

Contents

1 Characteristics of separation processes

1.1	Significance of separations	1
1.2	Characteristics of separation processes	4
1.2.1	Categorization	4
1.2.2	Separating agents	4
1.2.3	Separation factors	6
1.3	Industrial separation methods	7
1.3.1	Exploitable properties	7
1.3.2	Important molecular separations	9
1.4	Inherent selectivities	11
1.4.1	Equilibrium based processes	11
1.4.2	Rate controlled processes	12

2 Evaporation and distillation

2.1	Separation by evaporation	15
2.1.1	Introduction	15
2.1.2	Vapor-liquid equilibria	16
2.2	Separation by single-stage partial evaporation	21
2.2.1	Differential distillation	21
2.2.2	Flash distillation	22
2.2.2.1	Specifying T and L/V	24
2.2.2.2	Specifying T and p_{tot}	25
2.3	Multistage distillation	26
2.3.1	Distillation cascades	26
2.3.2	Column distillation	27
2.3.3	Feasible distillation conditions	29
2.3.4	External column balances	29
2.4	McCabe-Thiele analysis	30
2.4.1	Internal balances	30
2.4.1.1	Rectifying section	31
2.4.1.2	Stripping section	32
2.4.1.3	Feed stage considerations	33
2.4.1.4	Feed line	35
2.4.2	Required number of equilibrium stages	36
2.4.2.1	Graphical determination of stages and location of feed stage	36
2.4.2.2	Limiting conditions	37

2.4.2.3	Fenske and underwood equations	40
2.4.2.4	Use of murphree efficiency	42
2.4.3	Energy requirements	43
2.5	Advanced distillation techniques	44
2.5.1	Batch distillation	44
2.5.2	Continuous separation of multiple product mixtures	45
2.5.3	Separation of azeotropes	46

3 Absorption and stripping

3.1	Introduction	53
3.2	The aim of absorption	55
3.3	General design approach	56
3.4	Absorption and stripping equilibria	57
3.4.1	Gaseous solute solubilities	57
3.4.2	Minimum absorbent flow	59
3.5	Absorber and stripper design	60
3.5.1	Operating lines for absorption	60
3.5.2	Stripping analysis	64
3.5.3	Analytical kremser solution	65
3.6	Industrial absorbers	68
3.6.1	Packed columns	69
3.6.2	Plate columns	70
3.6.3	Spray and bubble columns	70
3.6.4	Comparison of absorption columns	71

4 General design of gas/liquid contactors

4.1	Introduction	77
4.2	Modeling mass-transfer	77
4.3	Plate columns	83
4.3.1	Dimensioning a tray column	85
4.3.2	Height of a tray column	86
4.3.3	Diameter of a tray column	91
4.4	Packed columns	97
4.4.1	Random packing	98
4.4.2	Structured packing	99
4.4.3	Dimensioning a packed column	100
4.4.4	Height of a packed column	101
4.4.5	Minimum column diameter	104
4.4.6	Pressure drop	106
4.5	Criteria for column selection	107

5 Liquid-liquid extraction

5.1	Liquid-liquid extraction	111
5.1.1	Introduction	111
5.1.2	Liquid-liquid equilibria	113
5.1.3	Solvent selection	115
5.2	Extraction schemes	117
5.2.1	Single equilibrium stage	117
5.2.2	Cocurrent cascade	118
5.2.3	Crosscurrent	119
5.2.4	Countercurrent	120
5.3	Design of countercurrent extractions	121
5.3.1	Graphical McCabe-Thiele method for immiscible systems	121
5.3.2	Analytical kremser method	124
5.3.3	Graphical method for partial miscible systems	124
5.3.4	Efficiency of an ideal non-equilibrium mixer	129
5.4	Industrial liquid-liquid extractors	130
5.4.1	Mixer-settlers	130
5.4.2	Mechanically agitated columns	131
5.4.3	Unagitated and pulsed columns	132
5.4.4	Centrifugal extractors	134
5.4.5	Selection of an extractor	135

6 Adsorption and ion exchange

6.1	Introduction	143
6.2	Adsorption fundamentals	145
6.2.1	Industrial adsorbents	145
6.2.2	Equilibria	150
6.2.3	Kinetics	154
6.3	Fixed-Bed adsorption	156
6.3.1	Bed profiles and breakthrough curves	156
6.3.2	Equilibrium theory model	158
6.3.3	Modeling of mass transfer effects	161
6.4	Basic adsorption cycles	162
6.4.1	Temperature-swing	164
6.4.2	Pressure-swing	165
6.4.3	Inert and displacement purge cycles	166
6.5	Principles of ion exchange	167
6.5.1	Ion exchange resins	167
6.5.2	Equilibria and selectivity	169
6.6	Ion exchange processes	170

7 Drying of solids

7.1	Introduction	177
7.2	Humidity definitions of carrier gas	178
7.2.1	Definitions	178

7.2.2	System air-water: a special case	180
7.2.3	Psychrometric charts	182
7.3	Moisture in solids	183
7.3.1	Bound and unbound water	184
7.4	Drying mechanisms	188
7.4.1	Constant drying rate	189
7.4.2	Falling drying rate	190
7.4.3	Estimation of drying time	190
7.5	Classification of drying operations	192
7.5.1	Direct-Heat dryers	194
7.5.2	Contact dryers	199
7.5.3	Other drying methods	201

8 Crystallization and precipitation

8.1	Introduction	207
8.2	Crystal characteristics	209
8.2.1	Morphology	210
8.2.2	Crystal size distribution	211
8.3	Crystallization operating modes from solutions	212
8.3.1	Operating modes	212
8.3.2	Cooling crystallizers	214
8.3.3	Evaporating and vacuum crystallizers	215
8.3.4	Continuous crystallizers	217
8.3.5	Basic yield calculations	219
8.4	Crystallizer modeling and design	221
8.4.1	Supersaturation and metastability	221
8.4.2	Nucleation	223
8.4.3	Crystal growth	226
8.4.4	Population balance equations for the MSMPR crystallizer	229
8.5	Other crystallization techniques	232
8.5.1	Precipitation	232
8.5.2	Melt crystallization	233

9 Sedimentation and settling

9.1	Introduction	241
9.2	Gravity sedimentation	242
9.2.1	Sedimentation mechanisms	242
9.2.2	Dilute sedimentation	245
9.2.3	Hindered settling	247
9.2.4	Continuous sedimentation tank (gravity settling tank)	248
9.2.5	Gravity sedimentation equipment	250
9.3	Centrifugal sedimentation	251
9.3.1	Particle velocity in a centrifugal field	251

9.3.2	Sedimenting centrifuges	252
9.3.3	Bowl centrifuge separation capability	254
9.3.4	The sigma concept	256
9.3.5	Capacity of disc centrifuges	258
9.3.6	Hydrocyclones	259
9.4	Electrostatic precipitation	263
9.4.1	Principles	263
9.4.2	Equipment and collecting efficiency	265

10 Filtration

10.1	The filtration processfiltration process	271
10.2	Filtration fundamentals	274
10.2.1	Flow through packed beds	274
10.2.2	Cake filtration	275
10.2.3	Constant pressure and constant rate filtration	277
10.2.4	Compressible cakes	278
10.3	Filtration equipment	279
10.3.1	Continuous large-scale vacuum filters	279
10.3.2	Batch vacuum filters	283
10.3.3	Pressure filters	284
10.4	Filter media	286
10.5	Centrifugal filtration	287
10.5.1	Centrifugal filters	287
10.5.2	Filtration rates in centrifuges	289
10.6	Interceptive filtration	292
10.6.1	Deep bed filtration	292
10.6.2	Impingement filtration of gases	293
10.6.3	Interception mechanisms	295
10.6.4	Lamellar plate separators	297

11 Membrane filtration

11.1	Introduction	301
11.2	Membrane selection	302
11.3	Membrane filtration processes	304
11.4	Flux equations and selectivity	307
11.4.1	Flux definitions	307
11.4.2	^{new} Permeability for diffusion in porous membranes	309
11.4.3	Permeability for solution-diffusion in dense membranes	310
11.4.4	Selectivity and retention	312
11.5	Concentration polarization	313

11.6	Membrane modules	316
11.6.1	Design procedure	320
11.6.2	Solution	320
11.7	Concluding remarks	321

12 Separation method selection

12.1	Introduction	325
12.1.1	Industrial separation processes	325
12.1.2	Factors influencing the choice of a separation process	327
12.1.2.1	Economics	327
12.1.2.2	Feasibility	328
12.1.2.3	Product stability	329
12.1.2.4	Design reliability	329
12.2	Selection of feasible separation processes	330
12.2.1	Classes of processes	330
12.2.2	Initial screening	330
12.2.3	Separation factor	332
12.3	Separation of homogeneous liquid mixtures	333
12.3.1	Strengths of distillation	333
12.3.2	Limitations of distillation	335
12.3.3	Low relative volatilities	337
12.3.4	Overlapping boiling points	340
12.3.5	Low concentrations	341
12.3.6	Dissolved solids	342
12.4	Separation systems for gas mixtures	343
12.4.1	General selection considerations	343
12.4.2	Comparison of gas separation	344
12.4.2.1	Absorption	344
12.4.2.2	Adsorption	345
12.4.2.3	Membrane separation	346
12.5	Separation methods for solid-liquid mixtures	346

Appendix

Answers to exercises	351
References and further reading	359
Index	363