



Novel Thin Film Nanocomposite Membranes with Improved Properties for Enhanced Desalination Performance

Masoumeh Zargar

B.Sc. (Hons), M.Sc.

Thesis submitted for the degree of

Doctor of Philosophy

School of Chemical Engineering

Faculty of Engineering, Computer & Mathematical Sciences

The University of Adelaide, Australia

January 2016

Dedication

This thesis is deeply dedicated to:

*My lovely parents, Parvin and Naser, for their great supports
and continuous care*

*My amazing husband, Alireza, for his love, understanding,
encouragements and sacrifices*

Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

I give consent to this copy of my thesis when deposited in the University Library, being made available for loan and photocopying, subject to the provisions of the Copyright Act 1968.

The author acknowledges that copyright of published works contained within this thesis resides with the copyright holder(s) of those works.

I also give permission for the digital version of my thesis to be made available on the web, via the University's digital research repository, the Library Search and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

Masoumeh Zargar

Date: 01.10.2015

List of Publications

The doctoral thesis is prepared in “Publication” style according to the “specifications for Thesis (2015)” of the University of Adelaide. It includes publications that have been published, submitted for publication, or ready to be submitted:

- M. Zargar, B. Jin and S. Dai*, In Membrane Processing for Dairy Ingredient Separation, ed. J. D. Kang Hu, Wiley-Blackwell, 2015, Ch. Development and application of reverse osmosis for separation p. 139 (ISBN: 978-1-118-59017-1).
- M. Zargar, B. Jin* and S. Dai*, An integrated statistic and systematic approach to determine synthesis-performance correlation of thin film composite reverse osmosis membranes, submitted to Industrial & Engineering Chemistry Research (IE-2105-019756).
- M. Zargar, Y. Hartanto, B. Jin* and S. Dai*, Understanding functionalized nanoparticle incorporation in thin film composite membranes: interaction and desalination performance, submitted to Journal of Membrane Science (JMS-15-1287)
- M. Zargar, Y. Hartanto, B. Jin* and S. Dai*, Hollow mesoporous silica nanoparticles: a peculiar structure for thin film nanocomposite membranes, submitted to the ACS Applied Materials & Interfaces (am-2015-094259).
- M. Zargar, Y. Hartanto, B. Jin* and S. Dai*, Polyethylenimine modification of silica nanoparticles: a positive approach to develop sustainable thin film nanocomposite membranes, will be submitted.

Some relevant components of the work have been presented in conferences and symposiums:

- M. Zargar, B. Jin, S. Dai, Static protein adsorption on nanocomposite membranes: the contribution of nanofillers’ surface functionality, ICONN 2016 - International Conference on Nanoscience and Nanotechnology, 7-11 Feb 2016, Canberra, Australia.
- M. Zargar, Y. Hartanto, S. Dai, B. Jin, Thin film nanocomposite membranes:

which medium to choose for nanoparticle integration, 12th International Conference on Membrane Science and Technology (MST2015), 1-3 November 2015, Tehran, Iran.

- M. Zargar, S. Dai, B. Jin, Thin film composite reverse osmosis membranes hybridized with surface modified silica nanoparticles for enhanced desalination performance, 2nd International Conference on Desalination using Membrane Technology, 26-29th July 2015, Singapore.
- M. Zargar, S. Dai, B. Jin, An optimization strategy to investigate the structure-performance correlation of thin film composite reverse osmosis membranes, 2nd International Conference on Desalination using Membrane Technology, 26-29th July 2015, Singapore.
- M. Zargar, S. Dai, B. Jin, An optimization strategy to fabricate thin film composite reverse osmosis (TFC-RO) membranes, RACI SA Student polymer & Bionanotechnology Symposium (SASPBS14), 29th August 2014, Adelaide, South Australia.
- M. Zargar, S. Dai, B. Jin, Effect of solid and porous nanoparticles' incorporation at low concentration into the polymeric membranes' structure, RACI SA Student polymer & Bionanotechnology Symposium (SASPBS14), 29th August 2014, Adelaide, South Australia.
- M. Zargar, S. Dai, B. Jin, Fabrication and characterization of uniform mesoporous silica nanoparticles with the average particle size of 100 nm, The International Conference on Nanoscience and Nanotechnology (ICONN 2014), 2-6 February 2014, Adelaide Convention Centre, South Australia.
- M. Zargar, B. Jin, S. Dai. Fabrication and characterization of polyamide thin film composite membranes, RACI SA Student polymer & Bionanotechnology Symposium (SASPBS13), 4th October 2013, Adelaide, South Australia.

I have also co-authored the following publications during my PhD candidature:

- Y. Hartanto M. Zargar, H. Wang, B. Jin* and S. Dai*, Thermo-responsive acidic microgels as functional draw agents for forward osmosis desalination, submitted

to Environmental Science & Technology (es-2015-04123d).

- Y. Hartanto, M. Zargar, B. Jin*, S. Dai*, Cationic thermos-responsive microgels as functional draw agents for forward osmosis desalination, will be submitted.

Acknowledgments

One of the joys of completion is to look over the journey past and remember all the friends and family who have helped and supported me along this long but fulfilling road.

First of all, I would like to express my profound appreciation and thanks to my lovely supervisors, Associate Professor Bo Jin who has always supported me and behaved like a father to me when I faced the difficult situations in my PhD mission and life and Associate Professor Sheng Dai who has always supported me with his generosity, care and deep technical knowledge. They were tremendous mentors for me. Without their enthusiastic supervision, inspiration, guidance and endless supports, completion of this thesis would not have been possible. I would like to sincerely thank them for encouraging my research and for allowing me to grow as a researcher. I owe them my confidence in speech and my research skills. Words cannot express the deepness of my gratitude to them.

I would like to give special thanks to all my group members and lab mates for their helps and supports. Working with them was a real joy. Special thanks to Mr Yusak Hartanto for his research contributions and fruitful discussions.

My grateful thanks go to the School of Chemical Engineering staff and administration for their individual helps. Special thanks to the Chemical Engineering workshop team, Mr Jason Peak, Mr Jeffrey Hiorns and Mr Michael Jung who always were ready to assist without making me feel indebted. Their immense supports for the setups establishment and helps to solve the problems of the instruments are priceless. Also thanks to Dr Tian Yi Ma for his help with N₂ sorption characterization.

Special thanks to my fellow friends who supported me and incited me to strive towards my goal: Ms Kiana Kashefi, Dr Sona Taheri, Dr Hamideh Elekaei Behjati, Dr Moein Navvab Kashani, Mrs Bita Bayatsarmadi, Mrs Shervin Kabiri, Ms Mahdieh Nemati, Dr Hadi Madani, Dr Sara Azari, Mrs Hanaa Heqab, Dr Sanaz Orandi, Mrs Mailin Misson, Dr Amir Mellati and Dr Meisam Valizadeh Kiamahaleh.

I would also like to acknowledge the University of Adelaide for IPRS scholarship to support me for my PhD study.

Last but not list, special thanks to my family. Words cannot express how grateful I am to my mother, father, my mother-in law and father-in-law, for all of the sacrifices that they've made on my behalf. Their prayer for me was what sustained me thus far. At the end, I would like to express my deep appreciation to my husband 'Alireza', who has always been my best friend. His unconditional support, encouragement, quiet patience and unwavering love were undeniably the bedrock upon which the past nine years of my life have been built. Without his supports, I could not surely conduct this work.

Abstract

Nowadays, polymeric thin film composite (TFC) membranes have received increasing applications for separation and purification processes such as desalination and wastewater treatment. The development of nanotechnology has opened new frontiers in the advancement of TFC membranes. The incorporation of nanomaterials into the thin film polyamide (PA) layer of TFC membranes, making a structure known as thin film nanocomposite (TFN) membrane, can offer the advantages of both inorganic nanofillers and organic polymeric membranes. However, the possibility of nanoparticles' leakage and their low compatibility with organic membranes make the successful fabrication of TFN membranes challenging. Hence, investigating the structure-performance correlation of TFC/TFN membranes and their interactions with the incorporated nanomaterials is of great importance.

In my PhD project, a serial of TFC membranes incorporated with variously sized, structured and surface functionalized silica nanoparticles have been developed and extensively characterized with the aim to advance the knowledge of interfacial interactions between inorganic nanomaterials and the thin film PA layer of TFC membranes.

A statistical analysis was applied to study some key fabrication parameters of TFC membranes including PSF concentration in phase separation and aqueous phase soaking time and heat curing time in the interfacial polymerization course. Our findings highlighted the importance of considering interactions when devising a strategy to fabricate TFC membranes in order to optimize the overall desalination performance.

After the study of the TFC fabrication parameters, fabrication of TFN membranes was performed to get a better understanding on the interfacial interactions between nanoparticles and TFC membranes. SN with different sizes (50 nm and 100 nm) and surface functionalities (hydroxyl, amine or epoxy) were synthesized and successfully incorporated into TFC membranes. Desalination performance evaluation of the TFN membranes showed that no matter which functional group was present on SN, the

resulting TFN membranes had higher water flux and comparable or higher salt rejection compared with the TFC membrane without nanoparticles. In addition, nanoparticle surface functionalization using epoxy and amine moieties facilitated the chemical interaction between SN and the TFC membranes, resulting in TFN membranes with higher crosslinking density of their PA selective layer and improved performance stability.

After studying the solid SN, hydrophilic hollow mesoporous silica nanoparticles (HMSN) have been used to fabricate novel TFN membranes in order to study the contribution of this peculiar porous structure on the properties and desalination performance of the resulting TFN membranes. The HMSN with an average particle size of ~ 68 nm were synthesized and incorporated into TFC membranes. The performance evaluation results revealed that with 0.03 wt % HMSN incorporation, water flux could improve up to 40 percent without obvious alteration of the salt rejection. Moreover, the compaction resistance of the resulting membranes was enhanced after HMSN incorporation.

To enhance the compatibility of introduced SN with the PA layer, polyethyleneimine (PEI) modified SN (SN-PEI) were fabricated and incorporated into the TFC membranes. Introduction of SN-PEI to the TFC membranes could facilitate the formation of strong covalent bonds between SN-PEI and PA layer, improve the compatibility of SN with the organic PA and enhance the physicochemical properties of the resulting TFN membranes. The cross-flow filtration performance evaluation of the fabricated membranes showed improved water flux and salt rejection capability in addition to a higher compaction resistance for the developed TFN membranes.

This thesis project has attempted to advance fundamental knowledge of the nanocomposite formation and fundamental processes governing water transport through reactive nanostructure to guide the development of nanoparticle-enabled multifunctional membranes.

Table of Contents

Declaration	i
List of Publications	ii
Acknowledgments	v
Abstract	vii
Table of Contents	ix
List of Tables	xiii
List of Figures	xiv
1. Introduction.....	1
1.1. Background and project objectives	2
1.2. Thesis Outline	4
2. Literature Review.....	9
2.1. Introduction.....	10
2.2. Reverse Osmosis and its Working Mechanism.....	11
2.3. Reverse Osmosis Membranes	12
2.3.1. Inorganic reverse osmosis membranes.....	13
2.3.2. Polymeric reverse osmosis membranes.....	13
2.3.3. Thin film composite reverse osmosis membranes	15
2.4. Membrane Modules and Configurations.....	17
2.4.1. Spiral wound configuration.....	17
2.4.2. Hollow fiber, flat sheet and tubular configurations.....	18
2.5. Transport Mechanisms and Models in Reverse Osmosis Membranes.....	20
2.5.1. Diffusion-based models	20
2.5.2. Pore models.....	23
2.6. Reverse Osmosis Process.....	26
2.6.1. Overview of the process and performance evaluation in reverse osmosis membranes	26
2.6.2. Parameters affecting performance of reverse osmosis membranes.....	27
2.7. Technical and Economic Challenges	30
2.7.1. Concentration polarization	30
2.7.2. Fouling	31
2.7.3. Energy	34

2.8.	Reverse Osmosis Process in Dairy Industry	35
2.8.1.	Application of reverse osmosis membranes in dairy industry	35
2.8.2.	Factors affecting the performance of reverse osmosis membranes in dairy processing.....	38
2.8.3.	Concentration polarization and fouling of reverse osmosis membranes during milk concentration.....	39
2.9.	Current Development in Reverse Osmosis Membranes	41
2.9.1.	Thin film nanocomposite reverse osmosis membranes.....	41
2.9.2.	Membrane surface modification and process optimization.....	42
2.10.	Conclusions and Outlook.....	43
3.	An Integrated Statistic and Systematic Approach to Study the Structure-Performance Correlation of Thin Film Composite Reverse Osmosis Membranes for Desalination.....	52
3.1.	Abstract	53
3.2.	Introduction	54
3.3.	Materials and Methods	56
3.3.1.	Materials.....	56
3.3.2.	TFC-RO membrane fabrication	56
3.3.3.	Membrane Characterization	58
3.3.4.	Membrane performance evaluation.....	58
3.4.	Results and Discussion.....	59
3.4.1.	Design of experiments and statistical analysis.....	59
3.4.2.	Effect of PSF concentration and its significant interactions	67
3.4.3.	Effect of aqueous phase soaking time and its significant interactions	69
3.4.4.	Effect of heat curing time and its interactions.....	70
3.5.	Conclusions	71
3.6.	Supporting Information.....	75
4.	Understanding Functionalized Nanoparticle Incorporation in Thin Film Composite Membranes: Interactions and Desalination Performance.....	80
4.1.	Abstract	81
4.2.	Introduction	82
4.3.	Experimental	84
4.3.1.	Materials.....	84
4.3.2.	Synthesis and surface modification of silica nanoparticles.....	84
4.3.3.	Fabrication of TFC and SN-TFC membranes	85

4.3.4.	Characterization of nanoparticles, TFC and SN-TFC membranes.....	86
4.3.5.	Membrane performance evaluation.....	88
4.4.	Results and Discussion.....	89
4.4.1.	Characterization of fabricated nanoparticles.....	89
4.4.2.	Characterization of TFC and SN-TFC membranes.....	90
4.4.3.	Performance evaluation of TFC and SN-TFC membranes.....	96
4.5.	Conclusions.....	100
4.6.	Supporting Information.....	106
5.	Hollow Mesoporous Silica Nanoparticles: a Peculiar Structure for Thin Film Nanocomposite Membranes.....	115
5.1.	Abstract.....	116
5.2.	Introduction.....	117
5.3.	Experimental.....	118
5.3.1.	Materials.....	118
5.3.2.	Fabrication of HMSN.....	119
5.3.3.	Fabrication of TFC and TFN membranes.....	119
5.3.4.	Characterization of nanoparticles, TFC and TFN membranes.....	120
5.3.5.	Membrane performance evaluation.....	122
5.4.	Results and Discussion.....	122
5.4.1.	Synthesis and characterization of HMSN.....	122
5.4.2.	Characterization of TFN membranes.....	127
5.4.3.	Desalination performance of TFN membranes.....	129
5.5.	Conclusions.....	132
5.6.	Supporting Information.....	138
6.	Polyethyleneimine Modification of Silica Nanoparticles: a Positive Approach to Develop Sustainable Thin Film Nanocomposite Membranes.....	142
6.1.	Abstract.....	143
6.2.	Introduction.....	144
6.3.	Experimental.....	146
6.3.1.	Materials.....	146
6.3.2.	Fabrication of PEI modified silica nanoparticles (SN-PEI).....	146
6.3.3.	Fabrication of TFC/TFN membranes.....	147
6.3.4.	Characterization.....	148

6.3.5.	Membrane performance evaluation.....	149
6.4.	Results and Discussion.....	150
6.4.1.	Synthesis and characterization of the surface modified nanoparticles	150
6.4.2.	Characterization of TFC and TFN membranes	153
6.4.3.	Performance evaluation of TFC and TFN membranes	157
6.5.	Conclusions	159
6.6.	Supporting Information.....	164
7.	Conclusions.....	166
7.1.	Conclusions	167
7.2.	Recommendations	169

List of Tables

Table 2-1 Commercially available RO membranes and modules (Chian et al. 2007). Reproduced with permission of Humana Press.....	19
Table 3-1 (a) TFC-RO membrane fabrication parameters, codes and actual levels as used in the full factorial design, (b) experimental design matrix, response values and factor levels for each run in the factorial design.	62
Table 3-2 Analysis of variance of the 2FI regression model for water flux and salt rejection.	62
Table 3-3 (a) Analysis of variance of the reduced 2FI regression model for water flux and salt rejection (b) Statistics used to investigate the goodness of fit for the reduced water flux and salt rejection models.....	64
Table 4-1 XPS results for SN50 with different surface functionalities.	90
Table 4-2 XPS results for TFC membrane and TFN membranes incorporated with different surface functionalized SN50.	95
Tab 5-1 XPS results for HMSN, TFC and 0.05 wt % HMSN incorporated TFN membrane.	127
Table 6-1 Hydrodynamic sizes and zeta potentials of SN, SN-NH ₂ and SN-PEI.	151
Table 6-2 XPS analysis for SN, SN-NH ₂ and SN-PEI.	153
Table 6-3 XPS analysis for SN-PEI, TFC and the TFN membrane with 0.05 wt % SN-PEI.	157

List of Figures

Figure 2-1 Schematic view of normal osmosis and reverse osmosis processes.....	12
Figure 2-2 The classification of polymeric membranes (Ren & Wang, 2011). Reproduced with permission of Springer.....	14
Figure 2-3 Schematic of the TFC-RO membranes and the chemical structure of the aromatic polyamide.....	16
Figure 2-4 Schematic diagram of a Spiral wound RO Module (Ettouney & Wilf 2009). Reproduced with permission of Springer.....	18
Figure 2-5 The schematic diagram of hollow fibre membrane (Chen et al., 2011). Reproduced with permission of Springer.....	19
Figure 2-6 The schematic diagram of membranes for solution diffusion mechanism.	21
Figure 2-7 Schematic view of the membrane pore for pore flow models.....	24
Figure 2-8 The schematic view of RO process.	26
Figure 2-9 The schematic view of concentration polarization profile in a cross flow membrane system.....	31
Figure 2-10 Conceptual illustrations of antifouling mechanisms: (a) steric repulsion; (b) formation of a water layer; (c) electrostatic repulsion (Kang &Cao, 2012). Reproduced with permission of Elsevier.....	33
Figure 3-1 Schematic illustration of the two-stage casting strategy to fabricate TFC-RO membranes (a) phase inversion process to fabricate PSF supporting interlayer; (b) Interfacial polymerization to synthesize the polyamide selective barrier layer including schematic of the final TFC-RO membranes.....	58
Figure 3-2 Pareto charts for the effect of various parameters on (a) water flux; (b) salt rejection (A: PSF concentration, B: MPD soaking time, and C: heat curing time).	63
Figure 3-3 Actual vs. predicted values of the responses by the regression models: (a) water flux; (b) salt rejection.	66
Figure 3-4 Response surface plots of water flux and salt rejection as a function of: (a, b) PSF concentration (A) and MPD soaking time (B) at a fixed heat curing time of 15 min; (c, d) MPD soaking time (B) and heat curing time (C) at a fixed MPD soaking time of 6 min.....	66
Figure 3-5 SEM micrographs displaying the cross-section (left) and bottom (right) of PSF support layers cast using different concentrations of PSF: (a,b) 9 %; (c,d) 12 %; (e,f) 15 %	68
Figure 4-1 micrographs and TEM images (inset) of the different sized SN, A) SN50, B) SN100, C) SN50-NH ₂ , D) SN100-NH ₂ , E) SN50-EPX and F) SN100-EPX. Particle size and morphology are similar as the SN before modification.	89
Figure 4-2 A) TGA thermograms for SN50 before and after surface functionalization, B) FTIR spectra for PES support, TFC membrane and a typical SN-TFC membrane.	91
Figure 4-3 SEM micrographs of the surfaces and cross-section of different TFC/SN-TFC membranes: A) TFC, B) SN50-TFC, C) SN50-NH ₂ -TFC, D) SN50-EPX-TFC, E) SN100-TFC, F) SN100-NH ₂ -TFC, G) SN100-EPX-TFC. For the surface images, the low magnification images were taken at 55000x and the high magnification images were taken at 200000x and for the cross-section images, the low magnification images were at 2000x and the high magnification ones were at 25000x.....	92

Figure 4-4 Cross-section TEM images of the A) TFC, B) SN50-TFC, C) SN50-NH ₂ -TFC and SN50-EPX-TFC membranes; the scale bars are 100 nm.	94
Figure 4-5 A) Comparison on the streaming potential measurements for the TFC membranes with and without SN50-NH ₂ , B) Contact angles for the TFC membranes incorporated with different concentrations of SN50 and 0.05 wt% SN-NH ₂ and SN-EPX, C) Performance evaluation for various TFC membranes incorporated with different concentrations of SN50.	97
Figure 4-6 A) Desalination performance evaluation for the TFC membranes incorporated with various SN with different surface functionalities, B) Normalized salt rejection for the fabricated SN-TFC membranes vs. filtration time.	100
Figure 5-1 The schematic illustration of the HMSN fabrication strategy. The CTAB and PtBA templates can be removed simultaneously through ion exchange and dissolution. ...	123
Figure 5-2 A) FTIR spectra for the CTAB and PtAB templates, HMSN-b and HMSN B) TGA thermograms for CTAB and PtBA templates, HMSN-b and HMSN.	125
Figure 5-3 High and low magnification A) TEM and B) SEM images of the HMSN. The hollow mesoporous structure of HMSN can be clearly seen from the high resolution TEM image. Scale bars for the TEM images are 100 nm and 50 nm (inset) and for the SEM images are 1 μ m and 200 nm (inset).	125
Figure 5-4 Nitrogen adsorption/ desorption isotherms for the fabricated HMSN; the inset is the pore size distribution obtained from the BJH method.	126
Figure 5-5 Low and high magnification SEM surface (top) and cross-section (bottom) images of the synthesized TFC membrane and TFN membranes incorporated with different concentrations of HMSN: A) TFC, B) TFN, 0.01 wt %, C) TFN, 0.03 wt %, D) TFN, 0.05 wt % and E) TFN, 0.1 wt %. For the surface images, the magnifications are 25000x and 120000x, and for the cross-section images, the magnifications are 2000x and 50000x.	127
Figure 5-6 Images taken from a typical TFN membrane incorporated with 0.05 wt % HMSN A) tilted surface images from cross-section SEM sample, and B) cross-section TEM images. For the SEM images, the scale bars are 4 μ m and 500 nm, and for the TEM images the scale bars are 200 nm and 50 nm.	128
Figure 5-7 Comparison on the contact angles of various fabricated TFC/TFN membranes as a function of HMSN loading. Contact angle of the TFN membrane incorporated with 0.05 % HMSN-b is also included for comparison. The reported contact angles are the average of at least 8 different positions on each membrane.	129
Figure 5-8 The performance evaluations of the fabricated TFC/TFN membranes in terms of water flux and salt rejection as a function of HMSN loading. The performance of the TFN membrane with 0.05 wt % HMSN-b is also shown for comparison.	130
Figure 5-9 The water flux of the fabricated TFC and TFN membranes versus compaction time against DI water at 1.5 MPa and 25 \pm 0.1 $^{\circ}$ C.	132
Figure 6-1 The schematic description of the general strategy to fabricate SN-PEI.	150
Figure 6-2 TGA thermograms for: a) SN, b) SN-NH ₂ , and c) SN-PEI.	152
Figure 6-3 SEM images, TEM images (inset), and EDX spectra for A) SN, and B) SN-PEI. The scale bars are 200 nm for TEM images and 5 μ m for SEM images.	152
Figure 6-4 High and low magnification SEM surface images of the fabricated membranes: A) control TFC, B) TFN incorporated with 0.03 wt % SN-PEI C) TFN incorporated with 0.05 wt % SN-PEI, and D) TFN incorporated with 0.1 wt % SN-PEI.	154

Figure 6-5 A) SEM cross-section image, B) surface SEM image obtained from the tilted cross-section SEM sample, and C) EDX spectra obtained through EDX mapping for the control TFC membrane; and D) SEM cross-section image, E) surface SEM image obtained from the tilted cross-section SEM sample, and F) EDX spectra obtained through EDX mapping for the TFN membrane incorporated with 0.1 wt % SN-PEI.	155
Figure 6-6 The comparison of the contact angles of various fabricated TFC and TFN membranes.	156
Figure 6-7 Performance evaluation for the fabricated TFC/TFN membranes in terms of water flux and salt rejection as a function of SN-PEI loading.	157
Figure 6-8 The water flux of the fabricated TFC and TFN membranes versus compaction time at 1.5 MPa and 25±0.1 °C.	158