A PILOT-SCALE FERTILISER DRAWN FORWARD OSMOSIS AND NANOFILTRATION HYBRID SYSTEM FOR DESALINATION

by

Jung Eun Kim

A Thesis submitted in fulfilment for the degree of

MASTER of ENGINEERING

School of Civil and Environmental Engineering
Faculty of Engineering and Information Technology
University of Technology, Sydney (UTS),
New South Wales, Australia

July 2013

CERTIFICATE OF AUTHORSHIP/ORIGINALITY

I certify that this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledge within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of candidate

ACKNOWLEDGEMENTS

I would like to express my gratitude to everyone for their hard work. I owe my supervisor Dr. Ho kyong Shon and Sherub Phuntsho who have supported and helped me an immeasurable debt of gratitude. And I wish to express my deepest appreciation to my research colleagues, Tahir Majeed, Soleyman Mamisaheby, Laura Chekli and Fezeh Lotfi.

I would like to extend my appreciation to all my family members and friends, especially my parents; they always believe and support me. And my younger sister, Amy, when she stayed with me in Australia, she always encourages me and cheers me up. I also would never imagine my life in UTS without my friends; Olivia, Irene, and Heather.

Writing this master thesis and organizing the data from all the experiments were a big challenge to me. However, my supervisor Dr. Ho Kyong Shon and Sherub Phunsto gave me the constant guidance and encouragement throughout the entire course of the Mater degree; as a result, I completed my master thesis very successfully.

Journal articles

1. Sherub Phuntsho, Soleyman Mamisahebi, Tahir Majeed, Fezeh Lotfi, **Jung Eun Kim**, Ho Kyong Shon. 'Assessing the major factors affecting the performances of forward osmosis and its implications on the desalination process' *Chemical Engineering Journal*, 2013 Accepted.

   http://www.sciencedirect.com/science/article/pii/S1385894713009650

2. **Jung Eun Kim**, Sherub Phuntsho, Fezeh Lotfi, Ho Kyong Shon. 'Investigation of pilot-scale 8040 FO membrane module at different operating conditions for brackish water desalination in a real field' *Desalination and Water Treatment*, 2013, Submitted.

3. Sherub Phuntsho, **Jung Eun Kim**, Fezeh Lotfi, and Ho Kyong Shon. 'Mono/di-ammonium phosphate fertilisers as draw solutions for forward osmosis desalination' *International Desalination Association on Desalination & Water Reuse*, 2013, Accepted.

4. **Jung Eun Kim**, Sherub Phuntsho, Ho Kyong Shon. 'Pilot-scale nanofiltration system as post-treatment for fertiliser-drawn forward osmosis desalination for direct fertigation' *Desalination and Water Treatment ahead-of-print* (2013), 1-9.

   http://www.tandfonline.com/doi/abs/10.1080/19443994.2013.780804

5. Tahir Majeed, Fezeh Lotfi, Soleyman Sahebi, Sherub Phuntsho, **Jung Eun Kim**, and Ho Kyong Shon. 'Fertilizer Drawn Forward Osmosis (FDFO) Desalination for Fertigation: Application to Tomato' *Desalination and Water Treatment*, 2013 Submitted.

Conference papers

1. Soleyman Mamisahebi, Ho Kyong Shon, Sherub Phuntsho, Fezeh Lotfi, **Jung Eun Kim**. Factors affecting performances of forward osmosis desalination process. Procedia Engineering, Volume 44, 2012, Pages 1449-1451

Book chapters

1. Sherub Phuntsho, **Jung Eun Kim**, Ho Kyong Shon. Fertiliser drawn forward osmosis desalination for direct fertigation. Chapter 18, 455-510. In “Forward Osmosis: Fundamentals and Applications” edited by Ho Kyong Shon, Sherub Phuntsho, T.C. Zhang, R.Y. Surampalli. The American Society of Civil Engineers (ASCE).
2. Laura Chekli, Sherub Phuntsho, **Jung Eun Kim**, Ho Kyong Shon. Draw solutions for forward osmosis. Chapter 6, 322-383. In “Forward Osmosis: Fundamentals and Applications” edited by Ho Kyong Shon, Sherub Phuntsho, T.C. Zhang, R.Y. Surampalli. The American Society of Civil Engineers (ASCE).

Awards

1. **Jung Eun Kim**, Sherub Phuntsho, Ho Kyong Shon. Pilot-scale nanofiltration system as post-treatment for fertiliser-drawn forward osmosis desalination for direct fertigation. Presentation at International Desalination and workshop (IDW), Jeju, Korea, 28-31 October 2012. Awarded best oral presentation award.
2. **Jung Eun Kim**. Pilot-scale low-energy forward osmosis process for brackish water desalination. Presentation at Faculty of Engineering & IT Showcase, 2013. Awarded best oral presentation award (The best innovation prize).
3. **Jung Eun Kim**. Pilot-scale low-energy forward osmosis process for brackish water desalination. Presentation at Faculty of Engineering & IT Showcase, 2013. Awarded best poster presentation award.

LIST OF ABBREVIATIONS

FO	Forward osmosis
FDFO	Fertiliser drawn forward osmosis
DS	Draw solution
FS	Feed solution
BGW	Brackish groundwater
MDB	Murray-Darling Basin
RSF	Reverse salt flux
RO	Reverse osmosis
SWRO	Seawater reverse osmosis
SWFO	Spiral wound forward osmosis
CP	Concentration polarisation
ICP	Internal concentration polarisation
ECP	External concentration polarisation
CTA	Cellulose triacetate
TFC	Thin film composite
PWP	Pure water permeability
DI	Deionized water
MW	Molecular weight
HTI	Hydration Technology Innovations
MF	Microfltration
NF	Nanofiltration
UF	Ultrafiltration
TDS	Total dissolved solids
SOA	Ammonium sulphate or $(NH_4)_2SO_4$

LIST OF SYMBOLS

A	Pure water permeability coefficient	$Lm^{-2}h^{-1}bar^{-1}$
B	Salt permeability coefficient	ms^{-1}
C	Solute molar concentration	Mg/L or M
D	Diffusion coefficient of solute	m^2s^{-1}
D_h	Hydraulic diameter	m
J_w	Water flux	$Lm^{-2}h^{-1}$ or LMH
J_s	Solute flux	moles $m^{-2} h^{-1}$
K	Solute resistivity	s/m
k	Mass transfer coefficient	m/s
M_w	Molecular weight	mol/g
Re	Reynolds number	
R	Salt rejection	%
S_c	Schmidt number	
Sh	Sherwood number	
π	Osmotic pressure	
σ	Reflection coefficient	
t	Thickness of membrane	m
τ	Tortuosity of membrane	
ε	Porosity of membrane	
$P_{i,pump}$	Pump input power	kWh
E_s	Specific energy consumption	kWh/m^3

Subscript

b	Bulk
d	Draw solution
f	Feed solution
i	Cation/Anion
m	Membrane wall

TABLE OF CONTENTS

CHAPTER 6

EVALUATION OF ENERGY CONSUMPTION OF FDFO-NF DESALINATION PROCESS

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

LIST OF FIGURES

LIST OF TABLES

SUMMARY

The usage of fresh water for both non-potable and potable purposes will increase with the surging growth in water demand. Rapid increases in population contribute to the significant consumption of fresh water resources and massive increase in food demand. Water consumption in the agricultural sector is more than 70% of the total water usage worldwide. Water scarcity is one of the greatest issues confronting people everywhere and almost one-fifth of the world's population lives in areas of physical water scarcity. Sustainable fresh water resources have to be created and developed to solve this water problem; however, 97.5% of the earth's water is seawater. Nevertheless, it is an abundant and unlimited source of saline water, and the desalination of seawater or brackish groundwater for both non-potable and potable water supply is therefore increasingly being considered as one of the solutions to water scarcity. A drawback is that the significant energy consumption of current desalination technologies mostly contributes to the cost of desalination. Cost-effective desalination technology for non-potable water, particularly for irrigation use, would contribute to a significant reduction in freshwater consumption and would make more freshwater available for other potable uses.

One of the most promising technologies is the forward osmosis (FO) process in which the driving force is generated by the concentration gradient, unlike the reverse osmosis (RO) process where the driving force is hydraulic pressure, which leads to significant energy consumption. In the FO process, freshwater is extracted from saline water and flows to a concentrated draw solution (DS) using a special FO membrane. However, the FO process still has issues such as the lack of a suitable DS and FO membrane, resulting in it is having limited application for drinking water supply purposes. In addition, an additional process to separate DS solutes and pure water is required which could lead to increased energy consumption.

Considering the challenges of the FO process for potable water, a novel concept of fertiliser drawn forward osmosis (FDFO) has recently been introduced. In this process, a highly concentrated fertiliser solution is used as the DS to extract water from saline water sources

using a semi-permeable membrane by natural osmosis. The main concept and advantages of the FDFO desalination process is that the final product water, the diluted fertiliser DS, can be used for direct fertigation and thus the separation of draw solutes is not necessary. The FDFO process requires significantly less energy because there is almost zero hydraulic pressure. However, because of a number of intrinsic process limitations with FO, the diluted fertiliser DS does not usually meet the water quality standards for direct fertigation especially when a high salt concentration of feed water is used. The final diluted DS may require dilution to several orders of magnitude before it is suitable for direct application. To reduce the concentration of the diluted DS, the nanofiltration (NF) process has been suggested as a post-treatment process to reduce fertiliser nutrient concentrations in the diluted fertiliser DS. The concept of the integrated FDFO desalination process with NF membrane has been suggested and evaluated in bench-scale experiments in earlier studies; consequently, a large-scale FDFO-NF desalination process has been fabricated and tested in this study on a pilot-scale level.

The pilot-scale unit consists of three main components: microfiltration (MF) pre-treatment for FDFO desalination and NF for post reduction of nutrient concentrations. The main objective of this study is the process optimisation of the FDFO-NF unit. Specific objectives include investigating the influence of operating conditions such as cross flow rates, DS concentration, feed salinity and type of spacer on the performance of the pilot-scale unit.

Two types of 8040 FO membrane modules (the corrugated spacer (CS) module and the medium spacer (MS) module) were used for the FDFO process. Ammonium sulphate (SOA) was used as the fertiliser DS, while the feed water was prepared using salts obtained from brackish groundwater in the Murray-Darling Basin. The water flux increased at higher feed flow rates caused by the increase in mass transfer coefficient across the membrane surface. In addition, the effect of feed total dissolved solids (TDS) played an important role in the flux performance in both FO modules. Furthermore, it was observed that the 8040 FO CS module (corrugated spacer) performed better than the 8040 FO MS (medium spacer) in all experiments. It is likely that this is because the corrugated spacer provides better hydrodynamic conditions within the channel for feed thereby reducing the dilutive and concentrative external concentration polarisation and ultimately enhancing the water flux. The other possibility is that the larger DS volume within the spacer, which can maintain a higher level of DS concentration, leading to a higher average water flux of modules but a lower dilution effect, was observed in the CS module. In this study, it has been indicated that the role of the spacer's design and thickness on the spiral wound module performance is important. Fertiliser nutrient concentrations from the NF process in the final product can be significantly influenced by both the concentration and the components of the diluted DS produced by both FO modules. Investigation of FO module performance shows the significance of the optimisation of various operating parameters and the modular design of the membrane in the overall performance of the FO process.

The performance of the pilot-scale NF (4040 module) process has been assessed in terms of water flux and salt rejection. A pilot-scale NF process was applied as a post-treatment for the diluted fertiliser DS produced by the FDFO desalination to reduce the concentration of fertiliser nutrient. The NF process was conducted under different operating parameters; feed flow rate and concentration and applied pressures. Nanofiltration was effective in reducing nitrogen (N) concentration in the diluted draw solution. Although other factors such as the applied pressure and cross flow rate played a role in the performance of the pilot-scale NF process, the influence of the feed concentration was more significant on the specific water flux and the nutrient rejection.

The energy requirements of the FDFO-NF desalination process were initially investigated using the operating values. In this study, the total energy consumption of the process refers to the electrical energy usage of the pumps thus the pump power efficiency has been converted to the specific energy consumption (SEC). The SEC of the pilot-scale system was dependent on the operation of the FDFO desalination process because the lower diluted fertiliser refers to lower energy consumption in the NF process. The most attractive advantage of the FO process is that it leads to lower energy consumption than current desalination processes due to the natural osmosis in the FO process. Therefore, in this study, it was proved that the specific energy consumption of our FDFO-NF hybrid system for brackish water desalination was around 47% less than the NF-SWRO hybrid system for desalination.