

CONTENTS

Preface	xvii
Acknowledgments	xix
Nomenclature	xxi
1. Introduction	1
1.1 Background	1
1.2 Definitions	7
1.3 Important Physicochemical Phenomena	8
1.4 Types of Aerosol Processes	11
1.5 Advantages and Disadvantages of Aerosol Processes	14
1.6 Recommended Books by Topic	16
1.7 References	18
2 Particle Size Distribution and Physical and Chemical Characteristics	19
2.1 Introduction	19
2.2 Mean Free Path of the Gas	20
2.3 Mass and Particle Concentration	23
2.4 Particle Size Distribution	24
2.4.1 Introduction	24
2.4.2 Average Particle Size	28
2.4.3 Spread of the Distribution	30
2.4.4 Moments of Particle Size Distribution	31
2.5 Density and Surface Area	32
2.6 Particle Morphology	33
2.7 Chemical and Phase Composition	38
2.8 Crystallinity	41
2.9 References	43

3 Particle Transport	45
3.1 Introduction	45
3.2 Diffusion	45
3.2.1 Wall Losses by Diffusion	50
3.3 Transport Coefficient Approach to Diffusional Deposition of Particles	52
3.4 Diffusion Equation Approach to Particle Deposition	54
3.5 Particle Motion in External Force Fields	55
3.5.1 Sedimentation in a Gravitational Field	56
3.5.2 Motion of Charged Particles in Electric Fields	59
3.5.3 Particle Motion in Thermal Gradients	62
3.6 Impaction	65
3.6.1 Particle Deposition by Impaction from Aerosol Jets	67
3.6.2 Particle Deposition in Tube Bends	69
3.6.3 Turbulent Deposition in Pipe Flows	70
3.7 Photophoresis and Radiometry	71
3.8 Structure of Deposits	71
3.9 References	72
4 Particle Growth, Evaporation, and Nucleation	75
4.1 Introduction	75
4.2 Qualitative Description of Particle Growth	76
4.3 Particle Growth: Free-Molecule and Transition Regimes	77
4.4 Transport: Continuum Regime	81
4.5 Droplet Evaporation: Characteristic Time for Gas-Phase Diffusion to a Particle	83
4.6 Evaporation from Solution Droplets	84
4.7 Droplet Evaporation during Materials Processing	85
4.8 Chemical Reactions: Surface-Reaction-Limited Growth	89
4.9 Chemical Reactions: Volume-Reaction-Limited Growth	92
4.10 Nucleation	93
4.10.1 Classical Homogeneous Nucleation	96
4.10.2 Collision-Controlled Nucleation	97
4.10.3 Chemical Nucleation	100
4.10.4 Materials That Sublime Dissociatively	101
4.11 References	102
5 Collision and Coalescence	105
5.1 Introduction	105
5.2 Brownian Coagulation	107
5.3 Characteristic Time for Coagulation	109
5.4 Shear-Induced and Turbulent Coagulation	110

5.5	Coagulation by Electric Forces	112
5.6	Self-Preserving Size Distributions: Uncharged Spherical Particles	113
5.7	Self-Preserving Size Distributions: Uncharged Agglomerates	119
5.8	Self-Preserving Size Distributions: Charged Particles	122
5.9	Coalescence of Particles	124
5.10	References	127
6	Intraparticle Transport Processes	129
6.1	Introduction	129
6.2	Solid-State and Liquid-Phase Diffusion	130
6.2.1	Introduction	130
6.2.2	Theory	132
6.2.3	Liquid Phase	135
6.2.4	Solid State	137
6.3	Heat Transfer within Particles	138
6.4	Gas–Solid Reactions	140
6.4.1	Introduction	140
6.4.2	Shrinking-Core Model	141
6.5	Gas–Liquid Reactions	143
6.6	References	144
7	Models Based on the General Dynamic Equation	146
7.1	Introduction	146
7.2	General Dynamic Equation	147
7.3	Discrete Models	148
7.4	Sectional Models	150
7.5	Lognormal and Other Moment Models	153
7.6	Monodisperse with Sintering	157
7.7	Comparison of Models	159
7.8	Modeling of Particle Deposition Processes	159
7.9	References	163
8	Chemistry	166
8.1	Introduction	166
8.2	General Features of Metal-Containing Compounds	172
8.3	Selection of Chemical Reagents as Precursors: Important Chemical Properties Related to Aerosol Processing	178
8.3.1	Solubility	179
8.3.2	Volatility	182
8.3.3	Reactivity	185

8.4 Thermally Induced Reactions of Metal-Containing Compounds	186
8.4.1 Thermal Decomposition of Inorganic Compounds	186
8.4.1.1 Metal Nitrates	187
8.4.1.2 Metal Carbonates	190
8.4.1.3 Metal Sulfates	192
8.4.1.4 Metal Halides	194
8.4.2 Thermal Decomposition of Metal-Organic Compounds	199
8.4.2.1 Metal Carboxylates	199
8.4.2.2 Metal Alkoxides	202
8.4.2.3 Metal Diketonates	203
8.4.2.4 Metal Amides	203
8.4.2.5 Other Derivatives	204
8.4.3 Thermal Decomposition of Organometallic Compounds	204
8.5 Photo-Induced Reactions	204
8.6 Plasma-Induced Reactions	206
8.7 Flame-Induced Reactions	210
8.8 Single-Source Precursors	214
8.9 Surface Processes	218
8.10 Solid-State Processes: Crystallization, Densification, Porosity, and Surface Properties	221
8.11 References	225
9 Characteristics of Nanostructured Materials	230
9.1 Introduction	230
9.2 Properties of Nanostructured Materials	238
9.2.1 Electronic Properties	239
9.2.2 Optical Properties	242
9.2.3 Magnetic Properties	244
9.2.4 Compositional and Phase Behavior	246
9.2.4.1 Crystal Lattice Distortions	246
9.2.4.2 Compositional Inhomogeneities	247
9.2.4.3 Phase Transitions and Temperatures	249
9.2.4.4 Vapor Pressure	250
9.2.4.5 Internal Pressure	251
9.2.4.6 Melting Point	252
9.2.4.7 Solubility	253
9.2.5 Mechanical Properties of Consolidated Nanoparticles	254
9.2.6 Chemical Reactivity	258

9.3	Applications of Nanostructured Materials	260
9.3.1	Current Applications	261
9.3.2	Future Applications	262
9.4	References	262
10	Overall Qualitative Behavior of Gas-to-Particle Conversion Processes	266
10.1	Introduction	266
10.2	Modes of Operation for Single-Component Systems	269
10.2.1	Nucleation–Coagulation	270
10.2.2	Nucleation–Condensation	275
10.3	Modes of Operation for Multicomponent Systems	279
10.3.1	Generation of Multicomponent Materials Using Two or More Volatile Species	279
10.3.2	Strategies for Avoiding Segregation in Multicomponent Materials	285
10.3.3	Strategies for Producing Composite Particles	288
10.3.4	Strategies for Producing Coated Particles	288
10.4	Fluidized Beds	290
10.5	References	291
11	Technology of Gas-to-Particle Conversion	293
11.1	Introduction	293
11.2	Comparison of Different Gas-to-Particle Conversion Routes and Their Comparison with Liquid-to-Solid and Solid-to-Solid Conversion Routes	296
11.3	Design	298
11.4	Chemical Routes: Tubular Flow Reactors	299
11.4.1	Introduction	299
11.4.2	Precursors and Products	302
11.4.3	Experimental Considerations	303
11.4.4	Theory	306
11.5	Chemical Routes: Flame Reactors	306
11.5.1	Introduction	306
11.5.2	Precursors and Products	308
11.5.3	Experimental Considerations	309
11.5.4	Theory	310
11.6	Chemical Routes: Laser-Driven Photothermal Reactors	311
11.6.1	Introduction	311
11.6.2	Precursors and Products	313
11.6.3	Experimental Details	314
11.6.4	Theory	315

11.7	Chemical Routes: Laser-Driven Photochemical Reactors	315
11.7.1	Introduction	315
11.7.2	Precursors and Products	315
11.7.3	Experimental Considerations	316
11.7.4	Theory	316
11.8	Chemical Routes: Thermal Plasma Reactors	316
11.8.1	Introduction	316
11.8.2	Precursors and Products	318
11.8.3	Experimental Considerations	318
11.8.4	Theory	321
11.9	Chemical Routes: Low-Temperature Plasma Reactors	323
11.9.1	Introduction	323
11.9.2	Precursors and Products	324
11.9.3	Experimental Considerations	324
11.9.4	Theory	324
11.10	Chemical Processes: Fluidized Beds	325
11.10.1	Introduction	325
11.10.2	Precursors and Products	326
11.10.3	Experimental Considerations	326
11.10.4	Theory	327
11.11	Physical Processes: Free Convective Plumes and Tubular Flow Systems	327
11.11.1	Introduction	327
11.11.2	Precursors and Products	329
11.11.3	Experimental Considerations	330
11.11.4	Theory	332
11.12	Physical Processes: Nozzle Expansion	334
11.12.1	Introduction	334
11.12.2	Precursors and Products	335
11.12.3	Experimental Considerations	335
11.12.4	Theory	336
11.13	Physical Processes: Laser Ablation	336
11.13.1	Introduction	336
11.13.2	Precursors and Products	337
11.13.3	Experimental Considerations	338
11.13.4	Theory	338
11.14	Physical Processes: Supercritical Spraying	338
11.14.1	Introduction	338
11.14.2	Precursors and Products	339
11.14.3	Experimental Considerations	340
11.14.4	Theory	340

11.15	Hybrid Processes: Evaporation–Condensation–Reaction	342
11.15.1	Introduction	342
11.15.2	Precursors and Products	343
11.15.3	Experimental Considerations	343
11.15.4	Theory	344
11.16	References	345
11.17	Tables	352
12	Overall Qualitative Behavior of Liquid-to-Solid and Solid-to-Solid Conversion Processes	380
12.1	Introduction	380
12.2	Overview of Basic Physicochemical Phenomena	381
12.2.1	Droplet Formation	384
12.2.2	Processes within Droplets	384
12.2.3	Particles Containing Solids and Liquids	384
12.2.4	Dried Particles	385
12.2.5	Product Particles	386
12.2.6	Aerosol Dynamics	386
12.2.7	Reactor-scale Phenomena	386
12.3	Individual Physical and Chemical Phenomena	387
12.3.1	Droplet Generation	387
12.3.2	Heat Transfer	389
12.3.3	Solvent Transport	392
12.3.4	Solute Transport in Droplets	396
12.3.5	Solute Precipitation in Droplets	399
12.3.6	Transport of Gaseous Species in Solid Particles	400
12.3.7	Intraparticle Reaction	402
12.4	Overall Qualitative Behavior of Liquid-to-Solid and Solid-to-Solid Conversion Processes	403
12.4.1	Droplet Evaporation in Flow Systems	403
12.4.2	Influence of Solvent Evaporation on Particle Morphology	410
12.4.3	Influence of Precursor Characteristics on Particle Morphology	415
12.4.4	Influence of Intraparticle Reaction on Particle Morphology	416
12.5	Modes of Reactor Behavior	418
12.5.1	Intraparticle Reaction with No Volatile Components	419
12.5.2	Intraparticle Reaction with Evaporation of Volatile Reactants	421

12.5.3	Intraparticle Reaction with Volatile Intermediates or Products	421
12.5.4	New-Particle Formation with a Single Volatile Component	427
12.5.5	Spray Combustion Synthesis	427
12.5.6	Aerosol-Phase Densification	429
12.6	References	432
13	Technology: Liquid-to-Solid and Solid-to-Solid Conversion	436
13.1	Liquid-to-Solid and Solid-to-Solid Conversion	436
13.1.1	Introduction	436
13.1.2	Commercial Potential	439
13.2	Spray Pyrolysis	440
13.2.1	Introduction	440
13.2.2	Precursors and Products	447
13.2.3	Metal-Oxide Powders	448
13.2.4	Nonoxide Powders	451
13.2.5	Metal Powders	452
13.2.6	Composite Powders	452
13.2.7	Coated Powders	455
13.2.8	Influence of Precursor Characteristics on Particle Morphology	457
13.2.9	Conditions Conducive to the Formation of Solid Particles	458
13.3	Spray-Drying	460
13.4	Freeze-Drying	463
13.5	Spray-Combustion Synthesis	464
13.6	Flame Spray Pyrolysis	466
13.7	Melt Atomization	468
13.8	Powder Synthesis and Densification in Thermal Plasmas	470
13.8.1.	Thermal-Plasma Densification	470
13.8.2	Thermal-Plasma Synthesis of Powders	470
13.9	References	470
13.10	Tables	474
14	Film Formation	492
14.1	Introduction	492
14.2	Film Characteristics	494
14.3	Deposition or Etching Using Nonevaporating Particles Formed Ex Situ	496
14.4	Deposition or Etching Using Evaporating Particles with Involatile Reactants Formed Ex Situ	499

14.5	Aerosol-Assisted Chemical Vapor Deposition	503
14.6	Deposition Using Droplets or Solid Particles Formed In Situ	512
14.7	Simultaneous Particle and Vapor Deposition	516
14.8	Particle Formation during CVD	520
14.9	Particle Formation during Low-Pressure Plasma Deposition and Etching	528
14.10	References	531
15.	Film Generation Technologies	533
15.1	Introduction	533
15.2	Liquid-Phase Precursors	533
15.2.1	Droplet Deposition (Film Pyrolysis)	533
15.2.1.1	Introduction	533
15.2.1.2	Precursors and Products	535
15.2.1.3	Experimental Details	536
15.2.1.4	Theory	537
15.2.2	Aerosol-Assisted Chemical Vapor Deposition	537
15.2.2.1	Introduction	537
15.2.2.2	Precursors and Products	540
15.2.2.3	Experimental Details	540
15.2.2.4	Theory	542
15.2.3	Supercritical Expansion of Solutions	543
15.2.3.1	Introduction	543
15.2.3.2	Precursors and Products	543
15.2.3.3	Experimental Details	544
15.2.3.4	Theory	545
15.2.4	Molten Droplet Deposition	545
15.2.4.1	Introduction	545
15.2.4.2	Precursors and Products	548
15.2.4.3	Experimental Details	548
15.2.4.4	Theory	549
15.2.5	Aerosol Jet Etching, Aerosol Cleaning, and Related Processes	550
15.2.5.1	Introduction	550
15.2.5.2	Precursors and Products	551
15.2.5.3	Experimental Details	551
15.2.5.4	Theory	552
15.3	Solid-Particle Deposition	554
15.3.1	Introduction	554
15.3.2	Ionized Cluster Beam Deposition	554

15.3.2.1	Introduction	554
15.3.2.2	Precursors and Products	556
15.3.2.3	Experimental Details	556
15.3.2.4	Theory	558
15.3.3	Neutral Cluster Beam	559
15.3.4	Inertial Particle Deposition	560
15.3.4.1	Introduction	560
15.3.4.2	Precursors and Products	561
15.3.4.3	Experimental Details	561
15.3.4.4	Theory	561
15.3.5	Thermophoretic Aerosol Deposition	562
15.3.5.1	Introduction	562
15.3.5.2	Precursors and Products	563
15.3.5.3	Experimental Details	563
15.3.5.4	Theory	563
15.3.6	Thermophoretic Aerosol Deposition: Optical Fibers	564
15.3.6.1	Introduction	564
15.3.6.2	Precursors and Products	566
15.3.6.3	Experimental Details	566
15.3.6.4	Theory	566
15.3.7	Deposition of Charged Solid Particles in Electric Fields	567
15.4	Simultaneous Particle Deposition and CVD	569
15.5	Particle Formation during CVD	571
15.5.1	Introduction	571
15.5.2	Precursors and Products	572
15.5.3	Experimental Details	572
15.5.4	Theory	572
15.6	References	574
15.7	Tables	577
16	Aerosol Reactor Components	602
16.1	Introduction	602
16.2	Atomization	602
16.2.1	Introduction	602
16.2.2	Classification of Atomizers	603
16.2.3	Pressure and Two-Fluid Atomization	604
16.2.4	Ultrasonic Atomizers	606
16.2.5	Electrostatic Atomizers	610
16.2.6	Summary of Atomizer Characteristics	612
16.3	Dry Powder Feeders	613

16.4	Droplet Impactors and Virtual Impactors	614
16.5	Powder Collection: Filtration and Electrostatic Precipitators	618
16.5.1	Filtration	619
16.5.2	Cyclones	620
16.5.3	Settling Chambers	621
16.5.4	Electrostatic Precipitators	621
16.6	Volatile Reactant Delivery Systems	622
16.7	References	626
17	Measurement Techniques	629
17.1	Introduction	629
17.2	Particle Collection Methods	629
17.3	Physical Properties: Size and Morphology	632
17.3.1	Dry Methods: Sieving	633
17.3.2	Dry Methods: Scanning and Transmission Electron Microscopy	633
17.3.3	Liquid-Phase Methods: Light Scattering	635
17.3.4	Liquid-Phase Methods: Sedimentation Velocity	635
17.3.5	Liquid-Phase Methods: Assorted	636
17.3.6	Gas-Phase Methods: Condensation Particle Counter	637
17.3.7	Gas-Phase Methods: Differential-Mobility Particle Sizer and Electrical Aerosol Analyzer	638
17.3.8	Gas-Phase Methods: Single-Particle Optical Particle Counter	640
17.3.9	Gas-Phase Methods: Dynamic Light Scattering	641
17.3.10	Gas-Phase Methods: Assorted	641
17.3.11	Gas-Phase Methods: Multistage Impactors	641
17.3.12	Gas-Phase Methods: Virtual Impactors	642
17.3.13	Gas-Phase Methods: Cyclones	642
17.3.14	Gas-Phase Methods: Aerodynamic Particle Sizer	642
17.4	Physical Properties: Microstructure	643
17.4.1	Mercury Porosimetry	643
17.4.2	Surface Area	644
17.4.3	Density	645
17.4.4	Pellet Green Density	646
17.4.5	Tap Density	646
17.4.6	Transmission Electron Microscopy	646
17.5	Physical Properties: Phase Composition and Distribution	647
17.5.1	X-ray Diffraction	648

17.5.2	Transmission Electron Microscopy and Electron Diffraction	648
17.6	Chemical Composition: Bulk Materials	648
17.6.1	X-ray Fluorescence	649
17.6.2	Fourier-Transform Infrared Spectroscopy	649
17.6.3	Proton-induced X-ray Emission Spectroscopy	649
17.6.4	Nuclear Reaction Analysis	650
17.6.5	Emission and Absorption Spectroscopy	650
17.6.6	Combustion Elemental Analysis	650
17.7	Chemical Composition: Surface-Sensitive Methods	651
17.7.1	Auger Electron Spectroscopy	651
17.7.2	Energy-Dispersive Spectroscopy	651
17.7.3	X-ray Photoelectron Spectroscopy	653
17.7.4	Mass Spectrometric Methods	654
17.8	Thermophysical and Thermochemical Analysis	654
17.8.1	Thermogravimetric Analysis	654
17.8.2	Differential Thermal Analysis and Differential Scanning Calorimetry	655
17.8.3	Dilatometry	655
17.9	Surface Properties	655
17.10	Assorted Methods	655
17.11	References	656
Index		659