

TABLE OF CONTENTS

1. INTRODUCTION.....	1
1.1 STATE OF THE ART OF URBAN WASTEWATER TREATMENT	3
1.2 ANAEROBIC TREATMENT OF URBAN WASTEWATER.....	4
1.2.1 <i>Main processes involved</i>	4
1.2.2 <i>Anaerobic vs. aerobic treatment</i>	5
1.3 MEMBRANE TECHNOLOGY FOR WASTEWATER TREATMENT	7
1.3.1 <i>Classification of MBR systems</i>	10
1.3.2 <i>Membrane technology applied to anaerobic wastewater treatment</i>	11
1.4 MEMBRANE FOULING IN MBR TECHNOLOGY	14
1.4.1 <i>Classification of membrane fouling</i>	14
1.4.2 <i>Main factors affecting membrane fouling</i>	15
1.4.2.1 Feed characteristics.....	16
1.4.2.2 Bulk characteristics.....	16
1.4.2.2.1 MLTS concentration	16
1.4.2.2.2 Viscosity	17
1.4.2.2.3 Extracellular polymeric substances (EPS)	17
1.4.2.2.4 Soluble microbial products (SMP).....	18
1.4.2.3 Operating conditions.....	18
1.4.2.3.1 Hydraulics and cleaning.....	18
1.4.2.3.2 Sludge retention time (SRT)	19
1.4.2.3.3 Air/gas sparging intensity	19
1.4.2.4 Membrane and module design	20
1.4.2.4.1 Membrane pore size.....	20
1.4.2.4.2 Membrane configuration.....	20
1.4.3 <i>Fouling control strategies</i>	20
1.4.3.1 Air/gas sparging intensity	22
1.4.3.2 Back-flushing.....	22
1.4.3.3 Sustainable operating flux	23
1.4.3.3.1 Critical Flux	23
1.5 FILTRATION PROCESS MODELLING IN MBR TECHNOLOGY	24
1.5.1 <i>State of the art of filtration modelling</i>	26
1.5.1.1 Resistances-in-series-based models	27
1.6 FILTRATION PROCESS CONTROL IN MBR TECHNOLOGY	29
1.6.1 <i>Control in wastewater treatment</i>	31
1.6.1.1 Control structure selection	32
1.6.1.1.1 Feedback control.....	33
1.6.1.1.2 Feedforward control.....	33

1.6.1.1.3	Combined feedback-feedforward control	33
1.6.1.2	Control algorithm design.....	34
1.6.1.2.1	On-off control.....	34
1.6.1.2.2	Proportional-integral-derivative (PID) control	34
1.6.1.2.3	Advanced control algorithms.....	36
1.6.2	<i>State of the art of filtration control</i>	41
1.7	SENSITIVITY ANALYSIS	43
1.7.1	<i>Sensitivity analysis strategies</i>	43
1.7.1.1	Global sensitivity analysis.....	44
1.7.1.1.1	The Morris screening method.....	45
1.8	SCOPE AND OUTLINE OF THIS THESIS.....	48
1.9	REFERENCES.....	49
2.	INSTRUMENTATION, CONTROL, AND AUTOMATION (ICA) FOR SUBMERGED ANAEROBIC MEMBRANE BIOREACTORS (SANMBRS)	59
2.1	INTRODUCTION	61
2.2	MATERIALS	62
2.2.1	<i>Demonstration plant description</i>	62
2.2.2	<i>Membrane performance</i>	63
2.3	PROPOSED ICA FOR SANMBR SYSTEMS	65
2.3.1	<i>Demonstration plant instrumentation</i>	65
2.3.1.1	pH sensors	66
2.3.1.2	ORP sensors	66
2.3.1.3	Total solids indicator transmitters	66
2.3.1.4	Biogas meter	67
2.3.1.5	Liquid flow indicator transmitters	67
2.3.1.6	TMP indicator transmitters.....	67
2.3.1.7	Gas flow indicator transmitters	68
2.3.1.8	Gas pressure indicator transmitters	68
2.3.1.9	Level indicator transmitters.....	69
2.3.2	<i>Demonstration plant automation</i>	69
2.3.3	<i>Demonstration plant control</i>	69
2.3.3.1	Lower layer controllers	70
2.3.3.1.1	Wastewater, sludge, and permeate flow control	71
2.3.3.1.2	Biogas flow and pressure control	72
2.3.3.1.3	SRT control	72
2.3.3.1.4	Temperature control	72
2.3.3.1.5	Safety layer control	73
2.3.3.2	Upper layer controllers.....	73
2.3.3.2.1	Organic loading rate control.....	73
2.4	RESULTS AND DISCUSSION.....	77

2.4.1	<i>Lower layer control performance</i>	77
2.4.1.1	Starting-up correcting action for the PID controllers	77
2.4.1.2	Mixed liquor level control	79
2.4.2	<i>OLR controller performance</i>	81
2.4.3	<i>Filtration system performance</i>	82
2.4.4	<i>Overall SAnMBR demonstration plant performance</i>	85
2.5	CONCLUSIONS	86
2.6	ACKNOWLEDGEMENTS	86
2.7	REFERENCES	86
3.	SUB-CRITICAL FILTRATION CONDITIONS OF COMMERCIAL HOLLOW-FIBRE MEMBRANES IN A SUBMERGED ANAEROBIC MBR (HF-SANMBR) SYSTEM: THE EFFECT OF GAS SPARGING INTENSITY	89
3.1	INTRODUCTION	91
3.2	MATERIALS AND METHODS	93
3.2.1	<i>Demonstration plant description</i>	93
3.2.2	<i>Demonstration plant monitoring</i>	94
3.2.3	<i>Demonstration plant operation</i>	95
3.2.4	<i>Demonstration plant monitoring</i>	95
3.2.4.1	Analytical monitoring	95
3.2.4.2	Modified flux-step method and membrane performance indices	96
3.3	RESULTS AND DISCUSSION	99
3.3.1	<i>Short-term trials: Effect of SGD_m on membrane performance</i>	99
3.3.2	<i>Short-term trials: Effect of SGD_m on J_{CW}</i>	101
3.3.3	<i>Short-term trials: Effect of SGD_m on residual TMP</i>	104
3.3.4	<i>Long-term trials: Assessment of sub-critical filtration conditions</i>	105
3.4	CONCLUSIONS	109
3.5	ACKNOWLEDGEMENTS	109
3.6	REFERENCES	109
4.	FACTORS THAT AFFECT THE PERMEABILITY OF COMMERCIAL HOLLOW-FIBRE MEMBRANES IN A SUBMERGED ANAEROBIC MBR (HF-SANMBR) SYSTEM	111
4.1	INTRODUCTION	113
4.1.1	<i>Anaerobic treatment of urban wastewater using MBR technology</i>	113
4.1.2	<i>Membrane fouling in SAnMBRs</i>	113
4.1.3	<i>Full-scale implementation of SAnMBRs</i>	114
4.2	MATERIALS AND METHODS	115
4.2.1	<i>Demonstration plant description</i>	115
4.2.2	<i>Operating conditions</i>	116

4.2.3	<i>Analytical methods</i>	118
4.2.3.1	Analytical monitoring	118
4.2.3.2	Membrane performance indices	118
4.3	RESULTS AND DISCUSSION.....	119
4.3.1	<i>Long-term performance</i>	119
4.3.2	<i>Short-term trials: main factors affecting membrane performance</i>	121
4.3.2.1	Effect of gas sparging intensity	121
4.3.2.1.1	Major role of gas sparging intensity when operating supra-critically.....	121
4.3.2.1.2	Gas sparging intensity as a key operating parameter for optimising SAnMBRs at the industrial scale	123
4.3.2.2	Effect of up-flow sludge velocity in the membrane tank.....	124
4.3.2.3	Effect of back-flush frequency	126
4.3.2.4	Effect of relaxation stage duration	127
4.3.2.5	Effect of filtration stage duration	129
4.3.2.6	Overall effect of MLTS and sustainable operating MLTS level	130
4.3.3	<i>Overall membrane operation compared to full-scale aerobic MBR plant</i>	131
4.3.3.1	Average operating values for transmembrane flux, membrane permeability and specific gas demand.	132
4.3.3.2	Physical and chemical cleaning requirements	133
4.4	CONCLUSIONS.....	134
4.5	ACKNOWLEDGEMENTS	135
4.6	REFERENCES.....	135

5.	SUB-CRITICAL LONG-TERM OPERATION OF INDUSTRIAL SCALE HOLLOW-FIBRE MEMBRANES IN A SUBMERGED ANAEROBIC MBR (HF-SANMBR) SYSTEM.....	139
5.1	INTRODUCTION	141
5.2	MATERIALS AND METHODS.....	143
5.2.1	<i>Demonstration plant description</i>	143
5.2.2	<i>Demonstration plant operation</i>	144
5.2.3	<i>Analytical methods</i>	144
5.2.3.1	Analytical monitoring	144
5.2.3.2	Membrane performance indices	145
5.3	RESULTS AND DISCUSSION.....	146
5.3.1	<i>Long-term SANMBR performance</i>	146
5.3.1.1	Evolution of the filtering resistance	146
5.3.1.2	Evolution of the fouling rate	148
5.3.2	<i>Sub-critical filtration conditions</i>	149
5.3.3	<i>Membrane operating mode</i>	151
5.3.4	<i>Chemical factors minimising the onset of irreversible fouling problems</i>	153
5.4	CONCLUSIONS.....	155
5.5	ACKNOWLEDGEMENTS	156
5.6	REFERENCES.....	156

6. PERFORMANCE OF INDUSTRIAL SCALE HOLLOW-FIBRE MEMBRANES IN A SUBMERGED ANAEROBIC MBR (HF-SANMBR) SYSTEM AT MESOPHILIC AND PSYCHROPHILIC CONDITIONS	159
6.1 INTRODUCTION	161
6.2 MATERIALS AND METHODS	162
6.2.1 <i>Demonstration plant description</i>	162
6.2.2 <i>Demonstration plant operation</i>	163
6.2.3 <i>Analytical methods</i>	164
6.2.3.1 Water quality analysis.....	164
6.2.3.2 Floc structure and particle size distribution	164
6.2.3.3 Microbiological analysis.....	165
6.2.3.4 EPS and SMP extraction and measurement	165
6.2.3.5 Membrane performance indices.....	165
6.3 RESULTS AND DISCUSSION	166
6.3.1 <i>Long-term membrane performance at mesophilic and psychrophilic conditions</i>	166
6.3.2 <i>Sludge properties affecting membrane performance at mesophilic and psychrophilic conditions</i> .168	168
6.3.2.1 Effect of MLTS on membrane performance	168
6.3.2.2 Effect of particle size distribution on membrane performance	169
6.3.2.3 Effect of biomass population, and EPS and SMP compounds on membrane performance	170
6.3.2.4 Other factors minimising the onset of irreversible fouling problems.....	173
6.3.3 <i>Overall biological process performance</i>	174
6.4 CONCLUSIONS	175
6.5 ACKNOWLEDGEMENTS.....	175
6.6 REFERENCES	175
7. A FILTRATION MODEL APPLIED TO SUBMERGED ANAEROBIC MBRS (SANMBRS)	179
7.1 INTRODUCTION	181
7.2 MATERIALS AND METHODS	183
7.2.1 <i>SAnMBR plant description</i>	183
7.2.2 <i>Monitoring system</i>	184
7.3 DESCRIPTION OF MODEL	184
7.3.1 <i>Conceptual modelling</i>	185
7.3.1.1 Resistance-in-series model	185
7.3.2 <i>Cake layer compression and sub-critical fouling</i>	187
7.3.3 <i>Modelling approach</i>	188
7.4 CALIBRATION OF MODEL.....	192
7.4.1 <i>Off-line calibration in the short-term</i>	192
7.4.2 <i>Dynamic calibration in the short-term</i>	194
7.4.3 <i>Parameter estimations using experimental data and long-term dynamic calibration</i>	196

7.4.4	<i>Default values</i>	197
7.5	VALIDATION OF MODEL	197
7.5.1	<i>Short-term validation</i>	197
7.5.2	<i>Long-term validation</i>	200
7.5.3	<i>Model applicability and future perspectives</i>	201
7.6	CONCLUSIONS.....	203
7.7	ACKNOWLEDGEMENTS	203
7.8	REFERENCES.....	203

8. MATHEMATICAL MODELLING OF FILTRATION IN SUBMERGED ANAEROBIC MBRs (SANMBRS): LONG-TERM VALIDATION207

8.1	INTRODUCTION	209
8.2	MATERIALS AND METHODS.....	210
8.2.1	<i>SAnMBR plant description</i>	210
8.2.2	<i>On-line and analytical monitoring</i>	210
8.2.3	<i>Model description</i>	211
8.2.3.1	Resistance-in-series model.....	211
8.2.3.2	Cake layer compression and sub-critical fouling.....	212
8.2.3.3	Black-box approach	212
8.2.4	<i>Long-term model validation</i>	213
8.3	RESULTS AND DISCUSSION.....	214
8.3.1	<i>Model validation using heavily-fouled membranes</i>	214
8.3.2	<i>Model validation using lightly-fouled membranes</i>	220
8.4	CONCLUSIONS.....	223
8.5	ACKNOWLEDGEMENTS	223
8.6	REFERENCES.....	224

9. SENSITIVITY ANALYSIS OF A FILTRATION MODEL FOR SUBMERGED ANAEROBIC MBRS (SANMBRS) USING A REVISED VERSION OF THE MORRIS SCREENING METHOD.....227

9.1	INTRODUCTION	229
9.2	MATERIALS AND METHODS.....	230
9.2.1	<i>SAnMBR plant description</i>	230
9.2.2	<i>Monitoring system</i>	230
9.2.3	<i>Model description</i>	231
9.2.4	<i>Simulation</i>	234
9.2.5	<i>Morris screening method</i>	234
9.2.6	<i>Dynamic calibration of the model being evaluated</i>	235
9.3	RESULTS AND DISCUSSION.....	236
9.3.1	<i>Sensitivity analysis results</i>	236

9.3.2	<i>Assessment of the modelling approach</i>	240
9.3.3	<i>Model calibration</i>	241
9.4	CONCLUSIONS.....	243
9.5	ACKNOWLEDGEMENTS.....	244
9.6	REFERENCES	244
10.	ADVANCED CONTROL SYSTEM FOR OPTIMAL FILTRATION IN SUBMERGED ANAEROBIC MBRS (SANMBRS).....	247
10.1	CHAPTER NOMENCLATURE	249
10.2	INTRODUCTION	252
10.3	MATERIALS AND METHODS	255
10.3.1	<i>SAnMBR plant description</i>	255
10.3.2	<i>Monitoring system description</i>	256
10.3.3	<i>Sampling and analytical monitoring</i>	257
10.3.4	<i>Operating conditions</i>	257
10.4	ADVANCED CONTROL SYSTEM DESCRIPTION.....	258
10.4.1	<i>Lower-layer controllers</i>	258
10.4.2	<i>Upper-layer controller</i>	260
10.4.2.1	Determining the control variables.....	261
10.4.2.2	Preliminary knowledge-based rules.....	263
10.4.2.3	Ventilation initiation.....	263
10.4.2.3.1	Back-flushing initiation.....	264
10.4.2.4	Fuzzy-logic controller.....	264
10.4.2.5	Description of fuzzy-logic controller structure	265
10.5	RESULTS AND DISCUSSION	267
10.5.1	<i>Performance of sludge recycling flow controller</i>	267
10.5.2	<i>Performance of knowledge-based rules</i>	268
10.5.2.1	Ventilation initiation.....	269
10.5.2.2	Back-flushing initiation	270
10.5.3	<i>Performance of fuzzy-logic controller</i>	272
10.5.4	<i>Overall performance of the advanced control system</i>	274
10.5.5	<i>Overall performance of the SAnMBR system</i>	277
10.6	CONCLUSIONS.....	278
10.7	ACKNOWLEDGEMENTS.....	278
10.8	REFERENCES	278
11.	MODEL-BASED AUTOMATIC TUNING OF A FILTRATION CONTROL SYSTEM FOR SUBMERGED ANAEROBIC MBRS (SANMBRS)	281
11.1	INTRODUCTION	283
11.2	MATERIALS AND METHODS	285

11.2.1	<i>SAnMBR plant description and monitoring</i>	285
11.2.2	<i>Advanced control system description</i>	285
11.2.2.1	Lower-layer controllers	286
11.2.2.2	Upper-layer control structure	286
11.2.2.2.1	Control variables.....	286
11.2.2.2.2	Preliminary knowledge-based rules	287
11.2.2.2.3	Fuzzy-logic controller description	288
11.2.3	<i>Model-based optimisation method</i>	288
11.2.3.1	Model description.....	290
11.2.3.2	Objective functions of the supervisory controller.....	290
11.2.3.3	Morris screening method.....	293
11.2.3.4	Monte Carlo method	295
11.2.3.5	Dynamic optimisation of the advanced control system.....	295
11.2.3.6	Simulation strategy.....	295
11.2.3.6.1	Morris screening method and Monte Carlo method.....	296
11.2.3.6.2	Model-based supervisory controller.....	297
11.3	RESULTS AND DISCUSSION	298
11.3.1	<i>Sensitivity analysis results</i>	298
11.3.2	<i>Monte Carlo method results</i>	303
11.3.3	<i>Performance of model-based supervisory controller</i>	304
11.3.3.1	Optimisation of fuzzy-logic controller	304
11.3.3.2	Optimisation of set points of advanced controller.....	305
11.3.4	<i>Overall performance</i>	307
11.4	CONCLUSIONS.....	309
11.5	ACKNOWLEDGEMENTS	310
11.6	REFERENCES	310

12. SUMMARY AND GENERAL DISCUSSION: IMPLICATIONS FOR FULL-SCALE IMPLEMENTATION AND RECOMMENDATIONS FOR FUTURE RESEARCH.....313

12.1	RESEARCH WORK MOTIVATION.....	315
12.2	INSTRUMENTATION, CONTROL, AND AUTOMATION (ICA) FOR SUBMERGED ANAEROBIC MBR (SANMBR).....	315
12.3	SUSTAINABLE MEMBRANE OPERATION	316
12.3.1	<i>Membrane scouring by gas sparging</i>	317
12.3.2	<i>Sludge recycling velocity through the membrane tank</i>	318
12.3.3	<i>Duration and frequency of the physical cleaning stages</i>	318
12.3.4	<i>The dilemma of operating sub-critically or supra-critically</i>	319
12.3.5	<i>Full-scale application of hollow-fibre membranes</i>	319
12.4	MINIMISING THE ONSET OF IRREVERSIBLE/IRRECOVERABLE FOULING.....	320
12.5	MODELLING FILTRATION PROCESS.....	321

12.6	OPTIMISING FILTRATION PROCESS.....	322
12.7	MOVING TOWARDS SUSTAINABLE URBAN WASTEWATER TREATMENT.....	323
12.8	REFERENCES	324
13.	GENERAL CONCLUSIONS	327