

Contents

Preface XIII

List of Contributors XV

Part One Introduction 1

- 1 Historical Retrospect on High-Pressure Processes** 3
Rudolf Eggers
 References 6
- 2 Basic Engineering Aspects** 7
Rudolf Eggers
 - 2.1 What are the Specifics of High-Pressure Processes? 7
 - 2.2 Thermodynamic Aspects: Phase Equilibrium 9
 - 2.3 Software and Data Collection 10
 - 2.4 Phase Equilibrium: Experimental Methods and Measuring Devices 10
 - 2.5 Interfacial Phenomena and Data 12
 - 2.6 Material Properties and Transport Data for Heat and Mass Transfer 20
 - 2.7 Evaporation and Condensation at High Pressures 37
 - 2.7.1 Evaporation 37
 - 2.8 Condensation 43
 - References 46

Part Two Processes 49

- 3 Catalytic and Noncatalytic Chemical Synthesis** 51
Joachim Rüther, Ivo Müller, and Reinhard Michel
 - 3.1 Thermodynamics as Driver for Selection of High Pressure 51
 - 3.1.1 Chemical Equilibrium: Law of Mass Action 51
 - 3.1.2 Reaction Kinetics 53
 - 3.1.3 Phase Equilibria and Transport Phenomena 55
 - 3.2 Ammonia Synthesis Process 55
 - 3.2.1 Basics and Principles 56
 - 3.2.2 History of the Ammonia Process 57
 - 3.2.3 Development of Process and Pressure 58

3.2.4	Special Aspects	63
3.3	Urea Process	64
3.3.1	Basics and Principles	65
3.3.2	History of Urea Process	67
3.3.3	Integration of Ammonia and Urea Processes	71
3.3.4	Special Construction Materials	71
3.4	General Aspects of HP Equipment	72
3.4.1	Multilayered Vessels	73
3.4.2	Recommendations to Vessel Design	73
3.4.3	Gaskets and Bolting	74
	References	75
4	Low-Density Polyethylene High-Pressure Process	77
	<i>Dieter Littmann, Giulia Mei, Diego Mauricio Castaneda-Zuniga, Christian-Ulrich Schmidt, and Gerd Mannebach</i>	
4.1	Introduction	77
4.1.1	Historical Background	77
4.1.2	Properties and Markets	77
4.1.3	Polyethylene High-Pressure Processes	78
4.1.4	Latest Developments	78
4.2	Reaction Kinetics and Thermodynamics	78
4.2.1	Initiation	79
4.2.2	Propagation	79
4.2.3	Chain Transfer	80
4.2.4	Termination	81
4.2.5	Reaction Kinetics	81
4.3	Process	82
4.3.1	General Process Description	82
4.3.2	Autoclave Reactor	84
4.3.3	Tubular Reactor	85
4.3.4	Safety	88
4.4	Products and Properties	89
4.4.1	Blown Film	89
4.4.2	Extrusion Coating	90
4.4.3	Injection Molding	90
4.4.4	Wire and Cable	90
4.4.5	Blow Molding	90
4.4.6	Copolymers	91
4.5	Simulation Tools and Advanced Process Control	91
4.5.1	Introduction	91
4.5.2	Off-Line Applications	91
4.5.2.1	Flow Sheet Simulations	91
4.5.2.2	Steady-State Simulation of the Tubular Reactor	92
4.5.2.3	Dynamic Simulation of the Process	92
4.5.3	Online Application	93

4.5.3.1	Soft Sensors	93
4.5.3.2	Advanced Process Control	94
	References	96
5	High-Pressure Homogenization for the Production of Emulsions	97
	<i>Heike P. Schuchmann, Née Karbstein, Lena L. Hecht, Marion Gedrat, and Karsten Köhler</i>	
5.1	Motivation: Why High-Pressure Homogenization for Emulsification Processes?	97
5.2	Equipment: High-Pressure Homogenizers	98
5.2.1	Principal Design	98
5.2.2	Disruption Systems for High-Pressure Homogenization	98
5.2.2.1	Valves	98
5.2.2.2	Orifices and Nozzles	99
5.2.3	Flow Conditions	100
5.2.3.1	Flow Conditions in the Disruption System	100
5.2.3.2	Effect of Flow Conditions in Homogenization Valves on Emulsion Droplets	101
5.2.4	Simultaneous Emulsification and Mixing (SEM) Systems	101
5.3	Processes: Emulsification and Process Functions	103
5.3.1	Droplet Disruption in High-Pressure Valves	103
5.3.2	Droplet Coalescence in Homogenization Valves	104
5.3.3	Droplet Agglomeration in Homogenization Valves	107
5.4	Homogenization Processes Using SEM-Type Valves	107
5.4.1	Dairy Processes	107
5.4.2	Pickering Emulsions	109
5.4.3	Melt Homogenization	111
5.4.4	Emulsion Droplets as Templates for Hybrid (Core–Shell) Nanoparticle Production	112
5.4.5	Submicron Emulsion Droplets as Nanoreactors	114
5.4.6	Nanoparticle Deagglomeration and Formulation of Nanoporous Carriers for Bioactives	116
5.5	Summary and Outlook	117
	References	118
6	Power Plant Processes: High-Pressure–High-Temperature Plants	123
	<i>Alfons Kather and Christian Mehrkens</i>	
6.1	Introduction	123
6.2	Coal-Fired Steam Power Plants	125
6.2.1	Thermodynamics and Power Plant Efficiency	125
6.2.2	Configuration of Modern Steam Power Plants	127
6.3	Steam Generator	130
6.3.1	Steam Generator Design	130
6.3.2	Membrane Wall	134
6.3.3	Final Superheater Heating Surface	135

6.3.4	Final Superheater Outlet Header and Live Steam Piping	136
6.4	High-Pressure Steam Turbines	138
6.4.1	Configuration of Modern Steam Turbines	138
6.4.2	Design Features of High-Pressure Steam Turbines	139
6.5	Summary and Outlook	142
	References	142
7	High-Pressure Application in Enhanced Crude Oil Recovery	145
	<i>Philip T. Jaeger, Mohammed B. Alotaibi, and Hisham A. Nasr-El-Din</i>	
7.1	Introduction	145
7.1.1	Principal Phenomena in Oil and Gas Reservoirs	145
7.1.2	Reservoir Conditions	145
7.2	Fundamentals	147
7.2.1	Miscibility at Elevated Pressures	147
7.2.2	Physical Chemical Properties of Reservoir Systems at Elevated Pressures	148
7.2.2.1	Density	148
7.2.2.2	Rheology	150
7.2.2.3	Interfacial Tension	151
7.2.2.4	Wetting	151
7.2.2.5	Diffusivity	153
7.2.2.6	Permeability	154
7.3	Enhanced Oil Recovery	155
7.3.1	Water Flooding	157
7.3.2	Chemical Injection	158
7.3.3	Thermal Recovery	158
7.3.4	Gas Injection	159
7.3.5	Carbon Dioxide Capture and Storage (CCS) in EOR	160
7.3.6	Combustion	160
7.4	Oil Reservoir Stimulation	161
7.5	Heavy Oil Recovery	161
7.6	Hydrates in Oil Recovery	162
7.7	Equipment	163
7.7.1	Pumps	163
7.7.2	Pipes	164
7.7.3	Seals	164
7.7.4	Separators	165
	References	166
8	Supercritical Processes	169
	<i>Rudolf Eggers and Eduard Lack</i>	
8.1	Introduction	169
8.2	Processing of Solid Material	172
8.2.1	Isobaric Process	174

8.2.2	Single or Cascade Operation with Multistep Separation	174
8.2.3	Cascade Operation and Multistep Separation	175
8.2.4	Extractable Substances	175
8.2.4.1	Selective Extraction	176
8.2.4.2	Total Extraction	176
8.2.5	Pretreatment of Raw Materials	176
8.2.6	Design Criteria	177
8.2.7	Design with the Use of Basket	178
8.2.8	Thermodynamic Conditions	179
8.2.9	Mass Transfer	179
8.2.10	Hydrodynamics	182
8.2.11	Energy Optimization	182
8.2.12	Pump Process	182
8.2.13	Compressor Process	183
8.2.14	Some Applications of Supercritical Extraction of Solids	184
8.2.14.1	Decaffeination of Green Coffee Beans	184
8.2.14.2	Production of Hops Extract	184
8.2.14.3	Extraction of Spices and Herbs	186
8.2.14.4	Extraction of Essential Oils	186
8.2.14.5	Production of Natural Antioxidants	188
8.2.14.6	Production of High-Value Fatty Oils	189
8.2.14.7	Extraction of γ -Linolenic Acid	189
8.2.14.8	Cleaning and Decontamination of Cereals Like Rice	189
8.2.14.9	Impregnation of Wood and Polymers	190
8.2.14.10	Cleaning of Cork	193
8.2.14.11	Economics – Especially Investment Cost for Multipurpose Plants	193
8.3	Processing of Liquids	194
8.4	Future Trends	202
8.4.1	Drying of Aerogels	202
8.4.2	Treating of Microorganisms	203
8.4.3	Use of Supercritical Fluids for the Generation of Renewable Energy	204
8.4.4	Gas-Assisted High-Pressure Processes	205
	References	206
9	Impact of High-Pressure on Enzymes	211
	<i>Leszek Kulisiewicz, Andreas Wierschem, Cornelia Rauh, and Antonio Delgado</i>	
9.1	Introduction	211
9.2	Influence of Pressure on Biomatter	212
9.3	Influence of Pressure on the Kinetics of Enzyme Inactivation	215
9.4	Technological Aspects	218
9.5	Summary	226
	References	227

10	High Pressure in Renewable Energy Processes	235
	<i>Nicolaus Dahmen and Andrea Kruse</i>	
10.1	Introduction	235
10.2	Thermochemical Processes	236
10.2.1	Pyrolysis	237
10.2.2	Liquefaction	238
10.2.3	Gasification	240
10.2.3.1	Fixed Bed Gasifier	242
10.2.3.2	Fluidized Bed Gasifiers	243
10.2.3.3	Entrained Flow Gasifiers	244
10.3	Hydrothermal Processes	248
10.3.1	Hydrothermal Carbonization	250
10.3.2	Hydrothermal Liquefaction	251
10.3.3	Hydrothermal Gasification	253
10.3.3.1	Catalytic Hydrothermal Gasification	253
10.3.3.2	Supercritical Hydrothermal Gasification	254
	References	256
11	Manufacturing Processes	257
	<i>Andrzej Karpinski and Rolf Wink</i>	
11.1	Autofrettage: A High-Pressure Process to Improve Fatigue Lifetime	260
11.2	Waterjet Cutting Technology	265
11.2.1	Generation of Waterjets	265
11.2.2	Cutting Process and Parameters	267
11.2.3	High-Pressure Pumps	269
11.2.4	Waterjet Cutting with 6000 bar	272
11.2.5	Cutting Devices	273
11.2.6	New Trends in the Waterjet Cutting	276
11.2.6.1	Abrasive Water Suspension Jet	276
11.2.6.2	Microcutting	276
11.2.6.3	Medical Applications	277
	References	278
Part Three Process Equipment and Safety 283		
12	High-Pressure Components	285
	<i>Waldemar Hiller and Matthias Zeiger</i>	
12.1	Materials for High-Pressure Components	285
12.1.1	Steel Selection Criteria	286
12.1.2	High-Strength Low-Alloy Steel	287
12.1.3	Weldable Fine-Grain and High-Temperature Structural Steels	287
12.1.4	High-Strength High-Alloy Steels	287
12.1.5	Austenitic Stainless Steels	288

12.1.6	Austenitic–Ferritic Duplex Steels	288
12.1.7	Chromium–Molybdenum Hydrogen-Resistant Steels	288
12.1.8	Fatigue and Fracture Properties of High-Strength Steels	289
12.2	Pressure Vessels	290
12.2.1	Leak Before Burst	292
12.2.2	Welded Pressure Vessels	292
12.2.3	Nonwelded Pressure Vessels	294
12.2.4	Prestressing Techniques	298
12.2.5	Sealing Systems	300
12.3	Heat Exchangers	301
12.4	Valves	303
12.5	Piping	304
	References	309
13	High-Pressure Pumps and Compressors	311
	<i>Eberhard Schluecker</i>	
13.1	Selection of Machinery	311
13.2	Influence of the Fluid on Selection and Design of the Machinery	313
13.3	Design Standards for High-Pressure Machines	314
13.4	Materials and Materials Testing	316
13.5	High-Pressure Centrifugal Pumps and High-Pressure Turbocompressors	317
13.6	Rotating Positive Displacement Machines	319
13.6.1	Discharge Rate	319
13.6.2	Gear Pumps	320
13.6.3	Screw Pumps	321
13.6.4	Progressing Cavity Pump	323
13.7	Reciprocating Positive Displacement Machines	323
13.7.1	Drive Technology for Reciprocating Positive Displacement Machines	324
13.7.2	Flow Behavior of Reciprocating Positive Displacement Machines	325
13.7.3	Pulsation Damping	327
13.7.4	Design Versions	328
13.7.4.1	Vertical Pump Head for 70 MPa	328
13.7.4.2	Horizontal Pump Head with Y-Piece for 300 MPa	329
13.7.4.3	Diaphragm Pump Heads	329
13.7.4.4	Piston Compressor for 30 MPa at the Maximum	330
13.7.4.5	Compressor for 300 MPa	332
13.7.4.6	Piston Compressor for 1400 MPa	333
	References	334
14	High-Pressure Measuring Devices and Test Equipment	335
	<i>Arne Pietsch</i>	
14.1	Introduction	335
14.2	Process Data Measuring – Online	336

14.2.1	Sensor Choice and Installation	337
14.2.2	Pressure and Differential Pressure	338
14.2.3	Temperature	341
14.2.4	Flow	343
14.2.5	Fluid Level	350
14.2.6	Density	351
14.2.7	Viscosity	351
14.2.8	Concentration – Solute in High-Pressure Gases and Fluids	352
14.2.9	Concentration – Gas Traces Dissolved in Liquids	358
14.3	Lab Determination – Additional Offline Test Equipment	359
14.3.1	Phase Equilibrium	359
14.3.2	Magnetic Sorption Balance	362
14.3.3	Interfacial Tension and Wetting	362
14.3.4	Gas Hydrates	363
14.3.5	Other Properties Online	364
14.4	Safety Aspects	364
14.5	Future	366
	References	367
15	Sizing of High-Pressure Safety Valves for Gas Service	369
	<i>Jürgen Schmidt</i>	
15.1	Standard Valve Sizing Procedure	369
15.2	Limits of the Standard Valve Sizing Procedure	371
15.3	Development of a Sizing Method for Real Gas Applications	372
15.3.1	Equation of State and Real Gas Factor	375
15.3.2	Isentropic Exponent	378
15.3.3	Critical Pressure Ratio	379
15.4	Sizing of Safety Valves for Real Gas Flow	380
15.5	Summary	382
Appendix 15.A	Calculation of Sizing Coefficient According to EN-ISO 4126-1 and a Real Gas Nozzle Flow Model	383
15.A.1	Inlet Stagnation Conditions	383
15.A.2	Property Data and Coefficients for Ethylene	383
15.A.3	Calculation of Flow Coefficient According to EN-ISO 4126-1	384
15.A.4	Calculation of Flow Coefficient Accounting for Real Gas Effects	385
15.A.5	Approximation of Mass Flux by an Analytical Method (Averaging Method)	386
Appendix 15.B	List of Symbols	387
	Subscripts	388
	References	389

Appendix: International Codes and Standards for High-Pressure Vessels 391

Index 397