



Biofouling of Spiral Wound Membrane Systems

Johannes Simon Vrouwenvelder,
Joop Kruithof and Mark van Loosdrecht

Contents

Preface	xiii
Contributors	xv
Summary	xvii
Chapter 1	
<i>Introduction</i>	1
Increasing demand for clean freshwater	1
Membrane filtration.....	4
Membrane element.....	8
Membrane filtration system.....	10
Membrane fouling	11
Biofilms and biofouling	13
Biofouling in membrane systems	14
Scope and outline	16
Analysis	19
Chapter 2	
<i>Biofouling studies in NF and RO installations</i>	21
Introduction	21
Materials and methods.....	23

Test rig experiments.....	23
Full-scale experiments.....	23
Normalized pressure drop.....	25
Sampling and study of membranes.....	25
Biomass in membrane elements.....	26
Biological parameters of feed water.....	27
Effect of cleaning.....	27
Statistical evaluation.....	27
Results.....	27
Biomass in membrane elements.....	27
Dose-effect studies.....	29
Fouling of membrane plants: use of biomass parameters.....	31
Use of biological parameters of water to predict fouling.....	33
Pretreatment and cleaning.....	34
Discussion.....	35
Selection of a suitable parameter for biofouling.....	35
Use of feed water parameters as process parameters.....	38
Practical implications.....	39
Summary.....	42
Method development.....	45
Chapter 3	
<i>Membrane fouling simulator development</i>.....	47
Introduction.....	47
Materials and methods.....	51
Membrane fouling simulator.....	51
Membranes and spacers.....	52
Experimental set-up for operation/monitoring of MFS and test rig.....	53
Sampling and analysis of membrane coupons.....	54
Results.....	54
Relationship between linear velocity and pressure drop.....	54
Flow distribution.....	55
Sensitivity for fouling detection.....	55
Reproducibility of MFS experiments.....	57
Comparison of fouling in MFS and membrane elements.....	58
Discussion.....	60
Evaluation of the membrane fouling simulator.....	60
Potential fields of application for the membrane fouling simulator.....	62

Development of a set of new monitors	64
MFS operation	67
MFS use.....	69
Summary.....	70
Chapter 4	
<i>Sensitive pressure drop measurement</i>	73
Introduction	73
Materials and methods.....	74
Experimental set-up.....	74
Pressure drop measurements.....	75
Sampling and study of membranes modules.....	76
Feed water	79
Results	79
UF pretreatment.....	81
Development of pressure drop.....	84
Comparison of pressure drop measurements	85
Fouling analysis	85
Discussion.....	86
Pretreatment effect	86
Biofouling mechanism in lead membrane elements	86
Biofouling monitoring	88
Selection of pressure transmitter	89
Potential fouling control.....	90
Summary.....	91
Chapter 5	
<i>Nuclear magnetic resonance measurement</i>	93
Introduction	93
Methodology.....	94
Membranes systems.....	94
Membrane module	94
Flow cell.....	94
Biofouling procedure	95
Membrane module	95
Flow cell.....	97
Nuclear magnetic resonance (NMR) microscopy	97
Membrane module	97

Flow cell	98
Results and discussion	98
Membrane	98
Flow cell	101
Summary	106
Chapter 6	
<i>Three-dimensional numerical model development</i>	109
Introduction	109
Model description	112
Model geometry and computational domains	112
Momentum balance (hydrodynamics)	113
Mass balance for soluble substrate	114
Mass balance for biomass	115
Model solution	117
Model results and discussion	118
Interaction between hydrodynamics and biofilm growth	120
Effect of biofilm formation on the residence time distribution	134
Effect of mass transport limitations on the biofilm development ...	139
Model evaluation	141
Summary	144
Basic studies	145
Chapter 7	
<i>Effect of flux</i>	147
Introduction	147
Materials and methods	148
Experimental set-up	148
Calculation of the ratio of diffusive and convective flux	152
Results	155
Fouling in monitor without flux	155
Fouling in monitors, test rigs and full-scale plant	157
Fouling in membrane elements with/without flux in NF pilot plant ...	159
Discussion	161
Flux and critical flux	161
Nutrient rejection	163
Biofouling is a feed spacer problem	163
Summary	164

Chapter 8

<i>Effect of feed spacer</i>	165
Introduction	165
Materials and methods	166
Terminology	166
Experimental set-up	167
Full-scale and test-rig investigations with different feed water types	168
Comparison full-scale, test-rig and MFS studies	169
NF pilot plant: membrane elements with/without permeate production	169
Laboratory study	169
MRI study	170
Pressure drop	173
Membrane autopsy	173
Results	174
Full-scale and test-rig investigations with different feed water types	174
Comparison full-scale, test-rig and MFS studies	175
Influence of permeate production on biofouling	175
In-situ visual observations on fouling accumulation	177
In-situ MRI observations of fouling accumulation and velocity distribution profiles	177
Feed spacer impact on biofouling	181
Discussion	182
Biomass accumulates on the location with highest impact on feed channel pressure drop	183
Biofouling is a feed spacer problem	183
Reduction of biofouling by adaptation of spacer geometry and hydrodynamics	185
Summary	186

Chapter 9

<i>Three-dimensional numerical model based evaluation of experimental data</i>	187
Introduction	187
Materials and methods	189
Feed spacer characterization	189
Model description	190

Experimental set-up.....	193
MRI study.....	194
Pressure drop	195
Membrane autopsy	195
Results	196
Inventory of feed spacers used in practice.....	196
Biomass growth parameters and pressure drop increase	196
Comparison model with experimental data.....	197
Influence feed spacer: model and experimental data	203
Discussion.....	209
Comparison model with practice.....	209
Spacer relevance	211
Future studies and practical implications	212
Summary.....	213
Control studies	215
Chapter 10	
<i>Effect of substrate load and linear flow velocity</i>	217
Introduction	217
Materials and methods.....	219
Membrane fouling simulator.....	219
Experimental set-up.....	220
Sampling and study of membranes	220
Results	221
Linear flow velocities applied in practice	226
Effect of substrate concentration at constant linear velocity	226
Effect of linear flow velocity at constant substrate concentration	227
Effect of linear velocity and substrate concentration at constant substrate load.....	227
Effect of flow velocity.....	228
Effect of substrate load reduction	229
Discussion.....	231
Plant performance.....	231
Biomass parameters	231
Linear flow velocities applied in practice.....	232
Biofilm accumulation	233
Pressure drop increase monitoring.....	235
Biofouling analysis	235
Biofouling control	236
Linear flow velocity adaptation: possible consequences.....	237
Summary.....	238

Chapter 11***Effect of flow regime on biomass accumulation and morphology***

<i>Effect of flow regime on biomass accumulation and morphology</i>	239
Introduction	239
Materials and methods	241
Experimental set-up	241
Membrane fouling simulator (MFS)	241
Pressure drop	243
Bubble flow studies	243
Feed water and substrate dosage	244
Relative friction factor	246
Results	246
Effect substrate concentration at constant linear flow velocity	247
Effect linear flow velocity at constant substrate concentration	248
Effect linear flow velocity at constant substrate load	248
Effect bubble flow at constant substrate load and linear flow velocity	252
Effect flow regime on biofilm cohesion strength	255
Discussion	255
Analogy biofilm formation in RO/NF and other systems	255
Manipulation of biofilm morphology	256
Quantification of biofouling effect	257
Future studies and practical implications	257
Summary	259

Chapter 12***Effect of phosphate limitation***

<i>Effect of phosphate limitation</i>	261
Introduction	261
Materials and methods	263
Experimental set-up	263
Plant description	263
Membrane fouling simulator	266
Pressure drop	270
Membrane autopsy from elements and MFSs	270
Results	271
Full-scale RO investigations	271
'Proof of principle' phosphate limitation	272
Comparison of antiscalants	273
Growth limiting conditions in RO installation	274

Low phosphate concentrations during water treatment	277
Discussion	278
Biofouling control	278
Follow up	280
Summary	280
Outlook	283
Chapter 13	
<i>Integrated approach for biofouling control</i>	285
Introduction	285
Problem analysis	286
Early detection	288
Biofouling control	289
Strategy	289
Potential approaches	290
Cleaning strategies	291
Advanced cleaning strategies	293
Biofouling inhibitor dosage	295
Chemical selection and use	296
Low flow velocities	296
Feed flow reversal	297
Feed spacer modification	298
Total membrane system	299
Growth limiting conditions	299
Repetitive stress conditions	300
Biofilm morphology engineering	300
Combined approaches	303
Most promising scenarios for biofouling control	304
Biofouling tolerant conditions in spiral wound membrane systems	304
Capillary membranes	304
Phosphate limitation	305
Summary	305
References	307
Nomenclature	327
Index	331