

Table of Contents

Acknowledgments	xi
Introduction	xiii
PART 1. APPROACH AND GENERAL EQUATIONS	1
Chapter 1. Towards a Unified Description of Multiphase Flows	3
1.1. Continuous approach and kinetic approach	3
1.2. Eulerian–Lagrangian and Eulerian formulations	7
Chapter 2. Instant Equations for a Piecewise Continuous Medium	9
2.1. Integral and differential forms of balance equations	10
2.2. Phase mass balance equations in a piecewise continuous medium	13
2.3. Momentum balances	17
2.4. Energy balances	21
2.5. Position and interface area balance equations.	23
2.6. Extension for a fluid phase that is a mixture	25
2.7. Completing the description of the medium	27
Chapter 3. Description of a “Mean Multiphase Medium”	29
3.1. The need for a mean description	29
3.2. How are mean values defined?	31
3.2.1. Temporal average	31
3.2.2. Volumetric average.	32
3.2.3. Statistical average.	34
3.2.4. Filtered average	35
3.3. Which average to choose, according to their advantages and disadvantages?	37

Chapter 4. Equations for the Mean Continuous Medium	39
4.1. Global balance equations for the mean medium	39
4.1.1. Total mass	39
4.1.2. Total momentum	40
4.1.3. Total energy	41
4.2. Balance equations for the phases of a mean medium	42
4.2.1. Phase mass	43
4.2.2. Phase momentum	44
4.2.3. Energies of each phase	47
4.2.4. Phase volume	49
4.3. Complete representation of the mean medium	49
4.3.1. Global representation	50
4.3.2. Multifluid representation	51
4.4. Mean equations of state	55
4.5. Extensions	58
4.5.1. Extension when a fluid phase is a mixture	58
4.5.2. Extension for dispersed media	59
4.6. Boundary conditions	61
 PART 2. MODELING: A SINGLE APPROACH ADAPTABLE TO MULTIPLE APPLICATIONS.	 67
 Chapter 5. The Modeling of Interphase Exchanges	 69
5.1. General methodology	69
5.2. Interface between phases and its mean area per unit of volume	71
5.2.1. Case of a suspension of liquid or solid particles	71
5.2.2. Case of a medium containing parcels of variable shapes and sizes	72
5.2.3. Case of a suspension of particles of constant and known sizes	74
5.3. Forces of contact and friction between phases	75
5.3.1. Pressure forces on spherical particles in a non-viscous flow	76
5.3.2. Friction on solid particles in steady flow	80
5.3.3. Slightly curved liquid–gas interfaces	87
5.3.4. Drops or bubbles	93
5.4. Heat transfers at the surface of a particle, without mass exchange	96
5.5. Heat and mass transfers during boiling	99
5.5.1. Slightly curved liquid–gas interfaces	99
5.5.2. Bubbles	105
5.6. Mass and heat exchanges by vaporization	107
5.6.1. Mass transfer by evaporation at a flat interface	107
5.6.2. Evaporation of a drop	113
5.6.3. Combustion of a drop	117

Chapter 6. Modeling Turbulent Dispersion Fluxes	119
6.1. Global modeling	119
6.1.1. General information	119
6.1.2. Kinetic energy of the “global fluctuations”.	123
6.1.3. Modeling the kinetic energy of the fluctuations	128
6.1.4. Length scales for fluctuations and time scale for the dissipation of kinetic energy of fluctuations	132
6.1.5. Further studies on the dispersion flux of a phase	137
6.2. “Multifluid” modeling	147
6.2.1. The kinetic energy of the fluctuations in each phase	149
6.2.2. Modeling the balance equations of the kinetic energies of turbulence	152
6.2.3. The modeling of time or spatial scales	158
6.2.4. Modeling of the Reynolds tensor for every phase	162
Chapter 7. Modeling the Mean Gas–Liquid Interface Area per Unit Volume	165
7.1. Introduction.	165
7.2. Initial equation for the mean interface area per unit volume	166
7.3. Model of the mean interface area during the “atomization” of a liquid jet.	168
7.4. Effects of vaporization on the interface area	172
Chapter 8. “Large Eddy Simulation” Style Models	175
8.1. Introduction.	175
8.2. Filtered equations and the nature of the models to be provided	177
8.3. Classic LES modeling for SGS additional fluxes.	181
8.3.1. Reminder of LES in single-phase, constant density turbulent flows	181
8.3.2. Toward an extension for multiphase flows	183
8.4. Subgrid modeling of the interface area per unit volume.	185
8.5. Partially Integrated Turbulence Modeling.	188
Chapter 9. Contribution of Thermodynamics of Irreversible Processes	191
9.1. Global two-phase medium models	192
9.1.1. Entropy of a mean two-phase medium using the Prandtl model	194
9.1.2. Entropy for the k – ϵ model, in a medium with a variable density	200
9.2. Contribution of thermodynamics to multifluid models	206

Chapter 10. Experimental Methods	213
10.1. Introduction	213
10.2. Intrusive methods	214
10.2.1. Pitot tubes	215
10.2.2. Hot films	216
10.2.3. Optical needle probes (single probes, bi-probes and quadri-probes)	219
10.2.4. Wire networks	223
10.3. Non-intrusive methods	224
10.3.1. Particle image velocimetry (PIV)	225
10.3.2. Droplet tracking velocimetry	230
10.3.3. Laser Doppler anemometry (LDA)	234
10.3.4. Phase Doppler anemometry (PDA)	237
10.3.5. Ultrasonic Doppler Anemometry	241
10.3.6. Densimetry by attenuation of gamma, X-ray or neutron radiation	243
10.4. Advanced optical methods	245
10.4.1. Laser induced fluorescence	245
10.4.2. Interferometric methods (digital inline holography, Fourier interferometric imaging, ILIDS/IPI, rainbow)	252
Chapter 11. Some Experimental Results Pertaining to Multiphase Flow Properties that Are Still Little Understood	265
11.1. Atomization/fragmentation of liquid jets	265
11.2. Isolated bubbles, bubbles in swarm and their effects on carrier fluid	274
11.3. Boiling crisis	285
PART 3. FROM FLUIDIZED BEDS TO GRANULAR MEDIA	297
Chapter 12. Fluidized Beds	299
12.1. Introduction	299
12.1.1. Classification of different fluidization regimes	299
12.1.2. Minimum fluidization and bubbling velocities	304
12.2. Complete models for the dynamics of fluidized beds	306
12.2.1. Bubbling fluidization regime	307
12.2.2. Turbulent fluidization regime	315
12.3. Global models for chemical conversion in fluidized beds	321
12.3.1. Bubbling regime fluidizations	321
12.3.2. Fast fluidization regime	324
12.3.3. Turbulent fluidization regime	325

12.4. Global models for heat transfers in fluidized beds	328
12.4.1. Bubbling fluidization regime	328
12.4.2. Fast fluidization regimes – circulating beds	331
12.5. Conclusion	334
Chapter 13. Generalizations for Granular Media	335
13.1. Introduction	335
13.2. Balance equations for mean granular media	336
13.3. Necessary closure approximations	342
13.4. Some already proposed methods	345
Chapter 14. Modeling of Cauchy Tensor of Sliding Contacts	349
14.1. Hypotheses and basic equations	349
14.2. Unclosed balance equation for Cauchy tensor of sliding contact.	351
14.3. Closure approximations for irreversible terms	358
Chapter 15. Modeling the Kinetic Cauchy Stress Tensor	363
15.1. Prandtl–Bagnold modeling	364
15.2. K- l_i or “turbulent granular gas” modeling	366
15.3. Toward a general model for all regimes	371
15.4. Boundary conditions at walls	373
PART 4. STUDYING FLUCTUATIONS AND PROBABILITY DENSITIES	377
Chapter 16. Fluctuations of the Gas Phase in Reactive Two-Phase Media	379
16.1. Specificities of reactive two-phase media	379
16.2. Probability density of composition fluctuations of the gas phase	380
16.2.1. Instant basic equations of the gas medium	382
16.2.2. PDF equation	385
16.3. Modeling the terms due to exchanges between phases.	390
16.3.1. Total mass exchange	390
16.3.2. Mass exchange for species.	392
16.3.3. Heat exchange	393
16.4. Modeling micromixing and turbulent dispersion	395
16.4.1. The “micromixing” term in PDF equations.	395
16.4.2. Turbulent diffusion terms in PDF equations	396
16.5. Practical use of PDF equations.	397

Chapter 17. Temperature Fluctuations in Condensed Phases	399
17.1. Problems.	399
17.2. Instantaneous equation for the temperature of the liquid phase.	401
17.3. Equation for the PDF of the temperature of the liquid	403
17.4. Closure of the equation of the temperature PDF	405
Chapter 18. Study of the PDF for Velocity Fluctuations and Sizes of Parcels	409
18.1. Phase velocity PDF equation.	410
18.2. Modeling the exchanges between phases and the internal interactions	415
18.2.1. Terms of exchanges between phases	415
18.2.2. Internal dissipation and production of fluctuations	418
18.3. Practical calculation of PDF	419
18.4. The study of the sizes of the dispersed phase parcels	420
18.5. Eulerian–Lagrangian simulation of dispersed media.	423
18.5.1. Lagrangian equations of the parcels	423
18.5.2. Stochastic simulations	426
Bibliography	431
Index	443