

Contents

Preface — V

1 The chemical industry — 1

- 1.1 Introduction — 1
- 1.2 General characteristics of the chemical industry segments — 3
- 1.3 Major raw materials — 5
- 1.4 Production structure of the chemical industry — 6

2 The structure of chemical and biochemical process systems — 11

- 2.1 Structure of chemical and biochemical processes — 11
- 2.2 Characteristics of production processes — 12
 - 2.2.1 Batch production technology — 12
 - 2.2.2 Continuous processes — 13
- 2.3 Unit operations — 15
 - 2.3.1 Reactors — 16
 - 2.3.2 Recovery, purification and fractionation technologies — 18
 - 2.3.3 Product finishing operations — 20
 - 2.3.4 Other important process units — 22
- 2.4 Process synthesis — 24

3 Principles of chemical reaction engineering — 27

- 3.1 Introduction — 27
- 3.2 Classification of reactions — 28
- 3.3 Rate of chemical reactions — 29
 - 3.3.1 Effect of concentration — 29
 - 3.3.2 Effect of temperature — 30
 - 3.3.3 Chemical equilibria — 31
- 3.4 Catalysis — 33
 - 3.4.1 Homogeneous catalysis — 33
 - 3.4.2 Heterogeneous catalysis — 35
- 3.5 Conversion, selectivity and yield — 37
 - 3.5.1 Conversion — 37
 - 3.5.2 Selectivity and yield — 38
 - 3.5.3 Multistep reactions — 39
- 3.6 Basic design equations for model reactors — 41
 - 3.6.1 Molar balances — 41
 - 3.6.2 The ideal batch reactor — 42
 - 3.6.3 The continuous ideal stirred tank reactor — 44
 - 3.6.4 Ideal continuous plug flow reactor — 45
 - 3.6.5 Cascade of continuous ideal stirred tanks reactors — 47

3.7	Heat effects in model reactors —	48
3.7.1	General heat balance —	48
3.7.2	Heat balance in a continuous ideal stirred tank reactor —	49
3.7.3	Heat balance in a batch reactor —	50

4 Chemical reactors and their industrial applications — 53

4.1	Introduction —	53
4.1.1	Classification of reactors —	53
4.1.2	Influence of heat of reaction on reactor type —	53
4.2	Stirred tank reactors —	54
4.2.1	Description —	54
4.2.2	Batch stirred tank reactors —	55
4.2.3	Continuous stirred tanks —	57
4.2.4	Cascade of stirred tanks —	60
4.3	Tubular reactors —	61
4.3.1	Introduction —	61
4.3.2	Gas-phase reactors —	62
4.3.3	Liquid-phase reactors —	64
4.4	Loop reactors —	65
4.4.1	Continuous loop reactors —	66
4.4.2	Buss loop reactor —	66
4.5	Bubble columns —	68
4.6	Fixed and moving bed reactors —	70
4.6.1	Fixed bed reactors —	70
4.6.2	Adiabatic fixed bed reactors —	71
4.6.3	Fixed bed reactors with supply or removal of heat —	72
4.6.4	Moving bed reactors —	74
4.7	Fluidized bed reactors —	75
4.7.1	The fluidization principle —	76
4.7.2	Fluidization properties of typical bed solids —	78
4.7.3	Applications —	78
4.8	Electrochemical reactors —	82
4.8.1	Basic elements of an electrochemical reactor —	82
4.8.2	Design of an electrochemical reactor —	83
4.8.3	Applications —	85

5 Biochemical reaction technology — 87

5.1	Characteristics of biochemical processes —	87
5.1.1	Fermentation —	88
5.1.2	Enzymatic conversions —	93
5.2	Biochemical reaction engineering —	96

- 5.2.1 Principles — **96**
- 5.2.2 Kinetics of biochemical reactions — **96**
- 5.2.3 Basic reactor operations — **100**
- 5.3 Industrial bioreactors — **102**
- 5.3.1 Classification — **102**
- 5.3.2 Bioreactors with mechanical mixing — **103**
- 5.3.3 Bioreactors with pneumatic mixing — **104**
- 5.3.4 Bioreactors for immobilized enzymes and cells — **106**

6 Evaporative separations — 109

- 6.1 Evaporative separation — **109**
- 6.1.1 Introduction — **109**
- 6.1.2 Vapor-liquid equilibria — **110**
- 6.1.3 Separation by single-stage partial evaporation — **113**
- 6.2 Multistage distillation — **115**
- 6.2.1 Distillation cascades — **115**
- 6.2.2 Column distillation — **116**
- 6.2.3 Feasible distillation conditions — **118**
- 6.2.4 Basic design calculations — **119**
- 6.2.5 Energy requirements — **122**
- 6.2.6 Batch distillation — **123**
- 6.2.7 Continuous separation of multiple products — **125**
- 6.2.8 Enhanced distillation techniques — **125**
- 6.3 Distillation equipment — **127**
- 6.3.1 Basic functions — **127**
- 6.3.2 Tray columns — **128**
- 6.3.3 Packed columns — **132**
- 6.3.4 Criteria for column selection — **137**
- 6.4 Polymer devolatilization — **137**
- 6.4.1 Introduction — **137**
- 6.4.2 Basic mechanisms — **138**
- 6.4.3 Multistage operation and devolatilization aids — **140**
- 6.4.4 Devolatilization equipment — **141**

7 Extraction and leaching — 147

- 7.1 Liquid-liquid extraction — **147**
- 7.1.1 Introduction — **147**
- 7.1.2 Liquid-liquid equilibria — **149**
- 7.1.3 Solvent selection — **151**
- 7.1.4 Extraction schemes — **152**
- 7.2 Industrial liquid-liquid extractors — **154**
- 7.2.1 Mixer settlers — **154**

7.2.2	Mechanically agitated columns —	155
7.2.3	Unagitated and pulsed columns —	155
7.2.4	Centrifugal extractors —	157
7.2.5	Selection of an extractor —	158
7.3	Leaching —	159
7.3.1	Mechanism and process of leaching —	160
7.3.2	Solid-liquid extractors —	161
7.4	Supercritical extraction —	165
7.4.1	Introduction —	165
7.4.2	Properties of supercritical fluids —	166
7.4.3	Processes and applications —	167
8	Absorption and stripping —	173
8.1	Introduction —	173
8.2	The aim of absorption —	175
8.3	General design approach —	176
8.3.1	Gas solubilities —	177
8.3.2	Minimum absorbent flow —	179
8.3.3	Number of equilibrium stages —	179
8.4	Basic characteristics of absorbers —	180
8.5	Industrial contactors —	181
8.5.1	Packed columns —	182
8.5.2	Tray columns —	183
8.5.3	Spray towers —	185
8.5.4	Bubble columns —	186
9	Adsorption and ion exchange —	189
9.1	Introduction —	189
9.2	Adsorption fundamentals —	191
9.2.1	Industrial adsorbents —	191
9.2.2	Adsorption equilibrium —	194
9.2.3	Adsorption kinetics —	196
9.2.4	Fixed bed adsorption —	198
9.3	Basic adsorption cycles —	200
9.3.1	Temperature swing —	201
9.3.2	Pressure swing —	202
9.3.3	Inert and displacement purge cycles —	203
9.4	Principles of ion exchange —	204
9.4.1	Ion exchange resins —	204
9.4.2	Equilibria and selectivity —	205
9.5	Ion exchange processes —	207

10	Solid-liquid separation — 211
10.1	Introduction — 211
10.2	Gravity sedimentation — 215
10.2.1	Sedimentation mechanisms — 216
10.2.2	Rate of sedimentation — 217
10.2.3	Design of continuous sedimentation tanks — 220
10.2.4	Gravity sedimentation equipment — 221
10.3	Centrifugal sedimentation — 223
10.3.1	Particle velocity in a centrifugal field — 223
10.3.2	Sedimenting centrifuges — 223
10.3.3	Bowl centrifuge separation capability — 226
10.3.4	Hydrocyclones — 227
10.4	Filtration fundamentals — 229
10.4.1	Flow through packed beds — 229
10.4.2	Cake filtration — 231
10.4.3	Constant pressure and constant rate filtration — 232
10.5	Filtration equipment — 233
10.5.1	Continuous large-scale vacuum filters — 234
10.5.2	Batch vacuum filters — 235
10.5.3	Pressure filters — 236
10.6	Filter media — 239
10.7	Centrifugal filtration — 240
10.8	Deep bed filtration — 242
11	Particle removal from gases — 245
11.1	Introduction — 245
11.1.1	Separation mechanisms — 245
11.2	Collecting efficiency — 246
11.3	Gravitational separators — 248
11.4	Cyclones — 251
11.5	Electrostatic precipitation — 253
11.5.1	Principles — 253
11.5.2	Equipment and collecting efficiency — 255
11.6	Particle interception mechanisms — 257
11.7	Dry impingement separators — 259
11.7.1	Deep bed filtration — 260
11.7.2	Surface filters — 261
11.7.3	Lamellar plate separators — 262
11.8	Wet scrubbers — 263

12 Membrane separations — 269

- 12.1 Introduction — 269
- 12.2 Principles — 272
 - 12.2.1 Membranes — 272
 - 12.2.2 Modules — 274
 - 12.2.3 Flux, permeability and selectivity — 276
 - 12.2.4 Concentration polarization and fouling — 278
 - 12.2.5 System design and cascades — 280
- 12.3 Membrane filtration processes — 282
 - 12.3.1 Microfiltration — 282
 - 12.3.2 Ultrafiltration — 283
 - 12.3.3 Reverse osmosis and nanofiltration — 284
- 12.4 Solubility-driven processes — 286
 - 12.4.1 Gas and vapor permeation — 286
 - 12.4.2 Pervaporation — 288
- 12.5 Electrodialysis — 290

13 Crystallization and precipitation — 293

- 13.1 Introduction — 293
- 13.2 Fundamentals — 295
 - 13.2.1 Solid-Liquid equilibria — 296
 - 13.2.2 Supersaturation and metastability — 297
 - 13.2.3 Nucleation — 298
 - 13.2.4 Crystal growth — 300
 - 13.2.5 Effects of impurities — 302
- 13.3 Crystal characteristics — 302
 - 13.3.1 Morphology — 303
 - 13.3.2 Crystal size distribution — 304
 - 13.3.3 Size control — 304
- 13.4 Types of solution crystallizers — 305
 - 13.4.1 Basic operations — 305
 - 13.4.2 Cooling crystallizers — 306
 - 13.4.3 Evaporating and vacuum crystallizers — 307
 - 13.4.4 Continuous crystallizers — 308
- 13.5 Crystallizer modeling and design — 309
 - 13.5.1 Basic yield calculations — 310
 - 13.5.2 Population balances — 312
 - 13.5.3 The well-mixed MSMPR crystallizer — 314
- 13.6 Precipitation — 314
- 13.7 Melt crystallization — 315

14 Solids finishing technologies — 321

- 14.1 Overview — 321
- 14.2 Drying — 322
 - 14.2.1 Classification of drying operations — 323
 - 14.2.2 Drying mechanisms — 324
 - 14.2.3 Direct heat dryers — 327
 - 14.2.4 Contact dryers — 331
 - 14.2.5 Other drying methods — 335
- 14.3 Size reduction — 336
 - 14.3.1 Particle breakage — 337
 - 14.3.2 Methods and selection criteria for size reduction — 339
 - 14.3.3 Size reduction equipment — 341
- 14.4 Size enlargement — 345
 - 14.4.1 Agglomeration principles — 346
 - 14.4.2 Methods of size enlargement — 348
 - 14.4.3 Growth/tumble agglomeration — 348
 - 14.4.4 Pressure agglomeration — 350
 - 14.4.5 Other agglomeration techniques — 352
- 14.5 Conveying — 353
 - 14.5.1 Transportation systems — 353
 - 14.5.2 Mechanical conveyors — 354
 - 14.5.3 Pneumatic conveying — 358

15 Product technology — 363

- 15.1 Cheese coating technology — 363
 - 15.1.1 Cheese production — 363
 - 15.1.2 Coatings — 364
 - 15.1.3 Application techniques — 364
- 15.2 Enzyme formulation — 367
 - 15.2.1 Introduction — 367
 - 15.2.2 Glucose isomerase immobilization — 368
 - 15.2.3 Detergent enzymes — 370
 - 15.2.4 Application research — 373
- 15.3 Compounding — 375
 - 15.3.1 Introduction — 375
 - 15.3.2 Compound formulation — 376
 - 15.3.3 Additives — 378
 - 15.3.4 Polymer mixing mechanisms — 381
 - 15.3.5 Compounding equipment — 383
- 15.4 Polymer processing — 387
 - 15.4.1 Extrusion processes — 388
 - 15.4.2 Injection and blow molding — 389

15.4.3	Melt and gel spinning —	392
15.4.4	Film production techniques —	394
15.4.5	Thermoforming —	398
15.4.6	Foam extrusion —	399
16	Development, scale-up and engineering —	401
16.1	Introduction —	401
16.1.1	General aspects of scaling up —	401
16.1.2	Ways of scaling up —	402
16.2	Development and scale-up in the bulk chemical industry —	403
16.2.1	Basic course of process development —	403
16.2.2	Laboratory and bench scale research —	406
16.2.3	Pilot plant research and demonstration plants —	408
16.2.4	Feasibility evaluation —	410
16.3	Engineering and construction —	412
16.3.1	Introduction —	412
16.3.2	Conceptual engineering —	414
16.3.3	Basic engineering —	415
16.3.4	Detailed engineering, procurement and construction —	417
16.4	Development and scale-up of fine chemical processes —	421
16.4.1	Differences between bulk and fine chemical industry —	421
16.4.2	Fine chemical process development —	421
16.4.3	Scale-Up challenges in multipurpose plants —	423
16.4.4	Future developments —	424
17	Hydrodynamic aspects of scale-up —	427
17.1	Introduction —	427
17.2	Hydrodynamic flows in process equipment —	428
17.2.1	Single-phase flows —	428
17.2.2	Multiphase flows —	429
17.2.3	Flows in mixers and stirrers —	430
17.2.4	Flows in bubble columns —	438
17.2.5	Flows in fluidized beds —	440
17.3	Scale-up —	440
17.3.1	Dimensional, similarity and regime analysis —	441
17.3.2	Important dimensionless numbers for mixing vessels —	442
17.3.3	Important dimensionless numbers for bubble columns —	443
17.3.4	Important dimensionless numbers for fluidized beds —	445
17.4	Computational fluid dynamics (CFD) —	446

17.4.1	Types of CFD simulations —	446
17.4.2	Basic principles of CFD —	449
17.4.3	Applications —	452
18	Process safety —	455
18.1	Safety problems in chemical plants —	455
18.2	Development, design and construction of safe plants —	456
18.2.1	Introduction —	456
18.2.2	Safety assessment —	457
18.2.3	Structure of safety studies —	459
18.3	Identification of hazardous properties of substances —	461
18.3.1	Pure components —	461
18.3.2	Exothermic chemical reactions —	464
18.4	Inherently safer plant design —	466
18.4.1	The concept and its benefits —	466
18.4.2	The road to friendlier plants —	467
A	Base chemicals —	471
A.1	Ammonia —	471
A.1.1	General description —	471
A.1.2	Desulfurization —	471
A.1.3	Primary and secondary reforming —	471
A.1.4	Shift conversion —	473
A.1.5	Carbon dioxide removal —	474
A.1.6	Final purification —	474
A.1.7	Ammonia syntheses and recovery —	475
A.2	Inorganic acids —	476
A.2.1	Nitric acid —	476
A.2.2	Sulfuric acid —	478
A.3	Ammonia-based products —	480
A.3.1	Caprolactam —	480
A.3.2	Acrylonitrile —	483
A.3.3	Urea —	484
A.3.4	Melamine —	486
A.4	Naphtha cracking —	488
A.4.1	Basic principles —	488
A.4.2	Hot section —	489
A.4.3	Cold section —	491
A.4.4	Coke formation —	492
A.5	Oxidation processes —	492
A.5.1	Toluene oxidation —	493
A.5.2	Cyclohexane oxidation —	495

- A.5.3 *n*-Butane oxidation — **496**
- A.6 Fischer-Tropsch — **498**
- A.6.1 Synthesis gas production — **499**
- A.6.2 Fischer-Tropsch synthesis — **501**
- A.7 Industrial electrochemical processes — **505**
- A.7.1 Chlorine gas production — **505**
- A.7.2 Hydrogen peroxide production — **507**
- A.7.3 Adiponitrile production — **508**

B Polymer manufacturing — 511

- B.1 Polyethylene — **511**
 - B.1.1 High-pressure process — **511**
 - B.1.2 Solution polymerization — **512**
 - B.1.3 Slurry process — **513**
 - B.1.4 Gas-phase process — **515**
- B.2 Polypropylene — **517**
 - B.2.1 Gas-phase process — **517**
 - B.2.2 Slurry process — **520**
- B.3 EPDM — **522**
- B.4 Polyamides — **525**
 - B.4.1 Introduction — **525**
 - B.4.2 Nylon 6 — **525**
 - B.4.3 Nylon 4,6 — **526**
- B.5 Saturated and unsaturated polyesters — **528**
 - B.5.1 Saturated polyesters — **528**
 - B.5.2 Unsaturated polyesters — **531**
 - B.5.3 Powder coatings — **532**

C Life science products — 533

- C.1 Benzaldehyde-based products — **533**
 - C.1.1 Amino acids — **533**
 - C.1.2 Cinnamon aldehyde and cinnamyl alcohol — **535**
 - C.1.3 Benzyl alcohol — **537**
- C.2 α -Picoline — **537**
- C.3 Aspartame — **540**
- C.4 Penicillin — **541**
- C.5 Synthetic antibiotics — **545**
 - C.5.1 Introduction — **545**
 - C.5.2 Cephalosporins — **546**
 - C.5.3 Amoxillins — **548**

C.6	Glyoxylic acid —	549
C.7	Food additives —	551
C.7.1	Quinine —	552
C.7.2	Enzymes —	552

References and further reading —	555
---	------------

Index —	565
----------------	------------

