Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2013.827299

52 (2014) 556–563
January

Taylor & Francis
Taylor & Francis Group

A preliminary study on the volume reduction of pre-treatment sludge in seawater desalination by forward osmosis

S. Liyanaarachchi[a], V. Jegatheesan[a,*], L. Shu[a], S. Muthukumaran[b], K. Baskaran[a]

[a]*School of Engineering, Deakin University, Waurn Ponds, 3216, Australia*
Email: jega.j@deakin.edu.au
[b]*College of Engineering and Science, Victoria University, Melbourne 8001, Australia*

Received 4 March 2013; Accepted 19 March 2013

ABSTRACT

Forward Osmosis (FO) can be applied to recover water from the pre-treatment sludge of seawater reverse osmosis process. This study investigated the effect of the concentration of two draw solutions ($MgCl_2$ and NaCl) in the reduction of $Fe(OH)_3$ sludge volume and the effect of cross flow velocity on flux through FO membrane. Higher the concentration of NaCl and $MgCl_2$ higher the water flux observed. However, the percentage increase was not significant due to the occurrence of internal concentration polarisation. $MgCl_2$ draws marginally increased water flux than NaCl, when the conditions of feed and draw solutions were similar. Increase in cross flow velocity (from 0.25 to 1.0 m/s) marginally changed the flux with both draw solutions as higher cross flow velocities were unproductive to beat the external CP effect along the membrane surface. However, at 1 m/s, highest fluxes were obtained for both draw solutions.

Keywords: Concentration polarisation; Desalination; Forward osmosis; Pre-treatment; Sludge

1. Introduction

Pre-treatment is one of the most important processes in a seawater desalination process. Seawater is pre-treated to remove suspended particles, organic matter and microorganisms. However, more research and development is needed in this area as current desalination industries experience various practical issues. Generation of high volume of sludge is the major practical issue in available pre-treatment methods. Sludge undergoes centrifugal process to reduce its volume before being discharged during which high amount of energy is consumed. Furthermore, disposal and transportation of sludge accounts for more than 90% of the total operation and maintenance cost [1]. Therefore, reduced sludge volume undoubtedly reduces the associated expenses in pre-treatment and hence the total operational cost.

Osmotically driven membrane process, forward osmosis (FO) or pressure retarded osmosis (PRO), is believed to be a promising emerging technology to reduce the volume of pre-treatment sludge. When a diluted solution and a concentrated solution are separated by a semi-permeable membrane, water permeates through membrane from diluted solution

---

*Corresponding author.

Presented at the Fifth Annual International Conference on "Challenges in Environmental Science & Engineering—CESE 2012" Melbourne, Australia, 9–13 September 2012

to the concentrated solution due to the difference in water chemical potential (osmotic pressure). As a result, diluted solution (feed) gets concentrated whereas concentrated solution (draw) gets diluted. The driving force for the water permeation is the osmotic pressure difference between the two solutions and this phenomenon is called osmosis.

Fertiliser drawn FO desalination has been successfully applied in lab scale to dilute fertilisers while concentrating saline ground water [2]. FO membranes have been used to dilute seawater using secondary wastewater effluent as draw solution, in order to reduce the energy cost associated with desalination [3]. A few studies has been carried out to treat land fill leachate, food industry effluent, and to increase the water recovery of RO [4–6]. FO has been given a significant attention over the past few years due its superior characteristics such as high feed water recoveries (up to ~85%), operates at low or no hydraulic pressure with a lower electrical consumption (~0.25 kWh/m^3 of product water) and lower membrane fouling tendency compared to other membrane treatments [7–9]. However, this technology is still in the development stage either in bench scale or pilot plant scale [10,11]. In the literature, there were no research have been conducted to evaluate the capability of FO to reduce the volume of pre-treatment sludge of seawater reverse osmosis (SWRO) process.

Table 1
Properties of initial seawater and sludge prior to the membrane separation

Parameter	Measurement
Seawater (collected near PSDP, Australia for pre-treatment)	
Suspended solids (mg/l)	30
Total dissolved solids (mg/l)	36,500
pH	8.17
Conductivity at 25˚C (mS/m)	5,100
Seawater (collected near Geelong, Australia for sludge dilution)	
Suspended solids (mg/l)	5.71
Total dissolved solids (mg/l)	33,433
pH	8.05
Conductivity at 22˚C (mS/m)	4,990
$Fe(OH)_3$ sludge	
Solids content (%TS)	4.04
pH	8.69[a]
Conductivity at 22˚C (mS/m)	5,150
Specific gravity	1.01

Note: [a]The pH value of feed solution is slightly out of the recommended range (4–8) for the operation of FO membrane. Though, the salt rejection was not evaluated in this preliminary study.

Therefore, the effect of concentration of draw solution in the reduction of volume of $Fe(OH)_3$ sludge that is generated in the pre-treatment of SWRO process and the effect of cross flow velocity on water flux are investigated in this study. Furthermore, experimental and theoretical water fluxes are compared using available literature.

2. Materials and methods

Flat sheet CTA membranes with a woven, embedded support backing (average pore diameter of 0.74 nm [12]) were obtained from Hydration Technologies Inc, USA and $Fe(OH)_3$ sludge (around 25% TS)

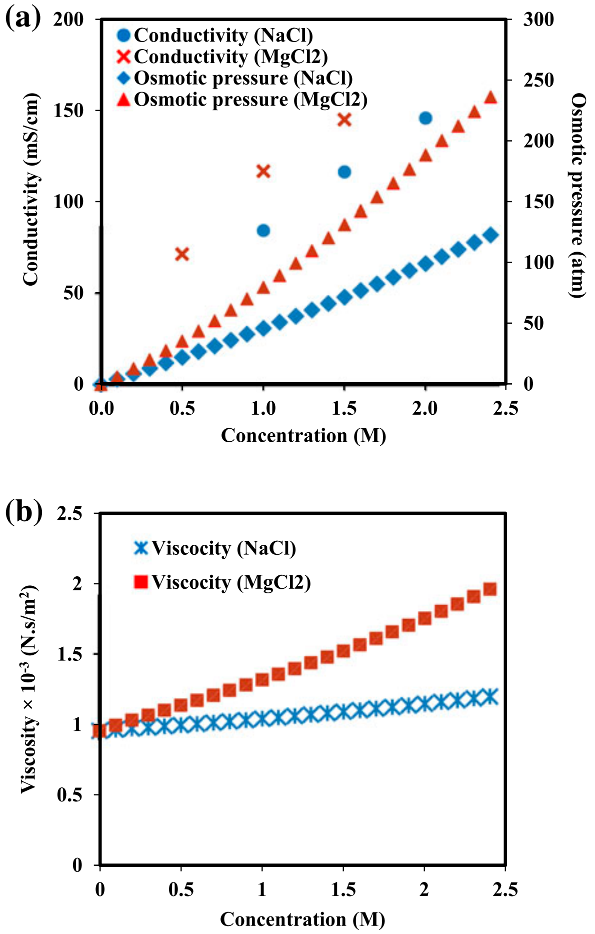

Fig. 1. (a) Variation of conductivity (experimental data) and osmotic pressure (OLI Stream Analyser software data) and (b) viscosity (OLI Stream Analyser software data) of selected draw solutions with corresponding molar concentrations.

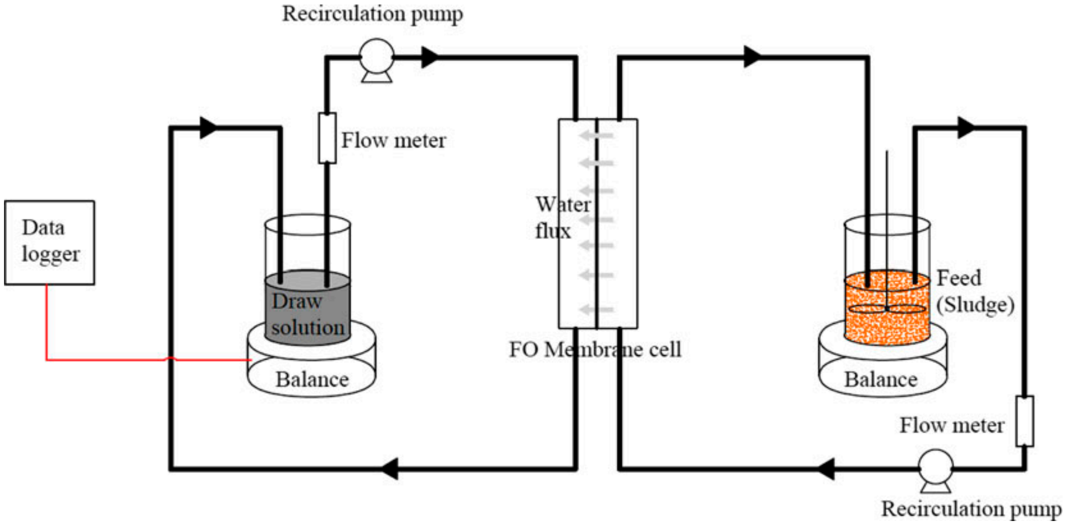

Fig. 2. Schematic diagram of the experimental setup (draw and feed solutions were maintained at room temperature).

was obtained from the perth seawater desalination plant (PSDP), Australia. Prior to the membrane separation, properties of feed ($Fe(OH)_3$ sludge) and draw solutions (NaCl and $MgCl_2$) were measured and have been summarized in Table 1 and Fig. 1. Since $Fe(OH)_3$ sludge contains around 4% TS after dual media filtration [1], seawater (Table 1) was used to dilute the $Fe(OH)_3$ feed from around 25% TS to around 4% TS. Feed and draw solutions were passed through the membrane at 0.25, 0.50 and 1.00 m/s cross flow velocities in counter current flow configuration as it provides constant osmotic pressure difference along

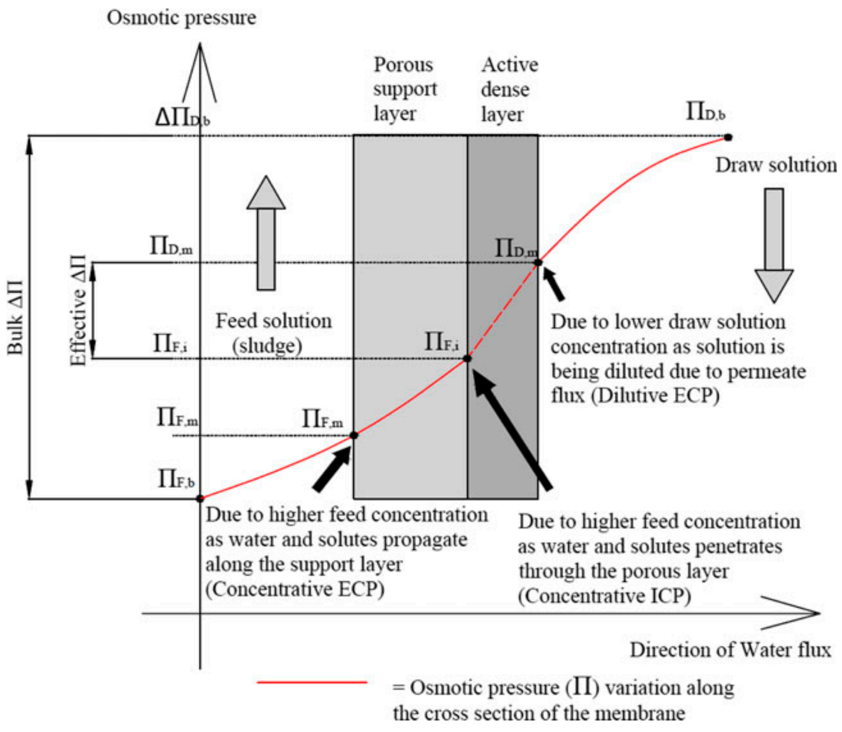

Fig. 3. CP effect on the membrane during experiment ($\Delta\pi$, ICP and ECP denote osmotic pressure difference, ICP and ECP, respectively. Bulk $\Delta\pi$ is the osmotic pressure difference of initial draw and feed solution. Effective $\Delta\pi$ is the actual driving force which leads to actual water permeation (J_w) through membrane).

the membrane cell. Sludge was circulated on the porous side of the membrane to obtain a higher water flux and stirred at a constant rate during the experiment to eliminate settling of particles. Schematic diagram of the experimental set up is given in Fig. 2. Experiments were run at room temperature, which was 22℃ with a coefficient of variation of 0.1. Experiments were conducted carefully and single run was performed at each operating condition. Change in the weight of the draw solution was programmed to be stored in a data logger at one minute time intervals. Experimental water flux ($J_{w,e}$) was determined by;

$$J_{w,e} = \frac{\text{change in weight in time}\,\Delta t}{\text{density of water} \times \text{effective membrane area} \times \Delta t} \tag{1}$$

After 3 h of filtration, properties of the feed and draw solutions were measured. Membrane was cleaned using 0.5 M NaCl and DI water in the opposite mode prior to each experiment. Theoretical water flux ($J_{w,t}$) was calculated and compared with that of experimental value.

2.1. Theoretical water flux calculation

The driving force for the water permeation is osmotic pressure difference of two solutions; hence theoretical water flux through membrane can be calculated using Eq. (2) where A, $\pi_{D,b}$, and $\pi_{F,b}$ are water permeability coefficient, bulk osmotic pressure of draw solution and bulk osmotic pressure of feed solution, respectively.

$$J_{w,t} = A[\pi_{D,b} - \pi_{F,b}] \tag{2}$$

However, in an osmotic process, on the feed side the polarised layer is more concentrated than bulk

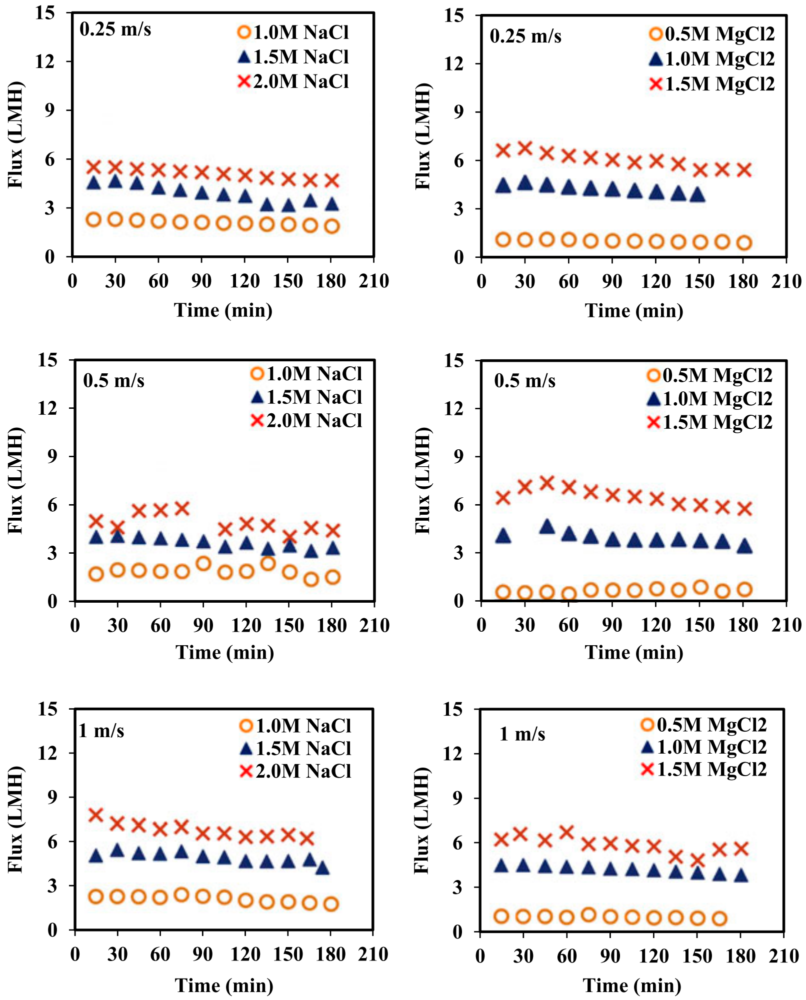

Fig. 4. Change in water flux with filtration time at different concentrations of draw solution and different cross flow velocities.

solution (with feed solutes). On the other side polarised layer is less dense than the bulk draw solution (with draw solutes). This polarisation effect governs the overall water flux through membrane (Fig. 3). Therefore, in the presence of concentration polarisation (CP), Eq. (2) can be modified as follows, where k_D and k are mass transfer coefficient in the draw solution side and solute resistivity for diffusion within the porous support layer, respectively.

$$J_{w,t} = A\left[\pi_{D,b}\exp\left(\frac{-J_{w,t}}{k_D}\right) - \pi_{F,b}\exp(J_{w,t}K)\right] \tag{3}$$

First term in Eq. (3) accounts for the dilutive external concentration polarisation (ECP) on the active layer of the membrane and the second term accounts for the concentrative internal concentration polarisation (ICP) within porous support layer. When the feed solution is in contact with the support layer of the membrane, the mode of filtration is called PRO mode and when it is in contact with the active layer of the membrane, the mode of filtration is called FO mode. Thus, Eq. (3) is applicable for PRO mode.

3. Results and discussion

3.1. Effect of cross flow velocity on flux behaviour

Change in the water flux with elapsed time is given in Fig. 4. Draw solution concentrations were selected as 0.5, 1.0 and 1.5 M. However due to lower osmotic pressure of 0.5 M NaCl (conductivity and pH was 45.8 mS/cm and 4.68, respectively) than that of sludge, water permeated from draw solution to sludge. Therefore flux behaviour at 2.0 M NaCl as draw solution was obtained to collect additional data.

There was a significant flux decline during 3 h of filtration despite the change in cross flow velocity or draw solution concentration. When cross flow velocity of feed and draw solutions were maintained at 0.25 m/s, water flux with 1.0, 1.5 and 2.0 M NaCl draw solutions decreased after 3 h by 18, 28 and 15%, respectively. At 0.5 m/s of cross flow velocity, water flux was fluctuated significantly with time for both the draw solutions. Average fluxes were calculated at corresponding cross flow velocity and draw solution concentration as shown in Fig. 5.

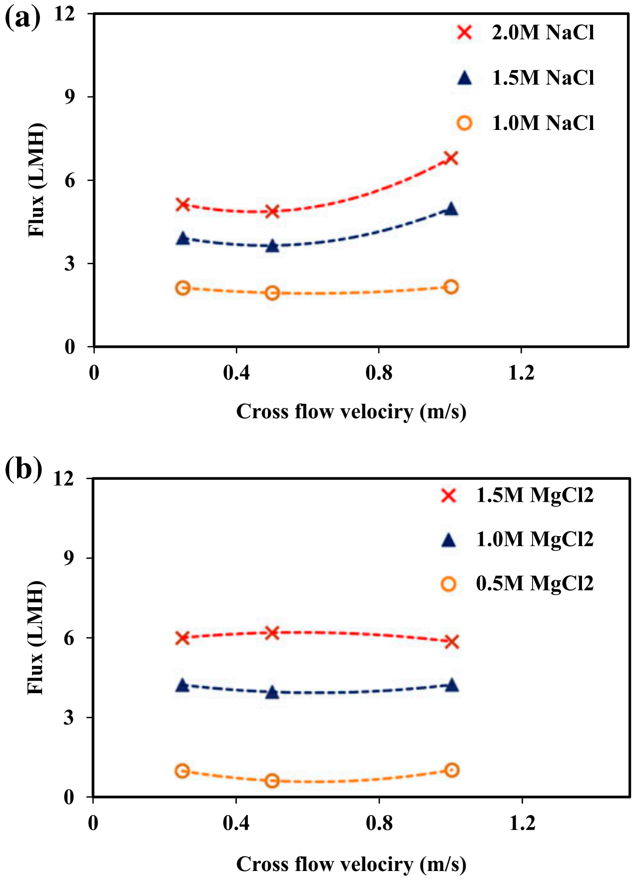

Fig. 5. Average water flux as a function of cross flow velocity at different concentrations of draw solution.

When the cross flow velocity increased from 0.25 to 0.5 m/s, there was no significant change in the flux. However, there was a marginal increase in the water flux, when the cross flow velocity was increased to 1 m/s. Increase in the cross flow velocity could reduce the dilutive ECP of the membrane due to increase in turbulence along the membrane active layer surface. However, effect of cross flow velocity on the dilutive ECP is not significant due to inherent lower water flux in FO membrane [11]. Marginal increase in water flux could be due to this phenomenon. This was observed at each concentration of draw solution. At lowest concentrations of the draw solutions (0.5 M $MgCl_2$ and 1 M NaCl) flux increased only by 4 and 2%, respectively when cross flow velocity increased from 0.25 to 1 m/s. However, water flux increased from 5.13 to 6.80 LMH (i.e. 33% increase) with the increase in cross flow velocity from 0.25 to 1 m/s at highest concentration of the draw solution (2 M NaCl).

Higher concentration of draw solution could draw higher amount of flux. However, the effect of dilutive ECP along the dense side of the membrane will become higher when the flux is higher which in turn will reduce the flux. Lower than expected flux at higher concentration of draw solution is explained by this phenomenon. Thus, it is evident that effect of cross flow velocity is not significant to change the water flux from the feed that contained $Fe(OH)_3$

Table 2
Osmotic pressure, theoretical and experimental flux and performance ratio of each draw solution

Concentration of draw solution (M)		Cross flow velocity, V (m/s)	Bulk π of draw solution (atm)	Bulk π difference $(\pi_{D,b} - \pi_{F,b})$ (atm)	Normalised driving force $\frac{(\pi_{D,b}-\pi_{F,b})}{\pi_{F,b}}$	Flux, $J_{w,e}$ (expt) (LMH)	Flux, $J_{w,t}$ (Eq. (2)) (LMH)	Performance ratio
NaCl	1.0	0.25	46.39	20.5	0.79	2.13	17.00	0.13
	1.5	0.25	72.03	46.2	1.78	3.92	38.24	0.10
	2.0	0.25	99.64	73.8	2.85	5.13	61.11	0.08
	1.0	0.50	46.39	20.5	0.79	1.95	17.00	0.11
	1.5	0.50	72.03	46.2	1.78	3.65	38.24	0.10
	2.0	0.50	99.64	73.8	2.85	4.88	61.11	0.08
	1.0	1.00	46.39	20.5	0.79	2.17	17.00	0.13
	1.5	1.00	72.03	46.2	1.78	4.99	38.24	0.13
	2.0	1.00	99.64	73.8	2.85	6.80	61.11	0.11
$MgCl_2$	0.5	0.25	35.72	9.9	0.38	1.02	8.16	0.13
	1.0	0.25	79.93	54.1	2.09	4.26	44.78	0.10
	1.5	0.25	131.55	105.7	4.08	6.03	87.54	0.07
	0.5	0.50	35.72	9.9	0.38	0.66	8.16	0.08
	1.0	0.50	79.93	54.1	2.09	3.99	44.78	0.09
	1.5	0.50	131.55	105.7	4.08	6.22	87.54	0.07
	0.5	1.00	35.72	9.9	0.38	1.06	8.16	0.13
	1.0	1.00	79.93	54.1	2.09	4.27	44.78	0.10
	1.5	1.00	131.55	105.7	4.08	5.89	87.54	0.07

Note: $\pi_{D,b}$ and $\pi_{F,b}$ are bulk osmotic pressures of draw and feed solutions, respectively. Normalised driving force = $\left(\frac{\pi_{D,b}-\pi_{F,b}}{\pi_{F,b}}\right)$. Theoritical flux was calculated using Eq. (2). Perforemance ratio is the ratio between experimental flux and theoritical flux. Feed solution (sludge) bulk osmotic pressure $(\pi_{F,b})$ is assumed to be 25.9 atm.

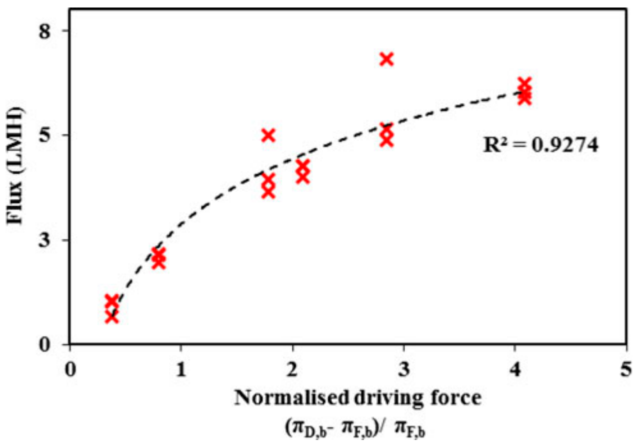

Fig. 6. Permeate flux as a function of normalised driving force, $\frac{\pi_{D,b}-\pi_{F,b}}{\pi_{F,b}}$, where $\pi_{D,b}$ and $\pi_{F,b}$ are bulk osmotic pressure of the draw and the feed solution, respectively.

sludge. Altering ECP by changing cross flow velocity may affect the solute flux thorough FO membrane [13]. However, solute flux was not examined in this preliminary study.

3.2. *Effect of ICP on water flux*

Higher the concentration of draw solution higher the flux obtained. Due to higher osmotic pressure of $MgCl_2$ solution than NaCl solution at the same molar concentration, higher flux was expected from former draw solution. However, there was no significant increase in the flux. Higher draw solution concentrations generate higher osmotic driving forces and hence produce more water flux. However, higher water fluxes increase the severity of concentrative ICP as interface of porous support layer and dense layer of the membrane gets more concentrated [14]. Therefore, significant increase in flux could not be obtained with increasing osmotic pressure. In order to evaluate the flux behaviour in the presence of concentrative ICP, water flux was plotted as a function of normalised driving force, as shown in Fig. 6.

The logarithmic water flux trend in the plot implies that higher normalsied driving forces caused by higher draw solution concentrations weakening the increment in water flux. This could be due to increase in severity of concentrative ICP with increase in water flux. Furthermore, viscosity of the draw solution and diffusivity of the solutes controls the water flux through membrane [13]. Viscosity of the $MgCl_2$ solution is higher than NaCl solution (at a specific molar concentration as shown in Fig. 1(b)) and diffusivity of $MgCl_2$ ($1.05 \times 10^{-9}\,m^2/s$) is lower than NaCl ($1.48 \times 10^{-9}\,m^2/s$). This could result in CP effect that would reduce the permeate water flux through the membrane [13–16]. In a study on FO mode conducted by Hancock and Cath [13], lower diffusion coefficent of magnesium compared to sodium (as draw solution) increased the severity of ICP and higher viscosity of $MgCl_2$ (at the same osmotic pressure) increased the severity of ECP. As reported elsewhere, one of the major negative impacts for further development of osmotically driven membrane process is the ICP [16].

Table 3
Coefficients used to solve Eq. (3)

	Draw solution concentration (M)				
	0.5	1.0	1.5	2.0	
k_D-Mass transfer coefficient in the $MgCl_2$ draw solution side ($\times 10^{-5}$ m/s)					
At 0.25 m/s	1.1918	1.1918	1.1918		
At 0.50 m/s	1.4981	1.4981	1.4981		
At 1.00 m/s	4.9497*	4.6700*	4.3840*		
k_D-Mass transfer coefficient in the NaCl draw solution side ($\times 10^{-5}$ m/s)					
At 0.25 m/s		1.5818	1.5818	1.5818	
At 0.50 m/s		1.9883	1.9883	1.9883	
At 1.00 m/s		7.1516*	7.0762*	6.9920*	
A-Water permeability coefficient at 22°C ($\times 10^{-7}$ m/s.atm)					2.3015
K-Solute resistivity for diffusion within porous layer ($MgCl_2$) ($\times 10^{5}$ s/m)					2.8381
K-Solute resistivity for diffusion within porous layer (sludge) ($\times 10^{5}$ s/m)					2.0135

$k_D = \frac{Sh \times D}{d_h}$ where *Sh*, *D* and d_h are Sherwood number, solute diffusion coefficient and hydraulic diameter, respectively.
Coefficient *A* obtained by running a RO experiment using the membrane

Note that all the experiments were run in PRO mode; *turbulent flow.

3.3. Comparison of experimental flux data with theoretical values

Theoretical flux was calculated using Eq. (2) (Table 2).

Performance ratio declines with the increase in draw solution concentration despite the change in cross flow velocity. Eq. (2) over predicts the flux as it does not consider the CP effect and hence lower performance ratio. However when Eq. (3) is used to compute the flux we were unable to find a solution. Our laboratory experiments produced the value for water permeability coefficient (A) as 2.3015×10^{-7} m/s.atm which did not allow the flux value to converge while solving Eq. (3). When lower values were used for A, Eq. (3) converged to obtain a value for the flux. This needs further investigation. The values used to solve Eq. (3) are shown in Table 3.

4. Conclusion

This study investigated the effect of the concentration of draw solution and cross flow velocity on the reduction of $Fe(OH)_3$ sludge volume through FO membranes. Following conclusions were drawn after the preliminary study.

(1) Increase in cross flow velocity (from 0.25 to 1.0 m/s) could not significantly reduce the presence of ECP, hence marginal increase in flux observed with increase in cross flow velocity.
(2) Higher the concentration of draw solution higher the water flux obtained from the FO process.
(3) Although $MgCl_2$ has a higher osmotic pressure than NaCl at the same molar concentration, there were no significant differences in water fluxes when $MgCl_2$ and NaCl were used as draw solutions. Higher viscosity of $MgCl_2$ (draw) solution and lower diffusivity of $MgCl_2$ (draw) solute control the water flux through membrane as both increase the severity of internal as well as ECP.

However, FO technology appears to be a promising technology to reduce the volume of sludge with further process developments.

Acknowledgements

Financial support provided through Engineering Collaborative Research Funding in 2012 by the School of Engineering, Deakin University is gratefully acknowledged. Authors appreciate the courtesy of Robert Vollprecht, Perth seawater desalination plant, who provided pre-treatment sludge. We thank Steve Bagshaw, Leanne Farago and Lube Veljanoski, Deakin University for their technical support. We acknowledge Ho Kyong Shon, Univeristy of Technology, Sydney for providing the facility to use OLI Stream Analyser software.

References

[1] Personnel communication with Robert Vollprecht, Degremont PTY LTD, Perth Seawater Desalination Plant, WA, Australia, 2012.
[2] S. Phuntsho, H. Shon, S. Hong, S. Lee, S. Vigneswaran, J. Kandasamy, Fertiliser drawn forward osmosis desalination: The concept, performance and limitations for fertigation, Rev. Environ. Sci. Bio/Technol. 11 (2012) 147–168.
[3] V. Yangali-Quintanilla, Z. Li, R. Valladares, Q. Li, G. Amy, Indirect desalination of Red Sea water with forward osmosis and low pressure reverse osmosis for water reuse, Desalination 280 (2011) 160–166.
[4] K.B. Petrotos, P.C. Quantick, H. Petropakis, Direct osmotic concentration of tomato juice in tubular membrane—module configuration. II. The effect of using clarified tomato juice on the process performance, J. Membr. Sci. 160 (1999) 171–177.
[5] A. Achilli, T.Y. Cath, E.A. Marchand, A.E. Childress, The forward osmosis membrane bioreactor: A low fouling alternative to MBR processes, Desalination 239 (2009) 10–21.
[6] C.R. Martinetti, A.E. Childress, T.Y. Cath, High recovery of concentrated RO brines using forward osmosis and membrane distillation, J. Membr. Sci. 331 (2009) 31–39.
[7] R.L. McGinnis, M. Elimelech, Energy requirements of ammonia–carbon dioxide forward osmosis desalination, Desalination 207 (2007) 370–382.
[8] S. Lee, C. Boo, M. Elimelech, S. Hong, Comparison of fouling behavior in forward osmosis (FO) and reverse osmosis (RO), J. Membr. Sci. 365 (2010) 34–39.
[9] J.R. McCutcheon, R.L. McGinnis, M. Elimelech, A novel ammonia—carbon dioxide forward (direct) osmosis desalination process, Desalination 174 (2005) 1–11.
[10] M. Elimelech, Yale constructs forward osmosis desalination pilot plant, Membr. Technol. 2007 (2007) 7–8.
[11] T.Y. Cath, A.E. Childress, M. Elimelech, Forward osmosis: Principles, applications, and recent developments, J. Membr. Sci. 281 (2006) 70–87.
[12] M. Xie, L.D. Nghiem, W.E. Price, M. Elimelech, Comparison of the removal of hydrophobic trace organic contaminants by forward osmosis and reverse osmosis, Water Res. 46 (2012) 2683–2692.
[13] N.T. Hancock, T.Y. Cath, Solute coupled diffusion in osmotically driven membrane processes, Environ. Sci. Technol. 43 (2009) 6769–6775.
[14] J.R. McCutcheon, R.L. McGinnis, M. Elimelech, Desalination by ammonia–carbon dioxide forward osmosis: Influence of draw and feed solution concentrations on process performance, J. Membr. Sci. 278 (2006) 114–123.
[15] A. Achilli, T.Y. Cath, A.E. Childress, Selection of inorganic-based draw solutions for forward osmosis applications, J. Membr. Sci. 364 (2010) 233–241.
[16] T.Y. Cath, M. Elimelech, J.R. McCutcheon, R.L. McGinnis, A. Achilli, D. Anastasio, A.R. Brady, A.E. Childress, I.V. Farr, N.T. Hancock, J. Lampi, L.D. Nghiem, M. Xie, N.Y. Yip, Standard methodology for evaluating membrane performance in osmotically driven membrane processes. Desalination, (article in press) http://dx.doi.org/10.1016/j.desal.2012.07.005 (2012).