

Contents

	<i>Preface</i>	page xv
	<i>Abbreviations</i>	xviii
1	Introduction to membrane filtration of liquids	1
1.1	Introduction	1
1.2	Definitions and terminology	3
1.2.1	Dead-end and crossflow configurations	3
1.2.2	Key process parameters in membrane filtration	6
1.2.3	Solute and particle rejection	7
1.3	Membranes and their properties	9
1.3.1	Membrane materials	9
1.3.2	Membrane morphology	9
1.4	Membrane modules	10
1.4.1	Flat sheet and spiral wound modules	10
1.4.2	Shell-and-tube modules	11
1.4.3	Stirred cells	12
1.5	Flux characteristics in membrane filtration	12
1.5.1	Dead-end filtration	12
1.5.2	Crossflow configuration	13
1.6	Conclusions	14
	References	15
	Additional reading	15
2	Dead-end filtration	16
2.1	Introduction to dead-end filtration	16
2.2	The filtrate flux equation	17
2.3	The specific cake resistance	19
2.3.1	Cake compressibility	19
2.3.2	Effects of particle and liquid properties	23
2.3.3	Filter aids	24
2.4	Analysis and design of batch dead-end filtration	25
2.4.1	Analysis and design of batch DEF at constant pressure	26
2.4.2	Analysis of batch DEF at constant filtrate flux	31

2.4.3	Analysis of batch DEF with a centrifugal pump	34
2.5	Continuous filtration	37
2.6	Modelling product transmission in DEF	39
2.7	Conclusions	41
	References	42
	Problems	43
	Further problems	45
3	Crossflow microfiltration	48
3.1	Introduction	48
3.2	Modes of operation	48
3.3	Flux characteristics during continuous operation	49
3.4	Theories of crossflow microfiltration	51
3.4.1	Concentration polarisation and shear-induced diffusion	51
3.4.2	The force balance approach	53
3.4.3	The spatial dependence of the flux	57
3.5	A simple kinetic model of CFMF	57
3.5.1	Steady state behaviour	59
3.5.2	Dynamic behaviour	60
3.5.3	Constant flux operation	63
3.5.4	Linking the kinetic model with force balance theory	65
3.5.5	Flux dynamics with a transition flux	67
3.6	Process design and analysis	68
3.6.1	Analysis of a continuous feed-and-bleed system	69
3.6.2	Modelling the dynamics of batch CFMF	70
3.6.3	Fed-batch operation	76
3.7	Cake properties in CFMF	78
3.8	Improving the flux	80
3.8.1	Backflushing	81
3.8.2	Crossflushing	82
3.8.3	Air sparging	82
3.9	Product recovery in CFMF	83
3.10	Conclusions	83
	References	84
	Problems	85
	Further problems	86
4	Ultrafiltration flux theories	88
4.1	Introduction	88
4.2	Concentration polarisation	89
4.3	Prediction of mass transfer coefficients	90
4.3.1	Prediction of diffusion coefficients	93
4.3.2	Prediction of solution viscosity	95

4.4	The limiting flux (LF) model	98
4.5	The osmotic pressure (OP) model	103
4.5.1	Flux characteristics predicted by the osmotic pressure model	106
4.6	The osmotic pressure model with viscosity effects	109
4.6.1	Is the VOP model 'correct'?	114
4.7	Conclusions	116
	References	116
	Problems	117
	Further problems	119
5	Ultrafiltration process analysis and design at the limiting flux	120
5.1	Introduction	120
5.2	Continuous feed-and-bleed ultrafiltration	120
5.2.1	Analysis of a single-stage system	122
5.2.2	Analysis of a multi-stage system	122
5.2.3	Analysis of a multi-stage system using ordinary differential equations	124
5.2.4	Analysis of a multi-stage system using a graphical method	125
5.2.5	Design of a single-stage system	127
5.2.6	Design of a multi-stage system with equal areas	128
5.2.7	Optimisation of multi-stage systems	129
5.2.8	Design with viscosity dependent mass transfer coefficient	131
5.3	Batch ultrafiltration	132
5.3.1	Calculation of final conditions for a fixed time	134
5.3.2	Calculation of batch time by solution of governing ODE	136
5.3.3	Calculation of batch time using special functions	137
5.3.4	Approximate methods for calculating the batch time	139
5.4	Fed-batch operation	141
5.5	Single pass operation	144
5.5.1	Single pass analysis with viscosity independent mass transfer coefficient	144
5.5.2	Single pass analysis with viscosity dependent mass transfer coefficient	146
5.5.3	Single pass design with constant mass transfer coefficient	146
5.6	Membrane fouling and limiting flux operation	147
5.7	Conclusions	148
	References	148
	Problems	149
	Further problems	150
6	Diafiltration at the limiting flux	152
6.1	Introduction	152
6.2	Discontinuous diafiltration	152

6.2.1	Volume reduction method	152
6.2.2	Dilution method	157
6.3	Constant volume diafiltration	160
6.3.1	Water consumption in CVD	161
6.3.2	Time taken for CVD	163
6.3.3	Ultrafiltration with constant volume diafiltration (UFCVD)	163
6.3.4	UFCVD time optimisation with viscosity dependent mass transfer coefficient	165
6.3.5	Economic optimisation of UFCVD	167
6.3.6	Economic optimisation with viscosity dependent mass transfer coefficient	169
6.3.7	Optimisation of UFCVD when $c_{Af} < c_{Aopt}$	170
6.4	Dynamic modelling of UFDF processes	172
6.4.1	Dynamic modelling of UFCVD	173
6.4.2	Dynamic modelling of variable volume diafiltration (VVD)	176
6.4.3	Generalised VVD processes and dynamic optimisation	179
6.4.4	Diafiltration of suspensions	180
6.5	Continuous diafiltration	184
6.5.1	Two-stage continuous UFDF	185
6.5.2	Counter-current diafiltration	186
6.6	Dialysis	187
6.7	Conclusions	190
	References	190
	Additional reading	191
	Problems	191
	Further problems	193
7	Ultrafiltration and diafiltration with incomplete rejection	194
7.1	Introduction	194
7.2	Quantifying rejection	194
7.3	Concentration polarisation	196
7.4	Flux dependence of the apparent rejection coefficient	196
7.5	Continuous feed-and-bleed ultrafiltration	197
7.5.1	Analysis and design of a single-stage system	198
7.5.2	Solving single-stage problems using a graphical method	199
7.5.3	Analysis and design of two-stage systems	201
7.6	Batch ultrafiltration	202
7.6.1	Batch UF with constant apparent rejection	203
7.6.2	Batch UF with constant intrinsic rejection	205
7.7	Fed-batch ultrafiltration	206
7.8	Single pass ultrafiltration	207
7.9	Constant volume diafiltration	209
7.9.1	Computation of diafiltration time	211

7.9.2	UFCVD with arbitrary rejection coefficients	212
7.9.3	Dynamic modelling of UFCVD	214
7.9.4	Optimisation of UFCVD with arbitrary rejection coefficients	216
7.10	Variable volume diafiltration	218
7.11	Conclusions	219
	References	220
	Additional reading	220
	Problems	220
	Further problems	222
8	The osmotic pressure model applied to ultrafiltration and diafiltration	223
8.1	Introduction	223
8.2	Analysis and design of continuous feed-and-bleed UF	224
8.2.1	Analysis and design of single-stage systems	224
8.2.2	Multi-stage systems	225
8.3	Dynamic modelling of batch UF	226
8.3.1	Batch UF with constant mass transfer coefficient	227
8.3.2	Batch UF with viscosity dependent mass transfer coefficient	229
8.4	Fed-batch ultrafiltration	231
8.5	Single pass ultrafiltration	233
8.6	Constant volume diafiltration	235
8.6.1	Optimisation of UFCVD – constant mass transfer coefficient	235
8.6.2	Optimisation of UFCVD – viscosity dependent mass transfer coefficient	237
8.7	Ultrafiltration with constant wall concentration	238
8.8	The osmotic pressure model with incomplete rejection	240
8.8.1	Single-stage feed-and-bleed UF	242
8.8.2	Dynamic modelling of batch UF	243
8.8.3	Constant volume diafiltration	245
8.9	Product transmission in CFMF	247
8.10	Conclusions	249
	References	250
	Additional reading	250
	Problems	250
	Further problems	251
9	Reverse osmosis and nanofiltration	253
9.1	Introduction to reverse osmosis	253
9.2	Reverse osmosis theory	254
9.2.1	Combining RO theory with concentration polarisation theory	257
9.3	Predicting osmotic pressures	258
9.4	Process configurations in RO	259
9.5	Analysis of a continuous feed-and-bleed system	260

9.6	Analysis of a single pass system	261
9.7	Reverse osmosis software	265
9.8	Introduction to nanofiltration	265
9.9	Nanofiltration theory	266
9.10	Fed-batch nanofiltration	267
9.11	Conclusions	270
	References	270
	Additional reading	271
	Problems	271
	Further problems	272
10	Membrane fouling	273
10.1	Introduction	273
10.1.1	The 'blocking' view of fouling	273
10.1.2	Empirical modelling	275
10.2	Dead-end filtration	275
10.2.1	Incompressible cakes	276
10.2.2	Compressible cakes	277
10.3	Crossflow microfiltration	279
10.3.1	The apparent specific resistance	279
10.4	Ultrafiltration	283
10.4.1	Membrane fouling and the limiting flux	284
10.4.2	Flux dynamics at constant composition	285
10.4.3	Dynamics of continuous feed-and-bleed UF	288
10.4.4	Constant volume diafiltration	290
10.4.5	Ultrafiltration with constant volume diafiltration (UFCVD)	292
10.5	Reverse osmosis and nanofiltration	295
10.6	Conclusions	296
	References	296
	Problems	297
	Further problems	298
	Appendix: Mathematical and computational background	299
A.1	Introduction	299
A.2	Calculus and symbolic computation	299
A.2.1	Differentiation	300
A.2.2	Series approximations to functions	303
A.2.3	Integration	304
A.3	Numerical solution of non-linear algebraic equations	306
A.3.1	The Newton–Raphson method	306
A.4	Numerical solution of ordinary differential equations	310
A.4.1	Euler's method for numerical solution of an ODE	310
A.4.2	Solution of systems of ODEs with the MATLAB function ode45	312

A.4.3 Differential algebraic equations	314
A.5 Numerical integration	315
A.6 Numerical differentiation	316
A.7 Non-linear regression	318
A.8 Conclusion	319
Further reading	319
Practice problems	320
<i>Index</i>	323