.2.3. Particle Reynolds and Peclet numbers, and sedimentation 80
4.3. Description of fiber orientation states 80
4.3.1. Orientation of a single fiber 80
4.3.2. Orientation of many fibers: the probability distribution function 81
4.3.3. Moments of PDF 82
4.4. Orientation evolution equations 85
4.4.1. Dilute suspensions 85
4.4.2. Recent advances for non-dilute suspensions 87
4.5. Rheological equations for fiber suspensions 92
4.5.1. Newtonian matrix suspensions 92
4.5.2. Non-Newtonian matrix suspensions 96

4.6. Closure approximations 98
4.6.1. Analytical solutions 99
4.6.2. Hybrid closure 100
4.6.3. Composite closures 101
4.6.4. Fitted closures 102
4.6.5. Closure approximations for a_6 105
4.6.6. Approximations for interaction tensors 106
4.7. Concluding remarks 108
4.8. Bibliography 108

CHAPTER 5. RHEOLOGY OF HIGHLY CONCENTRATED FIBER SUSPENSIONS 119

Laurent ORGÉAS, Pierre DUMONT and Steven LE CORRE

5.1. Introduction 119
5.2. Experimental trends observed at macro- and mesoscales 126
5.2.1. Rheometry difficulties 126
5.2.2. Typical trends 129
5.2.3. Influence of the strain rate 130
5.2.4. Influence of the fiber content ϕ and aspect ratio r on stress levels 131
5.2.5. Influence of the fiber orientation on stress levels and orientation dynamics 132
5.2.6. Migration phenomena 133
5.3. Microstructure and micromechanics 134
5.3.1. Microstructure imaging and modeling 134
5.3.2. Micromechanics 139
5.3.3. Simultaneous micromechanics and microstructure imaging 140
5.4. Rheological models: single-phase approaches 142
5.4.1. Macroscale versus multiscale approaches 142
5.4.2. Revisiting the validity domain of multiscale single-phase approaches 144
5.4.3. Application to fiber bundle suspensions 148
5.5. Rheological models: a two-phase approach 150
5.5.1. General principles of a two-phase model 151
5.5.2. Mass and momentum balance equations 152
5.5.3. Constitutive relations 152
5.5.4. Application to migration phenomena in fiber bundle suspensions 156
5.6. Conclusion 158
5.7. Bibliography 159

CHAPTER 6. TOWARDS A KINETIC THEORY DESCRIPTION OF ELECTRICAL CONDUCTION IN PERFECTLY DISPERSED CNT NANOCOMPOSITES 167

Marta PEREZ, Emmanuelle ABISSET-CHAVANNE, Anaïs BARASINSKI, Amine AMMAR, Francisco CHINESTA and Roland KEUNINGS

6.1. Introduction. 167
6.2. Orientation induced by the electric field 169
6.2.1. Microscopic description 169
6.2.2. Mesoscopic description 171
6.2.3. Macroscopic description. 172
6.3. Introducing randomizing mechanisms 175
6.4. Proper generalized decomposition and parametric solutions 177
6.5. Electrical properties 179
6.5.1. Evaluating the electric field 179
6.5.2. Evaluating the electrical properties 179
6.5.3. Determining electrical paths 181
6.6. Numerical results 182
6.6.1. Fluid at rest 182
6.6.2. Introducing the fluid flow 192
6.7. Conclusions. 199
6.8. Bibliography 199

CHAPTER 7. STICK-SLIP INSTABILITIES IN MAGNETORHEOLOGICAL FLUIDS 203

Modesto T. LÓPEZ-LÓPEZ, Laura RODRÍGUEZ-ARCO, Pavel KUZHIR, Juan D.G. DURAN, Andrey ZUBAREV and Georges BOSSIS

7.1. Introduction. 204
7.2. Materials and methods 205
7.2.1. Materials 205
7.2.2. Preparation of the MR fluids 206
7.2.3. Rheological measurements 207
7.3. Experimental results. 210
7.3.1. Flow curves 210
7.3.2. Stick-slip instabilities 212
7.4. Theory and discussion 216
7.4.1. Suspension of silica-coated iron particles in mineral oil (MR fluid 1) 216
7.4.2. Suspension of CIP in silicone oil (MR fluid 2) 220

7.4.3. Suspension of CoNi fibers in mineral oil (MR fluid 3) 224
7.5. Conclusions. 228
7.6. Acknowledgments 229
7.7. Bibliography 229

CHAPTER 8. NUMERICAL SIMULATIONS OF VISCOELASTIC SUSPENSION FLUID DYNAMICS 235

Gaetano D'AVINO

8.1. Introduction. 235
8.2. Mathematical model. 237
8.2.1. Governing equations 237
8.2.2. Constitutive equations 239
8.2.3. Dimensionless equations 241
8.3. Shear flow 244
8.3.1. Rotation of a spherical particle 245
8.3.2. Migration of a spherical particle 250
8.3.3. Rotation of an ellipsoidal particle 254
8.3.4. Interactions between two equally-sized particles 256
8.3.5. Flow-induced alignment 260
8.4. Poiseuille flow 267
8.4.1. Migration of a spherical particle 268
8.4.2. Dynamics of pairs and triplets of particles in a cylindrical channel 273
8.5. Summary 275
8.6. Bibliography 277

CHAPTER 9. BROWNIAN DYNAMICS SIMULATION FOR SPHEROID PARTICLE SUSPENSIONS IN POLYMER SOLUTION 281

Takehiro YAMAMOTO

9.1. Introduction. 281
9.2. Modeling of spheroid particles and polymer solutions 284
9.2.1. Expression of spheroid particles and polymers 284
9.2.2. Interaction between particles 286
9.2.3. Hydrodynamic drag force 290
9.2.4. Brownian force 292
9.3. Basic equations of the Brownian dynamics simulation for suspensions of spheroid particles in polymer solution 293
9.3.1. Formulation 293
9.3.2. Evaluation of flow-induced structures and rheological properties 298
9.3.3. Non-dimensionalization 302
9.3.4. Boundary conditions 302

9.4. Example of Brownian dynamics simulation of disk-like particle/polymer system . . . 303
9.4.1. Numerical conditions . . . 304
9.4.2. Simulation results . . . 304
9.5. Summary . . . 310
9.6. Bibliography . . . 311

CHAPTER 10. MULTISCALE MECHANICS AND THERMODYNAMICS OF SUSPENSIONS . . . 313

Miroslav GRMELA, Amine AMMAR and Guillaume MAÎTREJEAN

10.1. Introduction . . . 313
10.2. Rheological modeling . . . 314
10.2.1. State variables . . . 314
10.2.2. Compatibility with mechanics . . . 315
10.2.3. Compatibility with thermodynamics . . . 319
10.3. Rigid fibers and rigid lamellae . . . 322
10.3.1. State variables . . . 322
10.3.2. Kinematics . . . 324
10.3.3. Thermodynamic forces and Λ . . . 327
10.3.4. Thermodynamic potential Φ . . . 328
10.3.5. Governing equations, their solutions and comparison with the results of experimental observations . . . 328
10.4. Kinetic theory and closures . . . 332
10.4.1. State variables . . . 332
10.4.2. Kinematics . . . 333
10.4.3. Thermodynamic forces and Λ . . . 336
10.4.4. Thermodynamic potential Φ . . . 336
10.4.5. Governing equations, their solutions and comparison with experimental observations and reductions . . . 336
10.5. Deformable chains and deformable ellipsoids . . . 345
10.5.1. State variables . . . 345
10.5.2. Kinematics . . . 347
10.5.3. Thermodynamic forces and Λ . . . 348
10.5.4. Thermodynamic potential Φ . . . 349
10.5.5. Governing equations, their solutions and comparison with experimental observations . . . 349
10.6. Rigid spheres . . . 351
10.6.1. State variables . . . 353
10.6.2. Governing equations . . . 353
10.6.3. Derivation of the extended Smoluchowski equation . . . 356

10.7. Exercises. 370
10.8. Concluding remarks 372
10.9. Bibliography 374

LIST OF AUTHORS 379

INDEX 381