DESIGN AND OPTIMIZATION OF A FULL SCALE FORWARD OSMOSIS SYSTEM

by Syed Muztuza Ali

Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

under the supervision of Prof. Ho Kyong Shon and Dr. Sherub Phuntsho

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I, ***Syed Muztuza Ali*** declare that this thesis, is submitted in fulfilment of the requirements for the award of ***Doctor of Philosophy***, in the ***School of Civil and Environmental Engineering/Faculty of Engineering and IT*** at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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(Syed Muztuza Ali)

Date: 10/08/2020

This thesis is dedicated to the memory of my brother

Syed Mortuza Ali

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Journal Articles Published or Submitted**

1. **<u>Ali, S.M.,</u>** Kim, J. U., Phuntsho, S., Jang, A., Choi, J. Y., Shon, H.K. 2018, 'Forward osmosis system analysis for optimum design and operating conditions', Water Research, vol. 145, pp. 429-441. **(Chapter 4)**
2. **<u>Ali, S.M.,</u>** Qamar, A., Kerdi, S., Phuntsho, S., Vrouwenvelder, J. S., Ghaffour, N., Shon, H.K., 2019, 'Energy efficient 3D printed column type feed spacer for membrane filtration', Water Research, vol. 164, pp. 114961.
3. **<u>Ali, S.M.,</u>** Qamar, A., Kerdi, S., Phuntsho, Ghaffour, N., S., Vrouwenvelder, J. S., Shon, H.K., 2020, 'Conceptual design of a dynamic turbospacer for efficient low pressure membrane filtration', Desalination, vol. 496, pp. 114712.
4. **<u>Ali, S.M.,</u>** Kim, J. U., Phuntsho, S., Jang, A., Choi, J. Y., Shon, H.K. 2018, 'Forward osmosis system design and optimization using a hollow fibre membrane module for energy efficient desalination', under review in Desalination.
5. Kim, J. U., Phuntsho, S., **Ali, S.M.,** Choi, J. Y., Shon, H.K., 2018, 'Forward osmosis membrane modular configurations for osmotic dilution of seawater by forward osmosis and reverse osmosis hybrid system', Water Research, vol. 128, pp. 183-192.
6. Akther, N., **<u>Ali, S.M.,</u>** Phuntsho, S., Shon, H.K. 2020, 'Surface modification of thin-film composite forward osmosis membranes with polyvinyl alcohol–graphene oxide composite hydrogels for antifouling properties', Desalination, vol. 491, pp. p. 114591.
7. Qamar, A., Kerdi, S., **<u>Ali, S.M.,</u>** Shon, H.K., Vrouwenvelder, J. S., Ghaffour, N., 2020, 'Novel hole-pillar spacer design for improved hydrodynamics and

biofouling mitigation in membrane filtration', Under review in Scientific report - Nature.

Conference papers and presentation

1. **Ali, S.M.,** Kim, J. U., Phuntsho, S., Shon, H.K., 'Development of a user friendly software for full scale FO plant design and operation', 8th IWA Membrane Technology Conference & Exhibition on Water and Wastewater Treatment and Reuse (IWA-MTC 2017), 5-9 September, 2017, Singapore.
2. **Ali, S.M.,** Kim, J. U., Phuntsho, S., Shon, H.K., 'Forward Osmosis System Analysis for Optimum Design and Operating Conditions', The 6th IWA Regional Membrane Technology Conference (IWA-RMTC 2018), 10-12, December, 2018, Gujarat, India.
3. **Ali, S.M.,** Kim, J. U., Phuntsho, S., Shon, H.K., 'Development of an optimization algorithm for full scale forward osmosis plant design', Membrane Science & Technology (MST2019) Conference, 13-14 June 2019, Singapore.
4. **Ali, S.M.,** Im, S.J., Phuntsho, S., Jang, A., Choi, J.Y., Shon, H.K., 'Numerical Optimization of Full Scale Forward Osmosis System Using Hollow Fibre Membrane Module', 4th International Conference on Desalination using Membrane Technology, 1-4 December, 2019, Perth, Australia.
5. **Ali, S.M.,** Im, S.J., Phuntsho, S., Jang, A., Choi, J.Y., Shon, H.K., 'Development of system analysis software for optimum design configurations of the forward osmosis process', 3rd International Forward Osmosis Summit, 6 – 8 November, 2019, Korea.

Presentations made during the PhD candidature including proceedings, oral and poster presentations.

LIST OF ABBREVIATIONS

AL-DS	Active layer facing draw solution
AL-FS	Active layer facing feed solution
CTA	Cellulose triacetate
DI	Deionised
DS	Draw solution
ECP	External concentration polarization
FS	Feed solution
FDC	Final draw solution concention
ICP	Internal concentration polarization
LMH	Litres per square meter per hour
MBR	Membrane bioreactor
MF	Microfiltration
NF	Nanofiltration
PAO	Pressure Assisted Osmosis
PRO	Pressure retarded osmosis
RO	Reverse osmosis
RR	Recovery rate
RSF	Reverse salt flux
SWRO	Seawater reverse osmosis
TDS	Total dissolved solids
TFC	Thin-film composite
UF	Ultrafiltration

NOMENCLATURE

Symbol	Meaning	Unit
A	Water permeability coefficient	$Lm^{-2}hr^{-1}bar^{-1}$
B	Solute permeability coefficient	$Lm^{-2}hr^{-1}$
C	Concentration	M
f	Flexibility	%
J	Flux	LMH ($Lm^{-2}h^{-1}$)
k	Mass transfer coefficient	m/s
K	Diffusivity coefficient	m^2/s
N	Number	---
Q	Volumetric flowrate	m^3/s
R	Ideal gas constant	kJ/kg-K
S	Structural parameter	µm
U	Velocity	m/s
π	Osmotic pressure	bar
ε	Voidage	----
l	Discrete length	m
w	Discrete width	m
RF	Recovery fraction	---
CF	Concentration fraction	---
OPR	Overall performance rating	---
Fl	Flexibility	----

Subscripts	meaning	**Superscripts**	meaning
w	Water	m	Membrane surface
S or slt	Solute	b	Bulk
sp	Spacer	out	Outlet parameters
D	Draw Solution	in	Inlet parameters
F	Feed Solution	F	Final

Abstract

Forward osmosis (FO) process is a promising water filtration technology due to its low energy consumption and less fouling propensity. Performance of a full scale FO system is however significantly influenced by its operating conditions. Moreover, these operating parameters have both favorable and adverse effects on their performance. Therefore, it is very important to optimize its performance for efficient and economic operations. Although numerous studies optimized the lab scale FO system, theoretical optimization of the full scale FO system using commercially available membrane modules was rarely performed. Therefore, this thesis aims to design and optimize a full-scale FO system using different types of commercial membrane modules.

A comprehensive theoretical framework for mass transport through the membrane was developed by coupling the solution diffusion models with the fluid mass and momentum balance equations. The finite difference method was employed to apply the mass transport models at small discretized areas on the membrane surface to estimate the performance of the FO system using a commercial TFC (thin film composite) spiral wound FO module. Fluid flow paths inside the membrane module were simplified to analyze the module scale performance as the full scale analysis considering actual geometry of the flow channel employing computational fluid dynamic simulation technique is very time consuming and computationally expensive process. Analysis results were compared with the experimental results to validate the models. About 5% deviation of simulation results and the experimental findings show a very good agreement between them. A novel optimization algorithm was then developed to estimate the minimum required draw solution (DS) inlet flowrate and the number of elements in a pressure vessel to attain the

design objectives (i.e., the desired final DS concentration and recovery rate at a specific feed solution (FS) flowrate). A detailed parametric study was also conducted to determine the optimum operating conditions for different objectives. It showed that for a specific design objective, a higher recovery rate can be achieved by increasing the DS flowrate and the number of elements in a pressure vessel. In contrast, a lower final concentration can be obtained by lowering the DS flowrate and increasing the number of elements.

Owing to the higher packing density of hollow fiber membrane modules compared to the flat sheet membrane module, this study aimed to design and optimize a full scale FO plant using a hollow fiber module. Mathematical models were developed to simulate the mass transport through the membrane considering the actual geometry of the hollow fiber membrane. Module scale performances were then computed by employing the mass transport models with the fluid conservation laws. Pilot scale experiments were also conducted employing a commercial CTA (cellulose triacetate) hollow fiber FO module to validate the theoretical models. Less than 10% difference between the simulation and experimental results was observed which validated the reliability of the developed simulation models. These mathematical models were then applied to simulate and design a 1,000 m^3/day FO plant using 0.6 M NaCl as draw solution or DS (~seawater) and 0.02 M NaCl feed solution (~MBR effluent) to produce 0.25 M, 0.2 M and 0.15 M NaCl diluted seawater DS. For the full scale design, a single element parallel module arrangement was found more suitable for this commercial hollow fiber membrane element tested in this study. Moreover, the maximum feed solution (FS) inlet flowrate was 3 L/min per hollow fiber element considering the maximum allowable FS inlet pressure. Finally, the numerical simulations revealed that to achieve 0.25 M, 0.20 M, and 0.15 M final DS concentrations from the system, the optimum number of modules required were 370, 435, and 555 respectively. For the same final concentrations, the DS inlet flowrates to each module were found to be 0.8 L/min, 0.55 L/min, and 0.32 L/min, whereas the FS inlet flowrates were 2 L/min, 2.5 L/min, and 2.5 L/min respectively.

Considering the simple flow configuration and module design, in this study theoretical models were developed for a plate and frame type FO membrane element. These models were validated with the published experimental results and element scale performance data provided by the commercial element manufacturer. The actual flow configuration and the physical dimensions of a commercially available plate and frame element were considered for the simulation. About 10% difference between the experimental and simulation results was observed and hence showed good reliability of the developed models. An overall performance index (based on recovery rate, final draw solution concentration, and membrane elements per module) was then applied to optimize the full-scale FO plant for osmotic dilution of seawater. The simulation results showed that for a 1,000 m^3/day FO plant to produce 0.2 M diluted seawater as final FO product (using a 0.02 M FS (~MBR effluent), inlet flowrate per module of 20 L/min and at 50% feed recovery rate), a total of 47 modules containing 7 plate and frame membrane elements per module and 5 L/min DS inlet flowrate were the optimum design and operating conditions for this particular capacity plant. In addition, for the same recovery rate (50%) the optimum DS inlet flowrates to the system were found about 3, 4, and 6 times lower than the FS inlet flowrate when the desired final DS concentrations were 0.25 M, 0.2 M, and 0.15 M respectively.

From the previous three studies, it was found that designing a large scale FO system is not a trivial job, rather it is a difficult, time consuming, and tedious task. Therefore, this study is aimed at developing a user friendly FO system analysis software (referred to as

FOSA (forward osmosis system analysis) in this study) that can make the design process simple, economical, and efficient. This study first designed a few algorithms to develop the framework of the software. These algorithms were then coded to design the frontend (graphical user interface) and backend (simulation and optimization) layers of the software. The graphical user interface of FOSA receives the input for the design and optimization process from the user and displays the simulation results. However, for the simulation and optimization, FOSA employed the mathematical models and optimization algorithm developed in our previous studies [chapter 4, 5, and 6]. Finally, this software was used to design a 1,000 m^3/day FO plant to produce 0.2 M diluted draw solution using a commercial TFC 8040 spiral wound module, a CTA hollow fiber module, and a plate and frame module. For the same operating conditions (0.6 M NaCl and 0.02 M NaCl draw and feed solution inlet concentration, feed solution to draw solution inlet flowrate ratio was 4), the spiral wound module showed the best performance among the three modules. The CTA hollow fiber module although required smaller system footprint, required larger membrane area due to its lower water permeability. In contrast, the plate and frame module required less membrane area compared to the hollow fiber module due to its better membrane properties, but the lower packing density of this module results in the largest footprint of the system compared to the other modules. Therefore, the developed FO system design and optimization software FOSA is a useful product that came from this research and can play an important role in the uptake of FO by industry.

This thesis finally concludes with the recommendation to improve the accuracy and extend the scope of the FO system analysis software. Development of empirical models for pressure drop across the membrane module and the effects of fouling on the module performance can help to enhance the accuracy of the current FO system design and optimization studies. Further, the addition of more draw solutions, feed solutions, and membrane modules to the software can enable it to search for numerous potential applications of the FO process. Other osmotically driven processes (such as Pressure retarded osmosis (PRO), pressure assisted osmosis (PAO)) can also be included in the software to widen its scope. Finally, launching this software as a web application to make it available for diverse groups of industrial and academic users will significantly contribute to commercializing the FO process for various applications.

CONTENTS

List of Figures

List of Tables