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Reverse osmosis desalination process with feed flow reversal operation: experimental studies

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ABSTRACT

This study investigated the feed flow reversal operation in a single-spiral-wound reverse osmosis (RO) membrane module for low-concentration feeds. Different operating conditions of feed pressure, flow rate, concentration, and reversal period on the feed flow reversal RO operation were examined. The results showed that the feed pressure had a positive impact on the membrane recovery, while the feed flow rate and concentration played negative roles. With the increase of feed flow reversal period, the membrane recovery increased. The permeate flux and rejection were also examined for both feed flow reversal and cross flow RO. It is found that a higher permeate flux and rejection was achieved with a lower feed concentration or higher feed pressure. Comparing with cross flow RO, a slightly lower membrane recovery and rejection was obtained with feed flow reversal operations.

Keywords: Feed flow reversal; Cross flow; Reverse osmosis; Period; Rejection

1. Introduction

Reverse osmosis (RO) membrane desalination can produce fresh water from seawater, and it has become a dominant technology for water purification in coastal cities facing fresh water shortage [1–3]. For seawater RO desalination, spiral wound membrane module is widely used due to its advantages of relative high packing density and mass transfer with the presence of feed spacers [4]. In the conventional cross flow RO, the feed solution enters at the front end of the module (upstream), resulting in the higher solute concentration at the tail end (downstream), which significantly increases the filtration resistance and reduces the permeate flux. The accumulated solute retention can worsen the concentration polarization near the membrane surface, which has been found to be one of the main reasons for membrane scaling [5]. With multistage RO, the increase occurs from the first-stage element to the end-stage element in a similar manner [6]. By applying feed flow reversal, the feed solution enters at both ends of the RO module in an alternate manner. When reversing, the feed solute concentration at the tail end is reset; at the same time, it increases along the module in the flow direction due to solute rejection.

The feed flow reversal processes for multistage RO have been examined to improve the membrane filtration flux at the tail element. Gu et al. studied the feed flow reversal in six membrane elements [7]. They found that the flux of the tail element increased from 14 L/(m^2 h) to 28 L/(m^2 h) when feed flow reversal was applied under scaling operating conditions with a scale coverage of 69%. They attributed the sharp increase of membrane permeate flux to the dissolution and mixing of the precipitated solutes with the low-concentration feed and concluded that the feed flow reversal could greatly reduce membrane scaling and eliminate the usage of anti-scalants which can potentially induce

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eutrophication in coastal waters [8,9]. Uchymiak et al. also investigated the feed flow reversal with multistage RO for brackish water filtration [10]. They suggested that by reversing the feed flow frequently with a period less than the time to reach the mineral scaling threshold, the membrane scaling could be effectively prevented.

Compared with cross flow RO, feed flow reversal RO is able to prevent the solute accumulation at the downstream of the membrane system to mitigate membrane scaling [7,10]; thus, it can reduce the membrane cleaning frequency and increase the membrane lifetime. However, the effect of feed flow reversal on the membrane filtration performance without membrane scaling has not been explored before. By reversing the flow, the temporal and spatial salt concentration distribution along the membrane surface becomes variable, which makes the situation much more complex as compared with the steady-state conditions of cross flow RO. Hence, a comprehensive examination of the process in a single-membrane module was carried out in this study to reveal the effect of feed flow reversal on the membrane filtration performance (flux, flow rate, concentration, etc.). Moreover, previous studies mostly focused on the scaling removal where supersaturated feed solution was used, and the reversal period was quite long (i.e. hours) [11–13]. In the present study, we examined the feed flow reversal in a different angle to look into its culmination effect with unsaturated feed solution (i.e. standard seawater) and short reversal period (i.e. seconds), whereby the feed entered the two ends of a single-membrane module in an alternate manner. Various operating conditions of feed pressure, flow rate, concentration, and reversal period were examined, and their effects on the membrane recovery, permeate flux, and rejection were investigated. In addition, a direct comparison between the performance of the feed flow reversal and cross flow RO was conducted. Before the detailed experimental results are presented, the methodologies used in this study are first described in the following section.

2. Methodology

2.1. Cross flow and feed flow reversal RO

The schematic diagrams of cross flow and feed flow reversal RO in the single-membrane module are shown in Fig. 1. In the cross flow RO, the feed passed through the RO membrane module at the front end (upstream) and the brine comes out at the tail end (downstream). While in the feed flow reversal RO, the feed entered and brine left the RO membrane module at both front and tail ends in an alternate manner by controlling the pneumatic valves (PV)1/PV4 and PV2/PV3 in a periodical open and close manner. For both processes, the feed pressure was monitored by pressure sensors, and the flow rate and concentration of both feed and permeate were measured by flowmeters and conductivity sensors, respectively.

2.2. RO membrane module and feed solution

The RO membrane module adopted in this study was the product of SW30-2540, which was commercially available from the Dow Chemical Company. It has a total length of 40 inch, an effective area of 29 ft^2 (2.69 m^2). After each filtration test, the membrane was washed by clean water to completely remove the solute on the membrane surface.

Sodium chloride solutions with concentrations of 30, 35, and 40 g/L were used to represent the feed seawater solutions in this study.

2.3. Analysis

2.3.1. Membrane permeate flux

The membrane permeate flux is used to evaluate the membrane filtration performance of both cross flow and feed flow reversal RO in this study. The permeate flux F_P is calculated as follows,

$$F_P = \frac{Q_P}{S} \tag{1}$$

where Q_P is the permeate flow rate and S the effective surface area of the membrane module.

2.3.2. Membrane recovery

In this study, the membrane recovery is used to evaluate the feed flow reversal RO performance. The membrane recovery R_C is computed as follows:

$$R_C = \frac{Q_P}{Q_F} \times 100\% \tag{2}$$

where Q_F is the feed flow rate.

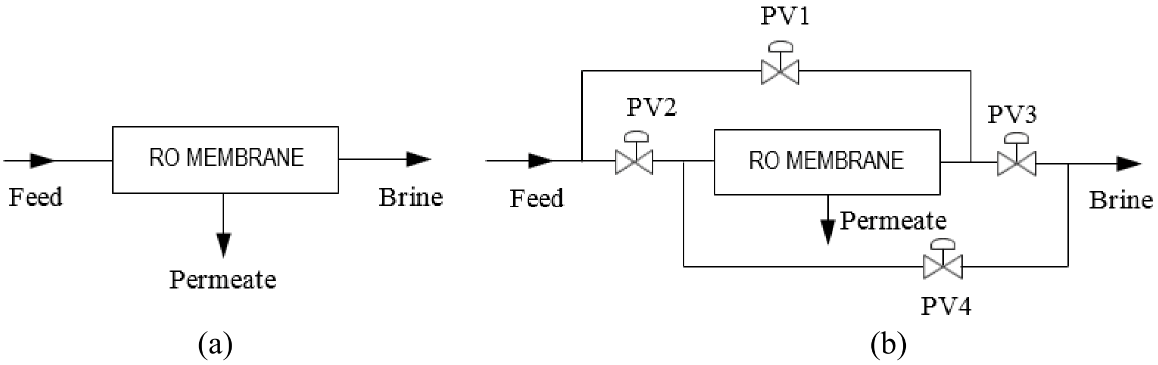


Fig. 1. Schematic diagrams of (a) cross flow reverse osmosis and (b) feed flow reversal reverse osmosis.

2.3.3. Membrane rejection

The membrane solute rejection is used in this study to evaluate the operation conditions on the membrane filtration performance of both cross flow and feed flow reversal RO. The membrane rejection R_J is calculated as:

$$R_J = \left(1 - \frac{C_P}{C_M}\right) \times 100\% \quad (3)$$

where C_M and C_P are the solute concentration at the membrane surface and permeate side, respectively. To evaluate the overall module performance, the solute concentration at the membrane surface is taken to be the feed concentration C_F, i.e. $C_M = C_F$. Higher rejection rate represents better permeate quality.

2.4. Theory

According to the solution-diffusion model [14], the water flux J_W is proportional to the pressure difference between the applied pressure and osmotic pressure,

$$J_W = A\left(P - \Delta\pi\right) \quad (4)$$

where A is the water permeability coefficient, P the applied feed pressure, and $\Delta\pi$ the osmotic pressure. For the solute, the solute flux J_S is proportional to the concentration difference across the membrane,

$$J_S = B\left(C_M - C_P\right) \quad (5)$$

where B is the solute permeability coefficient. The solute concentration on the permeate side of the membrane can be related to the water flux by the expression,

$$C_P = \frac{J_S}{J_W} \quad (6)$$

From Eqs. (3)–(6), the membrane rejection can be further expressed as,

$$R_J = \frac{A\left(P - \Delta\pi\right)}{A\left(P - \Delta\pi\right) + B} \times 100\% \quad (7)$$

3. Results and discussion

3.1. Effect of feed pressure on feed flow reversal RO

In conventional RO membrane filtration, a higher feed pressure usually provides a higher driving force, which leads to a larger permeate flow rate. The membrane module was operated at various feed pressures of 32–52 bar, and the effect of feed pressure on the feed flow reversal RO was examined. Fig. 2 shows the membrane recovery at three different feed pressures over 2.5 h filtration duration with an identical feed flow rate for the feed concentrations of 30 and 35 g/L NaCl solutions. Relatively stable recovery was obtained for all the conditions. It can also be observed that a higher feed pressure resulted in a larger membrane recovery, e.g. at feed concentration of 30 g/L NaCl solution, with a low feed pressure of 32.7 bar, a small recovery of around 15% was achieved, while with a high feed pressure of 51.3 bar, a large recovery of over 30% was obtained. This suggests that a larger quantity of permeate can be obtained when the RO membrane is operated at higher pressure with feed flow reversal. The trend is consistent with the cross flow RO, and this permeate increase shall be directly attributed to the larger driving force induced by the higher feed pressure [15,16].

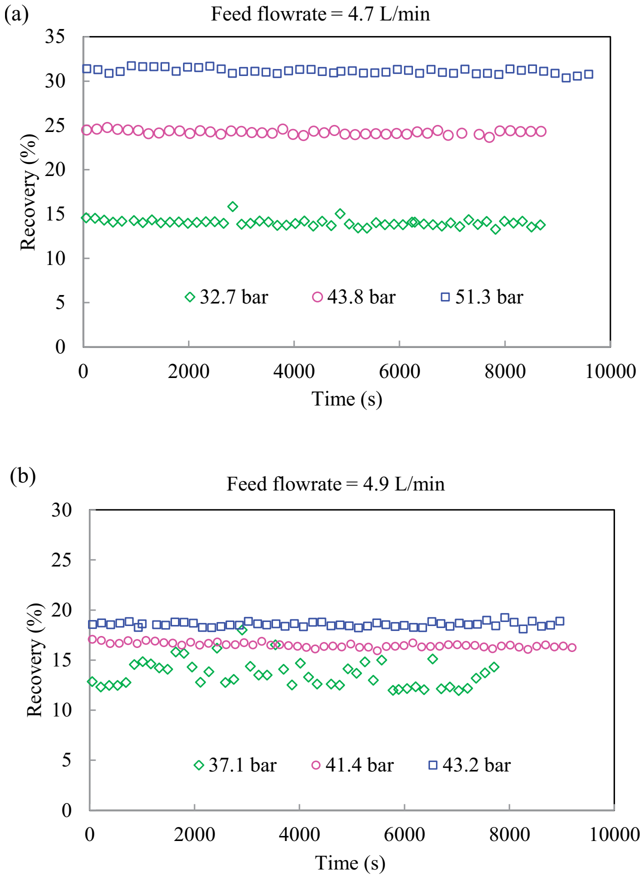


Fig. 2. Membrane recoveries of feed flow reversal reverse osmosis membrane module at different feed pressures and different feed concentrations of NaCl solutions: (a) 30 g/L and (b) 35 g/L.

3.2. Effect of feed flow rate on feed flow reversal RO

Feed flow rate is another important operating parameter in RO processes. In this study, the membrane module was operated at various feed flow rates of 4.7–5.3 L/min and the effect of feed flow rate on the feed flow reversal RO was examined. Fig. 3 shows the membrane recovery for 2.5 h operation with an identical feed pressure but different feed flow rates for both feed concentrations of 30 and 35 g/L NaCl solutions. It can be observed that similar recoveries were exhibited under different feed flow rates, i.e. about 30% and 17% for 30 and 35 g/L NaCl solutions, respectively. Compared with the feed pressure, the feed flow rate has negligible influence on the membrane recovery for feed flow reversal RO, which is probably due to the unchanged driving force for different feed flow rates. This trend is consistent with the cross flow RO and nanofiltration as well [16,17].

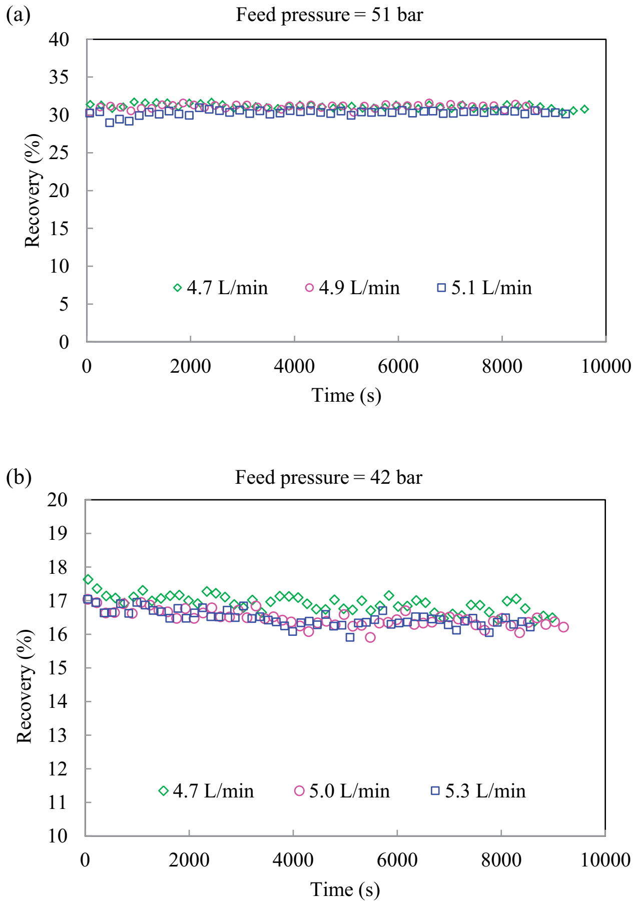


Fig. 3. Membrane recoveries of feed flow reversal reverse osmosis membrane module at different feed flow rates and different feed concentrations of NaCl solutions: (a) 30 g/L and (b) 35 g/L.

3.3. Effect of feed concentration on feed flow reversal RO

In RO membrane filtration, a higher feed concentration usually leads to a greater concentration polarization during filtration, which results in a larger membrane resistance. Fig. 4 shows the membrane recovery of three different feed concentrations of 30, 35 and 40 g/L NaCl solutions under the identical feed pressure of 43 bar and feed flow rate of 4.9 L/min for the feed flow reversal process. It can be seen that a relatively stable recovery was obtained over the 2.5-h duration for all three feed concentrations. With the increase of feed concentration of NaCl solution from 30 to 40 g/L, the recovery reduced from 24% to 13%. It suggested that the higher feed concentration had a negative impact on the membrane recovery with feed flow reversal. This is due to the fact that the osmotic pressure is higher with the larger feed concentration. Under the same applied pressure, a higher osmotic pressure implies a lower effective operating pressure thus a lower flux and recovery [Eq. (4)]. The influence of feed concentration on the feed flow reversal RO is similar to that to of the cross flow RO in both seawater and brackish water desalination systems [15,18].

3.4. Effect of period on feed flow reversal RO

In feed flow reversal RO, the direction of feed flow changes periodically. Under the operating conditions with scaling propensity, a shorter reversal period leads to more frequent mixing between the high-concentration retentate and low-concentration feed which mitigates scaling, thus the membrane filtration performance can be improved [7,11]. However, the feed flow reversal under operating conditions with undetectable scaling has not been reported before. In the present study, the membrane module was operated at various reversal periods of 56–72 s (half period of 28–36 s) for 2.5 h with a feed concentration of 30 g/L NaCl solution. Due to the low feed concentration and short reversal period, no scaling was observed in our study as expected. The membrane recovery under various reversal periods is presented in the form of combined effect of period with pressure and flow rate in Figs. 5(a) and (b), respectively. In both figures, with the increase of reversal period, the membrane recovery increased, which is different from the feed flow reversal with supersaturated solution and long reversal period [7,13,19]. This is due to the fact that feed flow reversal has a negative influence on the permeate flux since the average solute concentration along the membrane is enhanced by reversing the feed. This permeate reduction effect is obvious for fast reversal, while it is negligible in long period reversal as the reversing time (i.e. the feed flows from one end to the other) occupies a small amount in the whole reversal period [20]. At the same time, a shorter feed flow reversal period is more beneficial to mitigate scaling for supersaturated solutions. In our nonscaling condition, the potential benefits on scaling reduction and recovery improvement are not reflected.

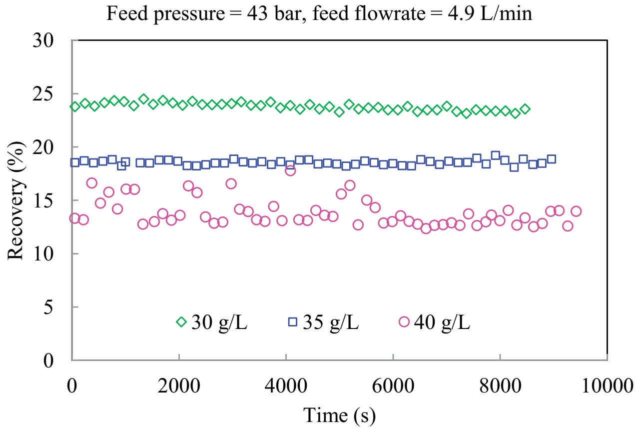
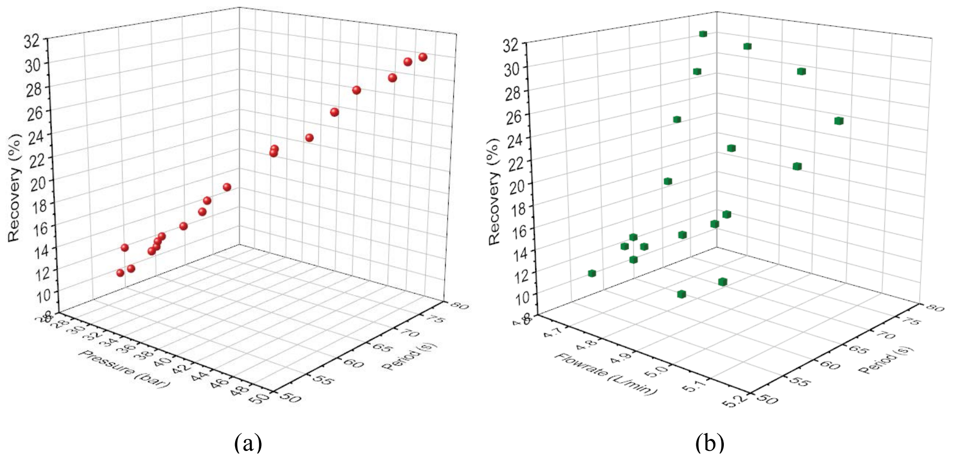


Fig. 4. Membrane recoveries of feed flow reversal reverse osmosis membrane module at different feed concentrations of NaCl solutions.

3.5. Comparison of feed flow reversal and cross flow RO

The performance of the feed flow reversal RO was compared with that of the cross flow RO. Fig. 6 shows the comparison on the permeate flux with feed concentrations of 30 and 35 g/L NaCl solutions. It was observed that a larger permeate flux was obtained at a higher feed pressure for both processes, e.g. with a feed concentration of 30 g/L, when the feed pressure was increased from 38 to 48 bar, the permeate flux increased from 21 to 31 L/(m^2 h) and 23 to 33 L/(m^2 h) for feed flow reversal and cross flow RO, respectively. By comparing these two, it was also found that under the same feed



(a) (b)

Fig. 5. Membrane recoveries of feed flow reversal reverse osmosis membrane module with the combined effect of period and (a) feed pressure and (b) feed flow rate.

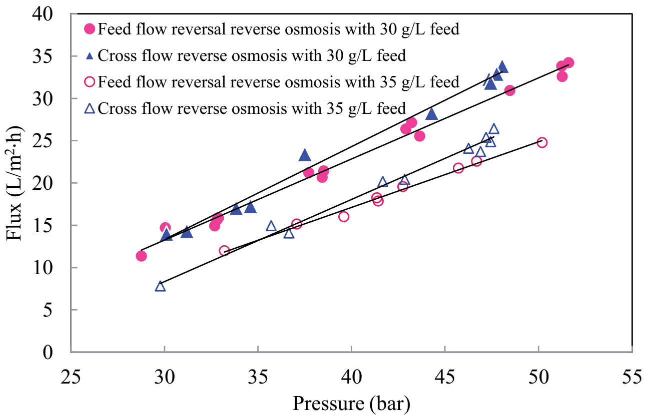


Fig. 6. Comparison of recovery between feed flow reversal reverse osmosis and cross flow reverse osmosis.

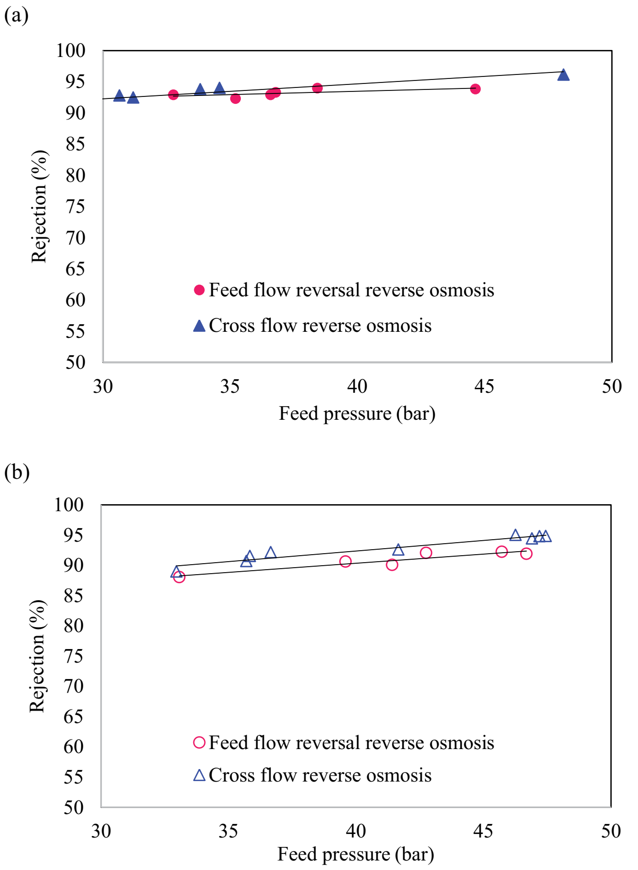


Fig. 7. Comparison of rejection between feed flow reversal reverse osmosis and cross flow reverse osmosis with different feed concentrations of NaCl solutions: (a) 30 g/L and (b) 35 g/L.

pressure, the feed flow reversal RO resulted in a slightly lower permeate flux than the cross flow RO, and the difference increased with the feed pressure. As mentioned previously, the reduction is caused by the higher average concentration over the membrane surface induced by the feed flow reversal operation.

The membrane salt rejection of feed flow reversal and cross flow RO was also evaluated, and the comparison is illustrated in Fig. 7. With a feed concentration of 30 g/L NaCl solution, when the feed pressure increased from 35 to 45 bar, the rejection increased slightly from 93% to 94% for the feed flow reversal RO, and it increased from 94% to 96% as feed pressure increased from 35 to 48 bar for the cross flow RO. Similar trend was also observed for the feed concentration of 35 g/L NaCl solution. This increase was attributed to the larger driving force by the higher feed pressure. The water flux increased and the solute flux remained the same, resulting in the increase of rejection [Eq. (7)]. It was also found that a lower rejection occurred with a higher feed concentration for both processes, e.g. at the feed pressure of 39 bar, the rejection reduced from 94% to 91% when the feed concentration increased from 30 to 35 g/L for feed flow reversal RO, and it reduced from 96% to 95% for the cross flow RO at a feed pressure of 48 bar. This decrease can be explained by the higher osmotic pressure induced by the larger feed concentration, which decreases the effective driving force and thus reduces the water flux and salt rejection [Eq. (7)]. Compared with cross flow RO, the feed flow reversal induces a slightly lower rejection, which is probably due to the higher solute concentration in the membrane element with the feed flow reversal operation, which increases the solute flux [Eq. (5)] and hence reduces the rejection.

4. Conclusions

In this study, the feed flow reversal operation in a single RO membrane module was investigated through experimental work. Experiments were performed to examine the membrane filtration performance with feed flow reversal under various operating conditions. The results showed that with feed flow reversal, the membrane recovery increased with feed pressure while it decreased with feed concentration, and the effect of feed flow rate was insignificant, which was similar to the conventional cross flow RO. Although it had been proven on previous studies that the application of feed flow reversal is beneficial to membrane scaling mitigation, we found that the feed flow reversal also enhances the average retentate concentration over the membrane, which leads to a lower membrane recovery, permeate flux, as well as rejection compared with cross flow RO. The reduction effect is especially obvious when the reversal period is short, i.e. comparable with the time for the feed to flow from one end of the module to the other. Hence, for different feed solutions, proper operation of feed flow reversal shall be applied to minimize the negative effects.

Acknowledgement

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Symbols

A	—	Water permeability coefficient, L/(m^2 h bar)
B	—	Solute permeability coefficient, L/(m^2 h)
C_F	—	Feed concentration, g/L
C_M	—	Solute concentration at membrane surface, g/L
C_P	—	Permeate concentration, g/L
F_P	—	Permeate flux, L/(m^2 h)
J_S	—	Solute flux, g/(m^2 h)
J_W	—	Water flux, L/(m^2 h)
P	—	Applied pressure, bar
PV	—	Pneumatic valve
Q_F	—	Feed flow rate, L/min
Q_P	—	Permeate flow rate, L/min
R_C	—	Recovery, %
R_J	—	Membrane rejection, %
RO	—	Reverse osmosis
S	—	Effective surface area of membrane module, m^2
$\Delta\pi$	—	Osmotic pressure, bar

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