

Contents

Series Preface XI

Preface of Volume 4 XV

List of Contributors XIX

Recommended Notation XXIII

EFCE Working Party on Drying; Address List XXIX

1	Fundamentals of Energy Analysis of Dryers	1
	<i>Ian C. Kemp</i>	
1.1	Introduction	1
1.2	Energy in Industrial Drying	2
1.3	Fundamentals of Dryer Energy Usage	3
1.3.1	Evaporation Load	3
1.3.2	Dryer Energy Supply	4
1.3.3	Evaluation of Energy Inefficiencies and Losses: Example	5
1.3.3.1	Dryer Thermal Inefficiencies	6
1.3.3.2	Inefficiencies in the Utility (Heat Supply) System	8
1.3.3.3	Other Energy Demands	13
1.3.4	Energy Cost and Environmental Impact	14
1.3.4.1	Primary Energy Use	14
1.3.4.2	Energy Costs	14
1.3.4.3	Carbon Dioxide Emissions and Carbon Footprint	15
1.4	Setting Targets for Energy Reduction	16
1.4.1	Energy Targets	16
1.4.2	Pinch Analysis	17
1.4.2.1	Basic Principles	17
1.4.2.2	Application of Pinch Analysis to Dryers	19
1.4.2.3	The Appropriate Placement Principle Applied to Dryers	21
1.4.2.4	Pinch Analysis and Utility Systems	24
1.4.3	Drying in the Context of the Overall Process	25
1.5	Classification of Energy Reduction Methods	26
1.5.1	Reducing the Heater Duty of a Convective Dryer	28
1.5.2	Direct Reduction of Dryer Heat Duty	29
1.5.2.1	Reducing the Inherent Heat Requirement for Drying	29

1.5.2.2	Altering Operating Conditions to Improve Dryer Efficiency	30
1.5.3	Heat Recovery and Heat Exchange	31
1.5.3.1	Heat Exchange Within the Dryer	31
1.5.3.2	Heat Exchange with Other Processes	32
1.5.4	Alternative Utility Supply Systems	32
1.5.4.1	Low Cost utilities	33
1.5.4.2	Improving Energy Supply System Efficiency	33
1.5.4.3	Combined Heat and Power	34
1.5.4.4	Heat Pumps	36
1.6	Case Study	37
1.6.1	Process Description and Dryer Options	37
1.6.2	Analysis of Dryer Energy Consumption	38
1.6.3	Utility Systems and CHP	42
1.7	Conclusions	43
	References	45
2	Mechanical Solid–Liquid Separation Processes and Techniques	47
	<i>Harald Anlauf</i>	
2.1	Introduction and Overview	47
2.2	Density Separation Processes	51
2.2.1	Froth Flotation	51
2.2.2	Sedimentation	54
2.3	Filtration	61
2.3.1	Cake Filtration	61
2.3.2	Sieving and Blocking Filtration	72
2.3.3	Crossflow Micro- and Ultra-Filtration	73
2.3.4	Depth and Precoat Filtration	75
2.4	Enhancement of Separation Processes by Additional Electric or Magnetic Forces	80
2.5	Mechanical/Thermal Hybrid Processes	83
2.6	Important Aspects of Efficient Solid–Liquid Separation Processes	85
2.6.1	Mode of Apparatus Operation	85
2.6.2	Combination of Separation Apparatuses	87
2.6.3	Suspension Pre-Treatment Methods to Improve Separation Conditions	91
2.7	Conclusions	94
	References	95
3	Energy Considerations in Osmotic Dehydration	99
	<i>Hosahalli S. Ramaswamy and Yetenayet Bekele Tola</i>	
3.1	Scope	99
3.2	Introduction	100
3.3	Mass Transfer Kinetics	101
3.3.1	Pretreatments	101
3.3.2	Product	102

3.3.3	Osmotic Solution	103
3.3.4	Treatment Conditions	103
3.4	Modeling of Osmotic Dehydration	104
3.5	Osmotic Dehydration – Two Major Issues	105
3.5.1	Quality Issues	105
3.5.2	Energy Issues	106
3.5.2.1	Osmo-Convective Drying	107
3.5.2.2	Osmo-Freeze Drying	109
3.5.2.3	Osmo-Microwave Drying	111
3.5.2.4	Osmotic-Vacuum Drying	113
3.6	Conclusions	114
	References	116
4	Heat Pump Assisted Drying Technology – Overview with Focus on Energy, Environment and Product Quality	121
	<i>Sachin V. Jangam and Arun S. Mujumdar</i>	
4.1	Introduction	121
4.2	Heat Pump Drying System – Fundamentals	122
4.2.1	Heat Pump	122
4.2.2	Refrigerants	125
4.2.3	Heat Pump Dryer	127
4.2.4	Advantages and Limitations of the Heat Pump Dryer	130
4.3	Various Configurations/Layout of a HPD	131
4.4	Heat Pumps – Diverse Options and Advances	132
4.4.1	Multi-Stage Heat Pump	132
4.4.2	Cascade Heat Pump System	133
4.4.3	Use of Heat Pipe	134
4.4.4	Chemical Heat Pump (CHP)	135
4.4.5	Absorption Refrigeration Cycle	138
4.5	Miscellaneous Heat Pump Drying Systems	140
4.5.1	Solar-Assisted Heat Pump Drying	140
4.5.2	Infrared-Assisted Heat Pump Dryer	143
4.5.3	Microwave-Assisted Heat Pump Drying	143
4.5.4	Time-Varying Drying Conditions and Multi-Mode Heat Pump Drying	145
4.5.5	Heat Pump Assisted Spray Drying	147
4.5.6	Modified Atmosphere Heat Pump Drying	148
4.5.7	Atmospheric Freeze Drying Using Heat Pump	149
4.6	Applications of Heat Pump Drying	150
4.6.1	Food and Agricultural Products	150
4.6.2	Drying of Wood/Timber	150
4.6.3	Drying of Pharmaceutical/Biological Products	152
4.7	Sizing of Heat Pump Dryer Components	153
4.8	Future Research and Development Needs in Heat Pump Drying	156
	References	158

5	Zeolites for Reducing Drying Energy Usage 163
	<i>Antonius J. B. van Boxtel, Moniek A. Boon, Henk C. van Deventer, and Paul J. Th. Bussmann</i>
5.1	Introduction 163
5.2	Zeolite as an Adsorption Material 164
5.2.1	Zeolite 164
5.2.2	Comparing the Main Sorption Properties of Zeolite with other Adsorbents 166
5.3	Using Zeolites in Drying Systems 168
5.3.1	Drying Systems 168
5.3.2	Direct Contact Drying 169
5.3.3	Air Dehumidification 170
5.4	Energy Efficiency and Heat Recovery 173
5.4.1	Defining Energy Efficiency 173
5.4.2	Energy Recovery for a Single-Stage System 174
5.4.3	Energy Recovery in a Multi-Stage System 176
5.4.4	Energy Recovery with Superheated Steam 178
5.5	Realization of Adsorption Dryer Systems 180
5.5.1	Adsorption Dryer Systems for Zeolite 180
5.5.2	Adsorption Wheel Versus Packed Bed 181
5.5.3	Zeolite Mechanical Strength 182
5.5.4	Long Term Capacity of Zeolite 183
5.5.5	Zeolite Adsorption Wheel 183
5.6	Cases 185
5.6.1	Zeolite-Assisted Drying in the Dairy Industry 185
5.6.2	Zeolite-Assisted Manure and Sludge Drying 189
5.6.3	Direct Contact Drying of Seeds with Zeolites 191
5.7	Economic Considerations 193
5.8	Perspectives 195
	References 196
 6	 Solar Drying 199
	<i>Joachim Müller and Werner Mühlbauer</i>
6.1	Introduction 199
6.2	Solar Radiation 200
6.3	Solar Air Heaters 204
6.4	Design and Function of Solar Dryers 210
6.4.1	Classification of Solar Dryers 210
6.4.2	Solar Dryers with Natural Convection for Direct Solar Drying 212
6.4.3	Solar Dryers with Natural Convection for Indirect Drying 213
6.4.4	Solar Dryers with Forced Convection for Direct Drying 214
6.4.5	Solar Dryers with Forced Convection for Indirect Drying 218
6.4.6	Dryers with Roof-Integrated Solar Air Heaters 223
6.5	Solar Drying Kinetics 226
6.5.1	Empirical Drying Curves in Solar Drying 226

6.5.2	Equilibrium Model for Solar Drying Kinetics	227
6.6	Control Strategies for Solar Dryers	231
6.6.1	Airflow Management During the Night	231
6.6.2	Recirculation of Drying Air	232
6.6.3	Back-Up Heating Systems	232
6.7	Economic Feasibility of Solar Drying	234
6.7.1	Drying of Timber in Brazil	235
6.7.2	Drying of Tobacco in Brazil	237
6.8	Conclusions and Outlook	239
	References	242
7	Energy Issues of Drying and Heat Treatment for Solid Wood and Other Biomass Sources	245
	<i>Patrick Perré, Giana Almeida, and Julien Colin</i>	
7.1	Introduction	245
7.2	Wood and Biomass as a Source of Renewable Material and Energy	245
7.3	Energy Consumption and Energy Savings in the Drying of Solid Wood	254
7.3.1	Kiln-Drying of Solid Wood: A Real Challenge	254
7.3.2	The Conventional Drying of Wood	258
7.3.2.1	The Design of Conventional Kilns	258
7.3.2.2	Drying Time and Energy Efficiency	259
7.3.3	Theoretical Evaluation of the Kiln Efficiency	263
7.3.4	Two Case Studies of Kiln Efficiency	266
7.3.5	Rules for Saving Energy	269
7.3.5.1	Energy Savings in Conventional Kilns	269
7.3.5.2	Energy Saving by Alternative Technologies	270
7.4	Preconditioning of Biomass as a Source of Energy: Drying and Heat Treatment	271
7.4.1	Importance of Biomass Drying as a Preconditioning Step	271
7.4.1.1	Dryers for Biomass	273
7.4.1.2	Numerical Approach to the Continuous Drying of Woody Biomass	276
7.4.2	Interest of Heat Treatment as a Preconditioning Step	281
7.5	Conclusions	287
	References	289
8	Efficient Sludge Thermal Processing: From Drying to Thermal Valorization	295
	<i>Patricia Arlabosse, Jean-Henry Ferrasse, Didier Lecomte, Michel Crine, Yohann Dumont, and Angélique Léonard</i>	
8.1	Introduction to the Sludge Context	295
8.1.1	Origin, Production and Valorization Issues	295
8.1.2	Sludge: A Complex Material	297
8.1.3	Useful Properties for Energy Valorization	299

8.2	Sludge Drying Technologies	300
8.2.1	General Remarks	300
8.2.2	Convective Drying Methods and Dryer Types	301
8.2.3	Indirect Contact Drying Methods and Dryer Types	305
8.2.3.1	Rotor Design and Operation of the Drying Process	306
8.2.3.2	Drying Performances	308
8.2.4	Solar Drying and Dryer Types	310
8.2.5	Combined and Hybrid Drying	311
8.2.6	Sludge Frying, an Alternative to Conventional Drying	311
8.2.6.1	Heat and Mass Transfer During Fry-Drying	312
8.2.6.2	Energy and Environmental Aspects	313
8.2.7	Pathogen Reduction	314
8.3	Energy Efficiency of Sludge Drying Processes	315
8.3.1	Specific Heat Consumption of Sludge Dryers	315
8.3.2	Towards the Reduction of Energy Consumption Associated with Sludge Drying	316
8.3.3	Case Studies	316
8.4	Thermal Valorization of Sewage Sludge	318
8.4.1	General Description of the Thermal Processes Available for Sewage Sludge	318
8.4.2	Desired Water Content for Thermal Processes	319
8.4.3	Including a Drying Step Before Thermal Valorization	320
8.5	Energy Efficiency of Thermal Valorization Routes	321
8.5.1	Importance of Dryer Efficiency	321
8.5.2	Combining Sludge Drying and Thermal Valorization by Integrating on Site	322
8.6	Conclusions	324
	References	325

Index	331
--------------	------------