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# Effect of feed temperature and membrane orientation on pre-treatment sludge volume reduction through forward osmosis

S. Liyanaarachchi[a], V. Jegatheesan[a,*], I. Obagbemi[a], S. Muthukumaran[b], L. Shu[a]

[a]*Faculty of Science, Engineering & Built Environment, School of Engineering, Deakin University, Waurn Ponds, Geelong, VIC 3216, Australia, Tel. +61 3 522 73403; email: jega.j@deakin.edu.au*
[b]*Institute for Sustainability and Innovation, College of Engineering and Science, Victoria University, PO Box 14428, Melbourne, VIC 8001, Australia*

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ABSTRACT

This study focuses on volume reduction of pre-treatment sludge as well as on dilution of reverse osmosis (RO) concentrate through emerging forward osmosis (FO) technology where RO concentrate draws water from the pre-treatment sludge (feed solution) in order to reduce pre-treatment sludge volume and increase the RO water recovery. Experiments were carried out using two different types of sludge i.e. (1) synthetic pre-treatment sludge (Lab sludge) which has lower salinity and (2) actual sludge from Perth Seawater Desalination Plant, Australia (Perth Seawater Desalination Plant (PSDP) sludge) which has higher salinity. Effect of membrane orientation (FO and pressure-retarded osmosis (PRO) modes) and temperature of pre-treatment sludge on permeate water flux was investigated. There was a significant increase in water flux from 3.2 to 10.2 LMH (i.e. ~3 times higher) when temperature increased from 20 to 40˚C for Lab sludge in PRO mode. However, there is no significant effect of temperature on water flux in FO mode for Lab sludge. On the contrary for PSPD sludge, there was no effect on water flux with increase in temperature at PRO mode. Dissolved ions in the porous side increased the severity of concentrative internal concentration polarization; hence, it could reduce the flux. There was no significant change in water flux when temperature increased from 20 to 40˚C for PSDP sludge in FO mode. However, higher amount of water has permeated from Lab sludge compared to PSDP sludge in FO mode.

*Keywords:* Forward osmosis; Reverse osmosis; Sludge pre-treatment; Water recovery

## 1. Introduction

Seawater desalination process has significantly moved towards membrane technology during last decade. Seawater reverse osmosis (SWRO) in general is the most familiar process due to higher water recovery (~upto 80%) and lower energy consumption (~3−4 kW h/m$^3$ of product water) compared to other desalination processes [1–5]. However, the greatest challenge in SWRO is to achieve higher water recoveries while

*Corresponding author.

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minimizing operational costs associated with waste (i.e. pre-treatment sludge and brine) management.

Sludge is generated during pre-treatment of seawater due to sedimentation as well as granular media filter backwash. In general, conventional granular media pre-treatment is more often used technique in current operating SWRO plants [6–8]. Typically, conventional granular media pre-treatment systems use chemicals (coagulants) for effective solids separation. Therefore, generated media backwash waste (pre-treatment sludge) is highly concentrated with excess chemicals and suspended particles. Properties of the sludge depend on the backwashing method. For example, Perth Seawater Desalination Plant (PSDP) in Australia sends coagulant added seawater to a dual media filter (DMF) and then use concentrated brine from the desalting process to backwash media filter [9]; hence, the total dissolved solid (TDS) of the sludge is very high. On contrary, Fujairah plant, UAE uses DMF filtered water for backwashing. However, they use an additional sedimentation tank prior to DMF, where DMF is only to filter out any particles that escape from the sedimentation tank [10]. Therefore, the TDS of Fujairah plant sludge certainly needs to be much lower than that of the PSPD sludge. Despite different backwashing methods, at present, one of the major issues in pre-treatment sludge management is higher volume which increases associated transportation and disposal expenses.

Brine, which is generated during desalting process, has a high salinity value depending on the recovery rate of the reverse osmosis (RO) unit. In general, brine TDS is nearly two times the value of source seawater. For example with a 45% of RO recovery, TDS of RO feed and brine are 40,070 and 72,500–72,700 mg/L, respectively at one-stage SWRO plant in Eni Gela, Sicily [11]. Post treatment of brine takes up 5–33% of the total cost of desalination [12]. Therefore, it is necessary to investigate a proper brine management option in order to reduce the associated costs.

Therefore, this study focuses on brine management while reducing the volume of pre-treatment sludge of the SWRO process using forward osmosis (FO) technology. Our previous studies showed that FO is a promising technology to dewater pre-treatment sludge [13]. However, regeneration of draw solution was an issue. Therefore, in this study we propose brine as the draw solution since it has following advantages: (1) Diluted brine can be sent back to desalting process to increase the overall water recovery or (2) if brine is discharged back to sea, dilution is an added advantage as many brine disposal regulations are based on concentrations but not on volume [12]. Figs. 1(a)–(c) show the proposed systems in this study. In all three proposed systems, System A shows where the concentrated brine and the sludge/chemical waste are generated in an existing typical desalination process. System B is the proposed system in this study. In System B, the sludge is used as feed solution and part of the brine from RO is used as draw solution for the FO unit and the remaining is discharged as waste. Characteristics of feed solution to the FO system will vary depending upon the way in which the sludge is generated. For example, in System 1 (Fig. 1(a)) 2nd pass RO concentrate is used as backwash water; hence, the salinity is lower in the generated sludge. Conversely as shown in Fig. 1(b), System 2 uses pre-treated seawater as backwash water. Therefore, salinity is significantly higher in the feed solution to the FO (compared to the feed solution to FO in System 1). The concentrated sludge is removed from the FO unit for further treatments if necessary and the diluted brine can either discharged back to a water body as shown in System 3 (Fig. 1(c)) or sent back to the second pass RO unit (Figs. 1(a) and (b)) in order to enhance the recovery of treated water.

However, depending on the pre-treatment sludge generation method, dewatered volume of sludge may vary as water permeation through FO depends on the concentration gradient of draw and feed solutions. Therefore, two types sludge having different concentrations will be used as feed solutions in this study. Optimum feed temperature and effect of membrane orientation in the reduction of pre-treatment sludge volume using the proposed system will be investigated.

## 2. Materials and methods

### 2.1. Feed solutions (pre-treatment sludge)

Two types of feed solutions were used in this study; (1) synthetic sludge prepared at lab scale (Lab sludge) with lower salinity, which is similar to the feed of System 1 (Fig. 1(a)) and (2) actual sludge received from PSDP (PSDP sludge) with higher salinity which is similar to the Feed of System 2 (Fig. 1(b)).

#### 2.1.1. Lab sludge

Seawater was collected from Southern Ocean near Geelong, Australia. Pre-filtered and optimum dosage of coagulant ($FeCl_3$) added seawater was passed through a cylindrical DMF at a rate of 7.6 m/h where DMF diameter, sand media bed depth and anthracite media bed depth are 50, 400 and 300 mm, respectively. After 4 h of filtration, filter media beds were backwashed for 2 min using tap water. The pH, total organic carbon (TOC), electrical conductivity (EC) and

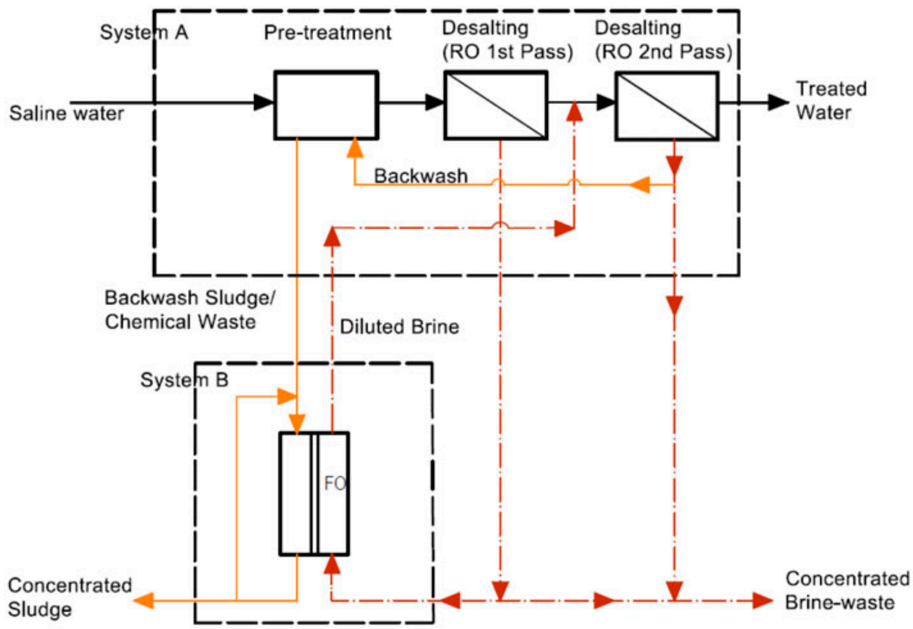


Fig. 1(a). New Proposed FO process for brine and sludge treatment in SWRO process (System 1) where feed and draw solutions are sludge backwash using 2nd pass RO reject and 1st pass RO brine, respectively.
Notes: System A is the schematic of existing process. System B is the additional system proposed in this study. Brown dash dot line and yellow continuous line denote brine and sludge flow, respectively. The 2nd pass RO concentrate (low TDS since 2nd pass RO treats permeate from 1st pass) is used to backwash media filter. The 1st pass RO concentrate used to draw water through FO as it has high TDS (hence high conductivity and osmotic pressure). Diluted brine is sent back to 1st pass RO for further desalting process in order to increase overall water recovery.

turbidity of the seawater and filtered seawater were determined. Furthermore particle size distribution of backwashed sludge was analysed using *Malvern* Mastersizer.

### 2.1.2. PSDP sludge

$Fe(OH)_3$ sludge was obtained from the PSDP, Australia. Sludge was diluted 1:1 using distilled water in order get the salinity similar to the feed of System 2. Properties of PSDP sludge have been summarized in the Table 1.

## 2.2. Draw solution (RO concentrate)

Spiral wound RO membranes with an effective area of 0.32 $m^2$ were purchased from GE water and process technologies, Australia. Following Lab sludge preparation experiment (section 2.1.1) pre-treated seawater was passed through the RO membrane at an average flux rate of 9.6 LMH until the brine conductivity is greater than 70 mS/cm [9]. Desalting pressure and frequency were selected to be 30 bar and 20 Hz, respectively. All the parameters mentioned in section 2.1.1 were analysed for the permeate and the concentrate of RO.

## 2.3. FO experiments

Flat sheet cellulose triacetate membranes with a woven, embedded support backing (average pore diameter of 0.74 nm [14]) were purchased from Hydration Technologies Inc, USA. Feed (Lab sludge or PSDP sludge) and draw solutions were passed through the membrane at 0.25/ms cross flow velocities in counter current flow configuration. Feed was circulated on the porous side (pressure retarded osmosis (PRO) mode) as well as on the active layer side (FO mode) of the membrane and stirred at a constant rate during the experiment to eliminate settling of particles. Feed temperature was varied from 20, 30 and to 40°C and new membrane sheet with an effective area of 33.54 $cm^2$ was used for each experiment. Change in the weight of the draw solution with filtration time was programmed to be stored in a data logger at 15 min time intervals ($\Delta t$). Experimental water flux ($J_{w,e}$) was determined by:

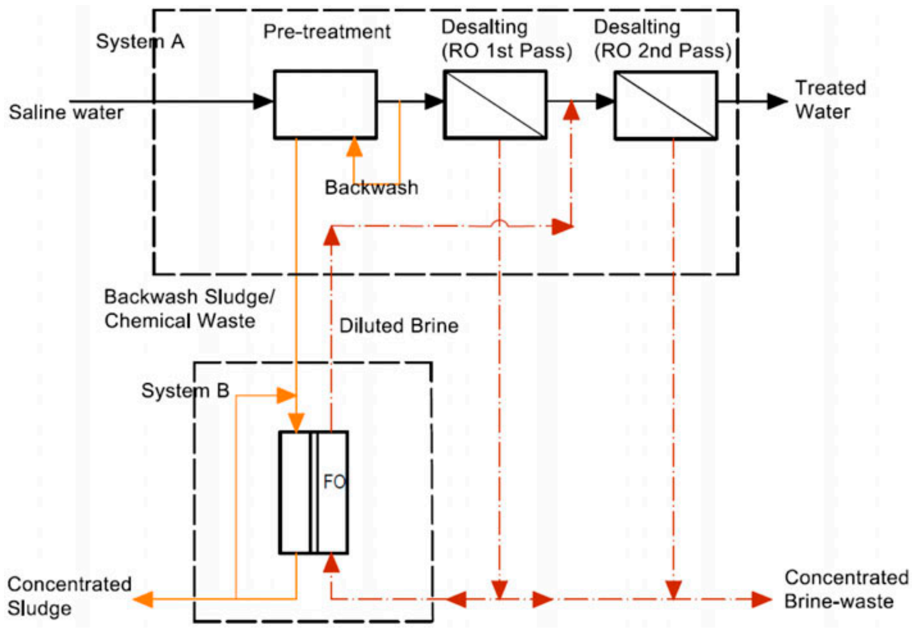


Fig. 1(b). New Proposed FO process for brine and sludge treatment in SWRO process (System 2) where feed and draw solutions are sludge backwash using filtered/polished water and 1st pass RO brine, respectively.
Notes: System A is the schematic of existing process. System B is the additional system proposed in this study. Brown dash dot line and yellow continuous line denote brine and sludge flow, respectively. Filtered/polished water after pretreatment is used to backwash media filter. The 1st pass RO concentrate used to draw water through FO as it has high TDS (hence high conductivity and osmotic pressure). Diluted brine is sent back to 2nd pass RO for further desalting process in order to increase the overall water recovery.

$$J_{w,e} = \frac{\text{Change in weight in time } \Delta t}{\text{Density of water} \times \text{Effective membrane area} \times \Delta t} \tag{1}$$

Properties of the feed and draw solutions were measured at every 15 min for 2 h of filtration.

## 3. Results and discussion

Properties of initial seawater, pre-treated seawater, DMF backwash water (Lab sludge), RO permeate and RO concentrate are given in the Fig. 2. Backwashed water (Lab sludge) contains 1% of total solids with a marginally increased TOC compared to seawater (from 1.708 to 1.944 mg/L). However, filtered seawater contains significantly lower amount of TOC (0.7342 mg/L) with 98% turbidity reduction (from 29.1 to 0.45 NTU). Since DMF removes dissolved organics and suspended solids, the EC of initial and filtered seawater practically unchanged, i.e. 44.5 and 44.7 mS/cm, respectively. However, after passing through spiral wound RO system, conductivity of RO reject (concentrate) increased to 73.0 mS/cm. Similarly TOC of the concentrate became four times higher than that of filtered water. Particle size distributions of Lab sludge and PSDP sludge are shown in Fig. 3. Distribution of PSDP sludge particles is wider compared to Lab sludge. Majority of PSDP sludge contains 24.8–33.6 μm particles whereas Lab sludge contains 34.7–39.8 μm particles. Temperatures of Lab sludge and PSDP sludge were changed from 20, 30 to 40˚C. Change in water flux with elapsed time is given in Fig. 4. There was a significant flux decline during 2 h of filtration despite the change in temperature or orientation of membrane. Average water fluxes were calculated at corresponding temperatures and given in Fig. 5. Results in each mode will be discussed in the following sections 3.1 and 3.2, separately.

### 3.1. Water flux in PRO mode

Water flux for PSDP and Lab sludge were approximately similar at 20˚C. However, there was a significant increase in water flux with increased temperature for Lab sludge. When temperature of feed solution was increased from 20 to 40˚C, water flux was three times greater at higher temperature. Decreased viscosity at elevated temperatures would have enhanced the water flux through the membrane. However, on the contrary, there

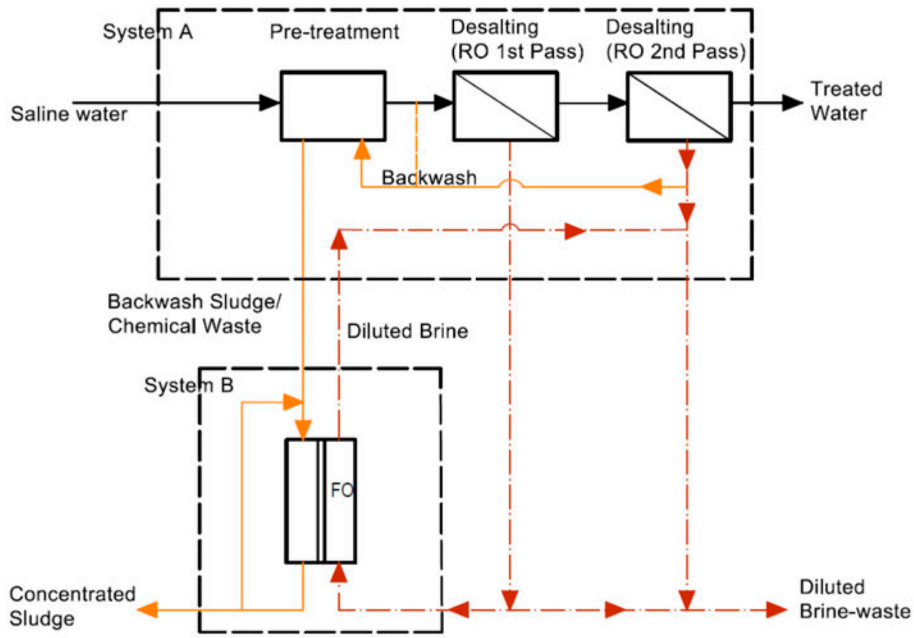


Fig. 1(c). New Proposed FO process for brine and sludge treatment in SWRO process (System 3) where feed solution is sludge backwash either using filtered/polished water or 2nd pass RO brine. Draw solution is part of 1st pass RO brine. Notes: System A is the schematic of existing process. System B is the additional system proposed in this study. Brown dash dot line and yellow continuous line denote brine and sludge flow, respectively. Either filtered/polished water after pre-treatment or concentrate from 2nd pass RO is used to backwash media filter. The 1st pass RO concentrate used to draw water through FO as it has high TDS (hence, high conductivity and osmotic pressure). Diluted brine is blended with the 1st and 2nd pass concentrate before discharged back to a water body.

Table 1
Properties of PSDP sludge used in this study. $Fe_2(SO_4)_3$ and anionic polymer have been used as the coagulant and the coagulant aid, respectively

| Solids content (% TS) | TOC (mg/L) | pH | Specific gravity | Conductivity (mS/cm) |
|---|---|---|---|---|
| 4.04 | 8.922 | 8.24 | 1.01 | 51.5 |

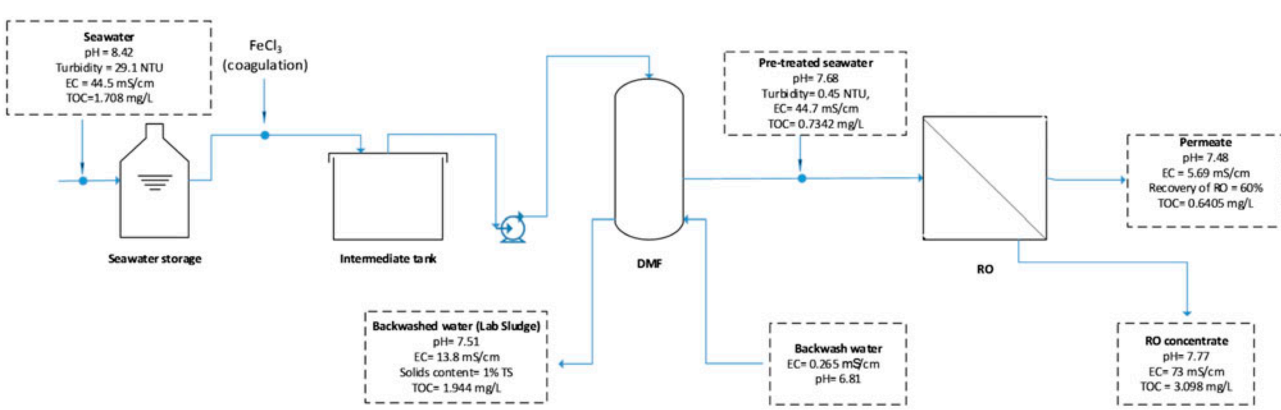


Fig. 2. Properties of initial seawater, pre-treated seawater and pre-treatment sludge prepared at lab scale. TOC and EC denote for total organic carbon and electrical conductivity, respectively. All the samples were prepared at batch scale.

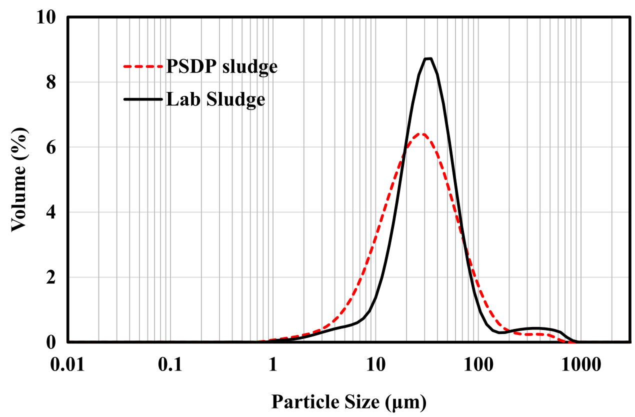


Fig. 3. Particle size distribution of PSDP sludge and Lab sludge.

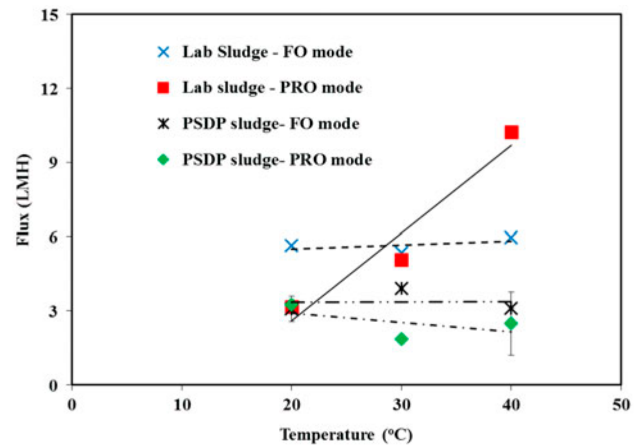


Fig. 5. Effect of membrane orientation on water flux. FO mode and PRO mode stand for draw solution facing porous support layer and feed solution facing porous support layer, respectively.

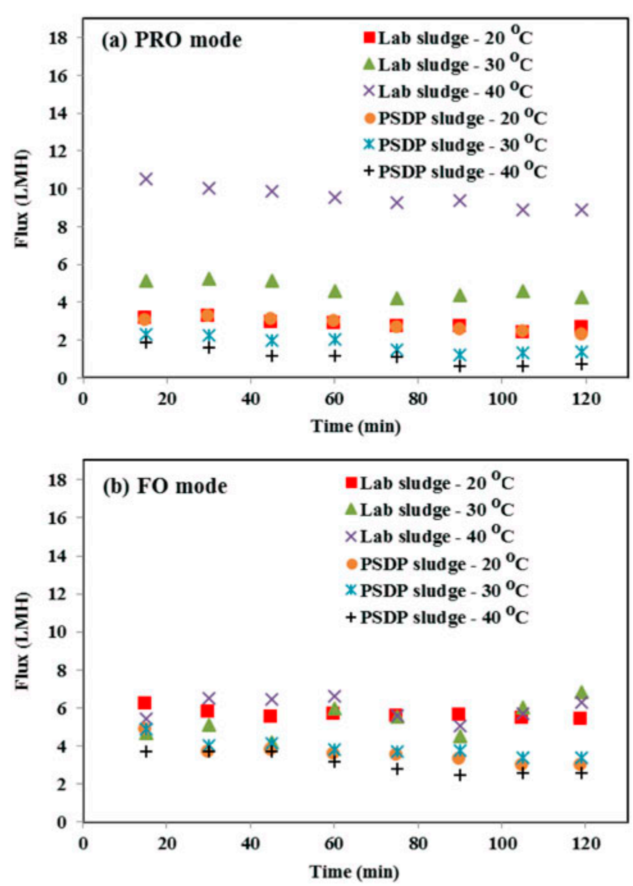


Fig. 4. Averaged water flux vs. elapsed time at different feed temperatures in (a) PRO mode (feed solution facing porous support layer) (b) FO mode (draw solution facing porous support layer).

was no significant change in water flux at increased feed temperatures for PSDP sludge. Even though both Lab sludge and PSDP sludge contain $Fe(OH)_3$, PSDP sludge contains more constituents such as coagulant aids, process-controlled chemicals (pH controllers, anti-scalants, sodium metabisulphite, etc) [9]. Furthermore, increase in temperature would have increased the mobility of ions in the feed solution. These dissolved ions may have increased the severity of internal concentration polarization effect at higher temperatures (since feed solution facing porous support layer), hence no significant increase in flux.

When experiments were conducted at elevated temperatures (40˚C) of feed solution (both lab and PSDP sludge), the temperature of the draw solution was initially kept at 20 ± 2˚C. During experiments, the temperature of the draw solution increased by 8˚C over a period of 2 h and the volume of the draw solution increased by 30 mL due to the passage of water from the feed side to the draw side. Thus, the increase in the osmotic pressure on the draw side was negligible. Although the osmotic pressure of the feed would have increased at higher temperatures, the viscosity will reduce. Increase in averaged water flux at higher temperatures for Lab sludge (as feed to FO system) indicates that the effect of viscosity is dominant over the effect of osmotic pressure. This should be the same for the PSDP sludge as feed. However, the averaged water flux did not increase when the temperature of the PSDP sludge was increased. This phenomenon must be mainly due to the fouling of PSDP sludge.

### 3.2. Water flux in FO mode

There was no significant change in water flux with increase in temperature for Lab sludge. At 20, 30 and 40˚C averaged water fluxes were, 5.72, 5.36 and 5.96 LMH, respectively. However, water flux is higher in FO mode than in PRO mode at 20˚C. Zhao et al. reports FO mode is more favourable when feed solution concentration and degree of concentration is higher [15]. Comparable results were achieved only with the lowest temperature (20˚C). When temperature increases, the water flux in PRO mode is significantly higher than FO mode for Lab sludge as shown in Fig. 5. At 40˚C water flux is 10.22 LMH in PRO mode whereas in FO mode flux is only 5.96 LMH. Similar to Lab sludge, there was no significant change in water flux with increase in temperature for PSDP sludge. However, flux is marginally higher than PRO mode.

## 4. Conclusions

A novel FO system was proposed for brine and pre-treatment sludge management in SWRO process. Furthermore effect of feed solution temperature and membrane orientation on water flux was investigated in this study. Following conclusions were made from this study.

(1) At elevated temperatures, PRO mode is more favourable for pre-treatment sludge solutions which have low constituents (Lab sludge where the concentration of dissolved ions was low). However, FO mode performed better at lower temperatures for the Lab sludge.
(2) FO mode is favourable for pre-treatment sludge solutions which have high constituents (PSDP sludge where the concentration of dissolved ions was high).

All proposed systems are capable in reducing the volume of pre-treatment sludge with further optimized process conditions.

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