Contents

Series Preface XI Preface of Volume 5 XV List of Contributors XIX Recommended Notation XXIII EFCE Working Party on Drying: Address List XXIX

- 1 Impinging Jet Drying 1
 - Eckehard Specht
- 1.1 Application 1
- 1.2 Single Nozzle 4
- 1.3 Nozzle Fields 7
- 1.3.1 Arrays of Single Nozzles 7
- 1.3.2 Hole Channels 12
- 1.3.3 Perforated Plates 13
- 1.3.4 Nozzles for Cylindrical Bodies 14
- 1.4 Summary of the Nusselt Functions 16
- 1.5 Design of Nozzle Field 17
- 1.6 Conclusion 23
 - References 24

2 Pulse Combustion Drying 27

- Ireneusz Zbicinski, Tadeusz Kudra, and Xiangdong Liu
- 2.1 Principle of Pulse Combustion 27
- 2.2 Pulse Combustors: Design and Operation 32
- 2.2.1 Pulse Combustors with Mechanical Valves 32
- 2.2.2 Pulse Combustors with Aerodynamic Valves 34
- 2.2.3 Frequency-Tunable Pulsed Combustors 35
- 2.3 Aerodynamics, Heat and Mass Transfer 36
- 2.3.1 Atomization 37
- 2.3.2 Heat and Mass Transfer 38
- 2.4 Modeling of Pulse Combustion Drying 42
- 2.5 Pulse Combustion in Drying 48
 - References 53

VI Contents

3	Superheated Steam Drying of Foods and Biomaterials 57
5	Sakamon Devahastin and Arun S. Mujumdar
3.1	Introduction 57
3.2	Principle of Superheated Steam Drying (SSD) 58
3.3	Atmospheric-Pressure Superheated Steam Drying 61
3.4	Low-Pressure Superheated Steam Drying (LPSSD) 69
3.5	Application of LPSSD to Improve the Quality of Foods and
	Biomaterials 76
3.6	Concluding Remarks 82
	References 83
4	Intensification of Fluidized-Bed Processes for Drying and
	Formulation 85
	Evangelos Tsotsas, Stefan Heinrich, Michael Jacob, Mirko Peglow,
	and Lothar Mörl
4.1	Introduction 85
4.2	Intensification by Apparatus and Flow Design 86
4.2.1	Different Types of Spouted Bed 86
4.2.2	Operating Characteristics of Spouted Beds 93
4.2.3	Mass and Heat Transfer in ProCell Units 100
4.2.4	Discrete Particle Modeling 107
4.3	Intensification by Contact Heating 112
4.3.1	General Principle 112
4.3.2	Main Effects and Influences 114
4.3.3	Further Remarks on Modeling 121
4.4	Further Methods of Intensification 126
4.5	Conclusion 127
	References 128
5	Intensification of Freeze-Drying for the Pharmaceutical and Food
	Industries 131
	Roberto Pisano, Davide Fissore, and Antonello A. Barresi
5.1	Introduction 131
5.2	Exergetic Analysis (and Optimization) of the Freeze-Drying Process 133
5.3	Process Intensification in Vacuum Freeze-Drying of Liquids 139
5.3.1	Regulation of Nucleation Temperature During Freezing 140
5.3.2	Use of Organic Solvents and Cosolvents 144
5.4	Atmospheric Freeze-Drying 146
5.5	Use of Combined Technologies for Drying Heat-Sensitive
	Products 150
5.5.1	Microwave-Assisted Drying 150
5.5.2	Ultrasound-Assisted Drying 152
5.6	Continuous Freeze-Drying 154
5.7	Conclusions 155
	References 157

6	Drying of Foamed Materials 163
	Ireneusz Zbicinski, Julia Rabaeva, and Artur Lewandowski
6.1	Introduction 163
6.2	Foam Properties 164
6.3	Foam Spray Drying 167
6.3.1	Processing Principles 167
6.3.2	Final Product Properties 172
6.4	Foam-Mat Drying 181
6.5	Summary 187
	References 188
7	Process-Induced Minimization of Mass Transfer Barriers
	for Improved Drying 191
	Henry Jäger, Katharina Schössler, and Dietrich Knorr
7.1	Introduction 191
7.2	Structural Characterization of Plant Raw Materials and Impact of PEF
	and Ultrasound 192
7.2.1	Methods for Analysis of Tissue Structure and Quantification
,	of Cell Damage 192
7.2.2	PEF: Principles and Impact on Plant Tissue Structure 195
7.2.2.1	Introduction to PEF Technology 195
7.2.2.2	PEF: Impact on Plant Tissue Structure 196
7.2.3	Ultrasound: Principles and Impact on Plant Tissue Structure 199
7.2.3.1	Introduction to Ultrasound Technology 199
7.2.3.2	Ultrasound: Impact on Plant Tissue Structure 200
7.3	Pulsed Electric Field (PEF) Application as a Pretreatment 204
7.3.1	Osmotic Dehydration 205
7.3.2	Air Drying 206
7.3.3	Impact of PEF on Freezing and Freeze-Drying Behavior of Raw
, 1010	Materials 208
7.3.4	Quality Characteristics Affected by PEF Pretreatment 211
7.4	Contact Ultrasound for Combined Drying Processes 216
7.4.1	Ultrasound in Osmotic Dehydration 217
7.4.2	Contact Ultrasound in Air Drying 218
7.4.3	Contact Ultrasound in Freeze-Drying 221
7.4.4	Quality Characteristics Affected by Ultrasound-Combined Drying
	Processes 224
7.5	Conclusion 226
	References 230
8	Drying Assisted by Power Ultrasound 237
	Juan Andrés Cárcel, José Vicente García-Pérez, Enrique Riera,
	Carmen Rosselló, and Antonio Mulet
8.1	Introduction 237
8.2	Ultrasound 239

VIII Contents

8.2.1	Ultrasound Waves 239
8.2.1.1	Power 239
8.2.1.2	Frequency 240
8.2.1.3	Attenuation 240
8.2.1.4	Acoustic Impedance 240
8.2.2	Effects of Ultrasound on Mass Transfer 241
8.3	Ultrasonic Equipment 242
8.3.1	Source of Energy 243
8.3.2	Transducers 243
8.3.3	Application Systems 245
8.3.3.1	Treatments in Liquid Media 245
8.3.3.2	Treatments in Gas Media 247
8.4	Influence of the Main Process Variables on Drying Intensification
	by Ultrasound 250
8.4.1	Ultrasonic Power Applied 250
8.4.1.1	**
8.4.1.2	Ultrasonic Intensity and Effects 252
8.4.1.3	
	Intensity 258
8.4.2	Drying Air Temperature 263
8.4.3	Ultrasound–Sample Interaction 266
8.5	Conclusions 272
	References 273
9	Microwave-Assisted Drying of Foods – Equipment, Process
9	
9	Microwave-Assisted Drying of Foods – Equipment, Process
9 9.1	Microwave-Assisted Drying of Foods – Equipment, Process and Product Quality 279
	Microwave-Assisted Drying of Foods – Equipment, Process and Product Quality 279 Yingqiang Wang, Min Zhang, and Arun S. Mujumdar
9.1	Microwave-Assisted Drying of Foods – Equipment, Process and Product Quality 279 Yingqiang Wang, Min Zhang, and Arun S. Mujumdar Introduction 279
9.1 9.2	Microwave-Assisted Drying of Foods – Equipment, Process and Product Quality 279 Yingqiang Wang, Min Zhang, and Arun S. Mujumdar Introduction 279 Microwave-Assisted Drying of Foods 281
9.1 9.2 9.2.1	Microwave-Assisted Drying of Foods – Equipment, Process and Product Quality 279 Yingqiang Wang, Min Zhang, and Arun S. Mujumdar Introduction 279 Microwave-Assisted Drying of Foods 281 Basic Principles of Microwave-Assisted Drying 281
9.1 9.2 9.2.1 9.2.2	Microwave-Assisted Drying of Foods – Equipment, Process and Product Quality 279 Yingqiang Wang, Min Zhang, and Arun S. Mujumdar Introduction 279 Microwave-Assisted Drying of Foods 281 Basic Principles of Microwave-Assisted Drying 281 Energy Absorption by Products During Dielectric Heating 283
9.1 9.2 9.2.1 9.2.2 9.2.3	Microwave-Assisted Drying of Foods – Equipment, Process and Product Quality 279 Yingqiang Wang, Min Zhang, and Arun S. Mujumdar Introduction 279 Microwave-Assisted Drying of Foods 281 Basic Principles of Microwave-Assisted Drying 281 Energy Absorption by Products During Dielectric Heating 283 Dielectric Properties 283
9.1 9.2 9.2.1 9.2.2 9.2.3 9.2.4	Microwave-Assisted Drying of Foods – Equipment, Process and Product Quality 279 Yingqiang Wang, Min Zhang, and Arun S. Mujumdar Introduction 279 Microwave-Assisted Drying of Foods 281 Basic Principles of Microwave-Assisted Drying 281 Energy Absorption by Products During Dielectric Heating 283 Dielectric Properties 283 Penetration Depth 285
9.1 9.2 9.2.1 9.2.2 9.2.3 9.2.4 9.3	Microwave-Assisted Drying of Foods – Equipment, Process and Product Quality 279 Yingqiang Wang, Min Zhang, and Arun S. Mujumdar Introduction 279 Microwave-Assisted Drying of Foods 281 Basic Principles of Microwave-Assisted Drying 281 Energy Absorption by Products During Dielectric Heating 283 Dielectric Properties 283 Penetration Depth 285 Microwave-Assisted Drying Equipment 285
9.1 9.2 9.2.1 9.2.2 9.2.3 9.2.4 9.3 9.3.1	Microwave-Assisted Drying of Foods – Equipment, Process and Product Quality 279 Yingqiang Wang, Min Zhang, and Arun S. Mujumdar Introduction 279 Microwave-Assisted Drying of Foods 281 Basic Principles of Microwave-Assisted Drying 281 Energy Absorption by Products During Dielectric Heating 283 Dielectric Properties 283 Penetration Depth 285 Microwave-Assisted Drying Equipment 285 Microwave-Assisted Convective Drying Equipment 286
9.1 9.2 9.2.1 9.2.2 9.2.3 9.2.4 9.3 9.3.1 9.3.2	Microwave-Assisted Drying of Foods – Equipment, Process and Product Quality 279 Yingqiang Wang, Min Zhang, and Arun S. Mujumdar Introduction 279 Microwave-Assisted Drying of Foods 281 Basic Principles of Microwave-Assisted Drying 281 Energy Absorption by Products During Dielectric Heating 283 Dielectric Properties 283 Penetration Depth 285 Microwave-Assisted Drying Equipment 285 Microwave-Assisted Convective Drying Equipment 286 Microwave-Assisted Vacuum Drying Equipment 287
9.1 9.2 9.2.1 9.2.2 9.2.3 9.2.4 9.3 9.3.1 9.3.2 9.3.3	Microwave-Assisted Drying of Foods – Equipment, Process and Product Quality 279 Yingqiang Wang, Min Zhang, and Arun S. Mujumdar Introduction 279 Microwave-Assisted Drying of Foods 281 Basic Principles of Microwave-Assisted Drying 281 Energy Absorption by Products During Dielectric Heating 283 Dielectric Properties 283 Penetration Depth 285 Microwave-Assisted Drying Equipment 285 Microwave-Assisted Convective Drying Equipment 286 Microwave-Assisted Vacuum Drying Equipment 287 Microwave-Assisted Freeze-Drying Equipment 290
9.1 9.2 9.2.1 9.2.2 9.2.3 9.2.4 9.3 9.3.1 9.3.2 9.3.3 9.3.4	Microwave-Assisted Drying of Foods – Equipment, Process and Product Quality 279 Yingqiang Wang, Min Zhang, and Arun S. Mujumdar Introduction 279 Microwave-Assisted Drying of Foods 281 Basic Principles of Microwave-Assisted Drying 281 Energy Absorption by Products During Dielectric Heating 283 Dielectric Properties 283 Penetration Depth 285 Microwave-Assisted Drying Equipment 285 Microwave-Assisted Convective Drying Equipment 286 Microwave-Assisted Vacuum Drying Equipment 287 Microwave-Assisted Freeze-Drying Equipment 290 Microwave-Assisted Spouted Bed Drying Equipment 291 Microwave-Assisted Drying Process 292 Moisture Loss 293
9.1 9.2 9.2.1 9.2.2 9.2.3 9.2.4 9.3 9.3.1 9.3.2 9.3.3 9.3.4 9.4	Microwave-Assisted Drying of Foods – Equipment, Process and Product Quality 279 Yingqiang Wang, Min Zhang, and Arun S. Mujumdar Introduction 279 Microwave-Assisted Drying of Foods 281 Basic Principles of Microwave-Assisted Drying 281 Energy Absorption by Products During Dielectric Heating 283 Dielectric Properties 283 Penetration Depth 285 Microwave-Assisted Drying Equipment 285 Microwave-Assisted Convective Drying Equipment 286 Microwave-Assisted Vacuum Drying Equipment 287 Microwave-Assisted Freeze-Drying Equipment 290 Microwave-Assisted Spouted Bed Drying Equipment 291 Microwave-Assisted Drying Process 292
9.1 9.2 9.2.1 9.2.2 9.2.3 9.2.4 9.3 9.3.1 9.3.2 9.3.3 9.3.4 9.4 9.4.1	Microwave-Assisted Drying of Foods – Equipment, Process and Product Quality 279 Yingqiang Wang, Min Zhang, and Arun S. Mujumdar Introduction 279 Microwave-Assisted Drying of Foods 281 Basic Principles of Microwave-Assisted Drying 281 Energy Absorption by Products During Dielectric Heating 283 Dielectric Properties 283 Penetration Depth 285 Microwave-Assisted Drying Equipment 285 Microwave-Assisted Convective Drying Equipment 286 Microwave-Assisted Vacuum Drying Equipment 287 Microwave-Assisted Freeze-Drying Equipment 290 Microwave-Assisted Drying Process 292 Moisture Loss 293 Temperature Distributions 295 Temperature Variations at Fixed Levels of Microwave Power 296
9.1 9.2 9.2.1 9.2.2 9.2.3 9.2.4 9.3 9.3.1 9.3.2 9.3.3 9.3.4 9.4 9.4.1 9.4.2	Microwave-Assisted Drying of Foods – Equipment, Process and Product Quality 279 Yingqiang Wang, Min Zhang, and Arun S. Mujumdar Introduction 279 Microwave-Assisted Drying of Foods 281 Basic Principles of Microwave-Assisted Drying 281 Energy Absorption by Products During Dielectric Heating 283 Dielectric Properties 283 Penetration Depth 285 Microwave-Assisted Drying Equipment 285 Microwave-Assisted Convective Drying Equipment 286 Microwave-Assisted Freeze-Drying Equipment 287 Microwave-Assisted Freeze-Drying Equipment 290 Microwave-Assisted Drying Process 292 Moisture Loss 293 Temperature Distributions 295
9.1 9.2 9.2.1 9.2.2 9.2.3 9.2.4 9.3 9.3.1 9.3.2 9.3.3 9.3.4 9.4 9.4.1 9.4.2 9.4.2	Microwave-Assisted Drying of Foods – Equipment, Process and Product Quality 279 Yingqiang Wang, Min Zhang, and Arun S. Mujumdar Introduction 279 Microwave-Assisted Drying of Foods 281 Basic Principles of Microwave-Assisted Drying 281 Energy Absorption by Products During Dielectric Heating 283 Dielectric Properties 283 Penetration Depth 285 Microwave-Assisted Drying Equipment 285 Microwave-Assisted Convective Drying Equipment 286 Microwave-Assisted Vacuum Drying Equipment 287 Microwave-Assisted Freeze-Drying Equipment 290 Microwave-Assisted Drying Process 292 Moisture Loss 293 Temperature Distributions 295 Temperature Variations at Fixed Levels of Microwave Power 296

Contents | IX

- 9.4.2.3 Temperature Change with Time-Adjusted Power in Feedback Temperature Control 299
- 9.4.3 Energy Consumption 299
- 9.4.4 Dielectric Breakdown 302
- 9.4.5 Changes in Dielectric Properties 304
- 9.4.6 Quality Changes in Food during Microwave-Assisted Drying 305
- 9.5 Microwave-Assisted Drying Process Control and Optimal Operation 308
- 9.5.1 Factors Controlling Microwave-Assisted Drying Processes 308
- 9.5.2 Optimal Operation Strategy 308
- 9.6 Concluding Remarks 310 References 312
- **10** Infrared Drying 317
 - German Efremov
- 10.1 Introduction 317
- 10.2 Radiation Heat Transfer 318
- 10.2.1 General Principles 318
- 10.2.2 Reflection, Absorption, and Transmission 319
- 10.2.3 Infrared Spectrum 321
- 10.3 Classification, Research, and Applications of Radiation Drying 323
- 10.3.1 Classification 323
- 10.3.2 Solar Drying 325
- 10.3.3 Infrared Drying 326
- 10.3.4 Catalytic Infrared Drying 329
- 10.4 Types of Radiators 332
- 10.4.1 General Considerations 332
- 10.4.2 Electric Radiators 333
- 10.4.3 Gas-Heated IR Radiators 335
- 10.5 Interaction between Matter and Infrared Radiation 337
- 10.5.1 General Relationships 337
- 10.5.2 Radiation Properties of Materials 339
- 10.6 Kinetics of Infrared Drying 342
- 10.7 Infrared Drying Combined with other Types of Drying 345
- 10.7.1 IR and Convective Drying 346
- 10.7.2 IR and Microwave Drying 347
- 10.7.3 IR and Freeze-Drying 348
- 10.7.4 IR with other Types of Drying 348
- 10.8 Conclusions 351
 - References 352

Index 357