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# Two-stage FO-BWRO/NF treatment of saline waters

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ABSTRACT

Two-stage forward osmosis (FO)–reverse osmosis (RO)/BWRO and conventional RO/BWRO processes were evaluated for saline water treatment. Three different salts, NaCl, $MgCl_2$ and $MgSO_4$, were used as a draw solution. The performance of FO, RO and BWRO regeneration processes was simulated using predeveloped software. The simulation results showed that the water and solute flux across the FO membrane decreased with increasing the FO recovery rate. The highest water flux was in case of 1.2 mol NaCl draw solution for seawater desalination. The total power consumption for seawater desalination was lower in the RO process than in the FO–RO process. However, as the RO recovery rate increased, the difference in total power consumption between the conventional RO process and 0.65 mol $MgCl_2$ FO–RO processes was insignificant. In case of brackish water desalination, the lowest specific power consumption and permeate TDS were in case of the conventional BWRO process and then followed by 0.32 mol $MgSO_4$, 0.22 mol $MgCl_2$ and 0.33 mol NaCl FO-BWRO processes. However, the specific power consumption of RO-BWRO process dropped to less than that in the conventional BWRO process when NF membrane was used for $MgSO_4$ regeneration and water extraction. In general, the high recovery rate can be achieved by the FO–RO/BWRO process which is particularly important especially in case of inland desalination.

*Keywords:* Forward osmosis; Desalination; Reverse osmosis; Brackish water desalination; Two-stage desalination

## 1. Introduction

Forward osmosis (FO) process was suggested for seawater desalination as an alternative to the conventional reverse osmosis (RO) process [1–6]. Comparing to the RO, the FO process exhibited lower membrane fouling propensity and power consumption than the RO [5,7–10]. The driving force in the FO process is the osmotic pressure gradient between the draw and feed solutions. Freshwater transports from the feed to the draw solution side of the FO membrane. Water flux across the FO membrane ceases when the difference

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in the concentrations between the feed and the draw solution is insignificant. The diluted draw solution requires further treatment for freshwater extraction and draw solution regeneration and reuse. Without draw solution recycling and reuse, the cost of FO process will be uneconomical [7–10]. The draw solution, therefore, should be carefully selected in order to maintain the cost of the FO process low. Ideally, the draw solution should be high soluble in water, cheap, readily available, environmental friendly, non-toxic and easily recycled [8–12]. The typical draw solutions used in past are $MgSO_4$, NaCl, glucose, $MgCl_2$, magnetic particles and ammonium carbon dioxide [8,13].

Different techniques were suggested for the regeneration of draw solution. Amongst the techniques were used for the regeneration of the draw solution are RO and nanofiltration (NF) filtration, membrane distillation (MD) and thermal evaporation [9–12]. Elimelech and co-workers proposed MD process for the regeneration of draw solution [9,10]. Ammonium carbon dioxide was used as a draw solution because of its high osmotic pressure. In the MD regeneration system, the draw solution will be recycled in the permeate side of the membrane leaving the freshwater behind on the other side of the membrane. Using MD for the draw solution regeneration has a number of drawbacks such as the lower recovery rate of the MD and membrane wetting [13,14]. Abdulsalam and Adel proposed using two-stage FO–NF/RO hybrid system [15]. Multivalent ionic solutions such as $MgSO_4$ and $MgCl_2$ were proposed as a draw solution when the regeneration process is carried out by an NF membrane, while RO membrane was suggested in the regeneration of monovalent draw solution such as NaCl and KCl. The NF/RO process is more energy intensive than the MD, but higher recovery rate can be achieved in the NF/RO than in the MD. Shung and co-workers used magnetic nanoparticles coated with hydrophilic polymers as a draw solution in the FO process. Although the magnetic nanoparticles exhibited high osmotic pressure, regeneration was a problem due to the agglomeration of nanoparticles [16]. Hydrogel polymers were proposed as a draw solution in the FO process because of their high osmotic pressure. Water flux across the FO membrane increased when carbon nanoparticles were added, but the excessive addition of carbon nanoparticles resulted in a flux reduction [17]. NF process was used for the regeneration of draw solution in two-stage FO–NF desalination system [14,18]. $MgSO_4$ was used as a draw solution because of the high rejection rate of the NF membranes to the divalent ions and the lower power consumption compared to the RO process. The FO–NF process was found to be more efficient than a single RO process. However, the study was carried out on the desalination of brackish water, and no information was provided about the process efficiency for seawater desalination. Additionally, the power consumption in the FO–NF system was not calculated. It should be noted here that the regeneration cost of draw solution should be added to the total cost of the desalination.

Two-stage FO–RO and FO-BWRO processes were proposed for seawater and brackish water desalination. In the first stage, FO membranes are used for feed water pretreatment, while in the second stage, RO or BWRO membranes are used for the regeneration of draw solution and freshwater extraction. Using RO and BWRO for regenerating the draw solution has a number of advantages such as high salt rejection rate, high recovery rate and high membrane flux. Despite the advantages of the RO process, its major drawback is the high power consumption. Practically, the power consumption in the RO and BWRO processes is affected by a number of factors such as feed water salinity, feed temperature, membrane permeability and feed pressure [2,5,18]. Typically, power consumption in the hyperfiltration processes increases with increasing the feed water salinity.

The study presented in this study evaluated the feasibility of FO–RO/BWRO for seawater and brackish water desalination using different inorganic salts as draw solutions. The effect of draw solution on the performance of FO–RO/BWRO process was investigated. Performance of conventional RO/BWRO was compared with the performance of FO–RO/BWRO especially in terms of specific power consumption and recovery rate. The latter parameter is of particular importance in inland saline water treatment where brine waste disposal is problematic. Three seawater salinities and two brackish water feed salinities were evaluated for the desalination by the FO–RO and the FO-BWRO processes, respectively. In the FO–RO process, the TDS of seawater feeds were 32, 38 and 45 g/L, while the feed TDS in the FO-BWRO process were 1.5, 3 and 5 g/L. The effect of draw solution type on the performance of FO–RO/BWRO was evaluated. Three types of chemical compounds were investigated as draw solution, that is MgSO4, NaCl and $MgCl_2$, because of their high osmotic pressure. Furthermore, these inorganic salts are cheap, easy to regenerate by RO/BWRO and readily available in market. A predeveloped software models were used throughout this study to estimate the performance of the FO and RO membranes [11,12]. Reverse osmosis system analysis (ROSA6.1) was used to model the performance of BW30-400 and NF90-400 membrane modules which are included in the software library. In practice, the recovery rate in RO system does not exceed 50% for seawater salinity ~35,000 mg/L because of the fouling problems and the increased power consumption. For brackish water desalination, the range of recovery rates varied between 50 and 75%. With FO pretreatment, however, higher recovery rates can be achieved in the RO and the BWRO membrane because of the high purity of draw solution. This is particularly important in case of inland desalination and brine management. In this study, the recovery rate of the second-stage FO–RO and FO-BWRO process was increased over 50 and 75%, respectively.

## 2. Methodology

Water flux in the FO and RO membranes, $J_w$, is a function of the membrane permeability and the net driving pressure across the membrane. In the RO process, the driving force is the difference between the hydraulic and the osmotic pressure of the feed solution; while in the FO process, it is the osmotic pressure gradient between the draw and the feed solution. It is assumed here that the FO process requires no or negligible hydraulic pressure for its operation. In general, water flux in the RO and FO process can be estimated from the following equation [19]:

$$J_w = A_w \times (\Delta P - \Delta\pi) \tag{1}$$

In Eq. (1), $A_w$ is the coefficient of membrane permeability (L/m$^2$ h bar), $P$ is the feed pressure (bar), and $\pi$ is the osmotic pressure on solution (bar). In this study, a conservative $A_w$ value of 0.79 L/m$^2$ h bar was used for the FO membrane [9]. A Filmtec seawater membrane SW30HRLE-400i, with $A_w$ equal to 1.13 L/m$^2$ h bar, was used for seawater desalination in the RO system . The other important parameter in the filtration process is the membrane salt permeability, $J_s$, which can be estimated from the following equation:

$$J_s = B(C_{f-in} - C_p) \tag{2}$$

where $C_{f\text{-}in}$ is the concentration of feed solution (mg/L), $B$ is the salt permeability coefficient (kg/m$^2$ h), and $C_p$ is the permeate concentration (mg/L). The $B$ factor in Eq. (3) can be estimated from the following equation:

$$B = \frac{(1 - Rj) \times J_w}{Rj} \tag{3}$$

Membrane rejection, $Rj$, is the ratio of the permeate concentration to the feed concentration, that is $Rj = 1 - (C_p/C_f)$. The membrane rejection rate increases with the membrane selectivity. The concentration of permeate, $C_p$, can be calculated from the following equation:

$$C_p = \frac{BC_{f-in}}{J_w + B} \tag{4}$$

In Eq. (4), $C_{f\text{-}in}$ is the concentration of seawater feed to the FO (mg/L). In case of the RO membrane, the permeate concentration is calculated from Eq. (5) [20]:

$$C_p = B \times C_{fc} \times CP \times Rj \times \frac{A_m}{Q_p} \tag{5}$$

where $A_m$ is the membrane area (m$^2$). Altaee et al. have explained the processes of RO and FO–RO for seawater desalination as shown in Fig. 1. The schematic diagram in Fig. 1 also applied on the brackish water desalination, but instead of the RO membrane, a BWRO membrane is used in the second filtration stage. BWRO process, usually, requires less energy for saline water treatment because the BWRO membranes have higher water permeability coefficient than the RO membranes [20]. In addition to the BWRO, NF membrane was evaluated in this study for the regeneration of draw solution and freshwater extraction. NF membranes have high rejection to divalent ions such as magnesium and sulphate. NF membranes rejection rate to $SO_4$ ions is >90% [5,11]. In the FO–NF system, FO was used in the first stage for freshwater extraction from saline solution using $MgSO_4$ draw solution. In the second stage, NF membrane was used for the regeneration of $MgSO_4$ draw solution and freshwater extraction. A Filmtec RO and BWRO/NF membranes were used in the second filtration stage for seawater and brackish water desalination, respectively. The Filmtec RO membrane was type SW30HRLE 440i, while BW30-400 and NF90-400 membranes were used in second FO-BWRO and FO–NF filtration processes, respectively.

Three inorganic metal salts were evaluated in this study as draw solutions, that is NaCl, $MgSO_4$, and $MgCl_2$, because of their (i) wide availability, (ii) high osmotic pressure, (iii) high rejection by RO membranes and (iv) high solubility in water. A number of sea water salinities were evaluated in this study. Table 1 shows the salt concentration and the composition of seawaters under investigation in this study [19]. It should be mentioned here that the feed and draw solution pressure of the FO process was assumed 1 bar and the pump efficiency, $\eta$ 0.8. The osmotic pressure of feed and draw solutions was

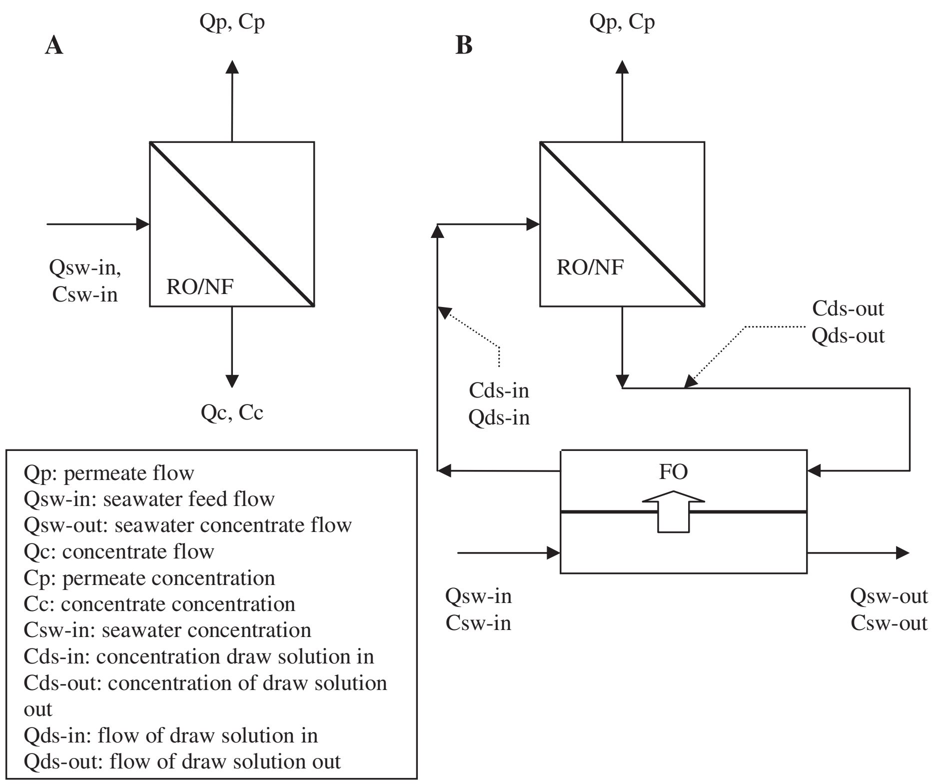


Fig. 1. RO and FO–RO processes diagram Altaee et al. [12].

Table 1
Seawater composition [19]

| SW TDS (mg/L) | Ions concentration (mg/L) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | K | Na | Mg | Ca | $HCO_3$ | Cl | $SO_4$ | $SiO_2$ |
| 32,000 | 354 | 9,854 | 1,182 | 385 | 130 | 17,742 | 2,477 | 0.9 |
| 35,000 | 387 | 10,778 | 1,293 | 421 | 142 | 19,406 | 2,710 | 1.0 |
| 38,000 | 419 | 11,663 | 1,399 | 456 | 154 | 20,999 | 2,932 | 1.0 |
| 45,000 | 496 | 13,812 | 1,657 | 539 | 182 | 24,868 | 3,472 | 1.2 |

estimated using Van't Hoff equation [20]. For simplicity, it is assumed here that the composition of all brackish water feeds is $Na^+$ and $Cl^-$ ions only.

## 3. Results and discussion

### 3.1. Performance of FO process for seawater desalination

Water and salt flux in the FO membrane was evaluated for a number of seawater salinities. Fig. 2 shows the water permeability in the FO membrane for seawater salinities 32,000, 38,000, and 45,000 mg/L. The FO recovery rates varied from 16 to 60% at 4% interval. The simulation results showed that the FO water flux decreased with increasing the seawater salinity. Increasing seawater salinity resulted in an increase in the osmotic pressure of the feed solution, and hence, the net driving force across the FO membrane decreased (Fig. 2(a)–(c)). Water flux across the FO membrane was the highest when 1.2 mol NaCl was used as a draw solution. However, the difference in water flux between 1 mol NaCl, 0.657 mol $MgCl_2$ and 1.45 mol $MgSO_4$ was insignificant due to the equal driving force generated by these draw solutions (Fig. 2(a)–(c)). Using high-concentration draw solution would not only increase water flux but also salt flux from the feed to the draw solution. This phenomenon is shown in Fig. 3(a)–(c). The simulation results showed that the highest salt diffusion occurred when 1.2 mol NaCl was used as a draw solution. This was

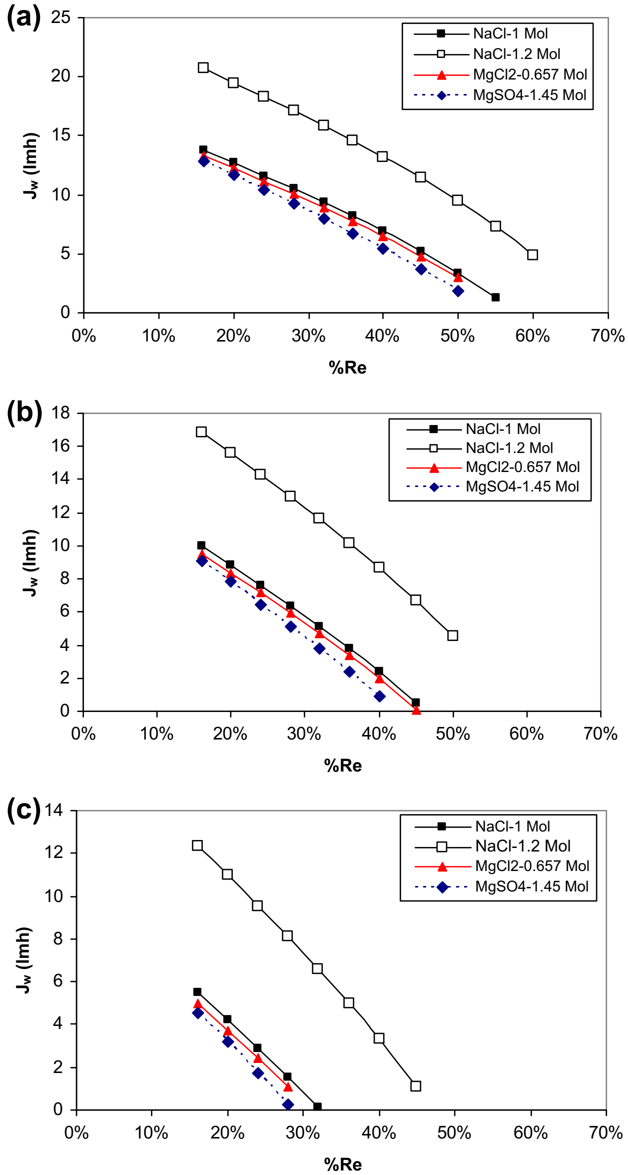


Fig. 2. Water flux through the FO at different membrane recovery rates (a) seawater salinity 32,000 mg/L (b) seawater salinity 38,000 mg/L, and (c) seawater salinity 45,000 mg/L.

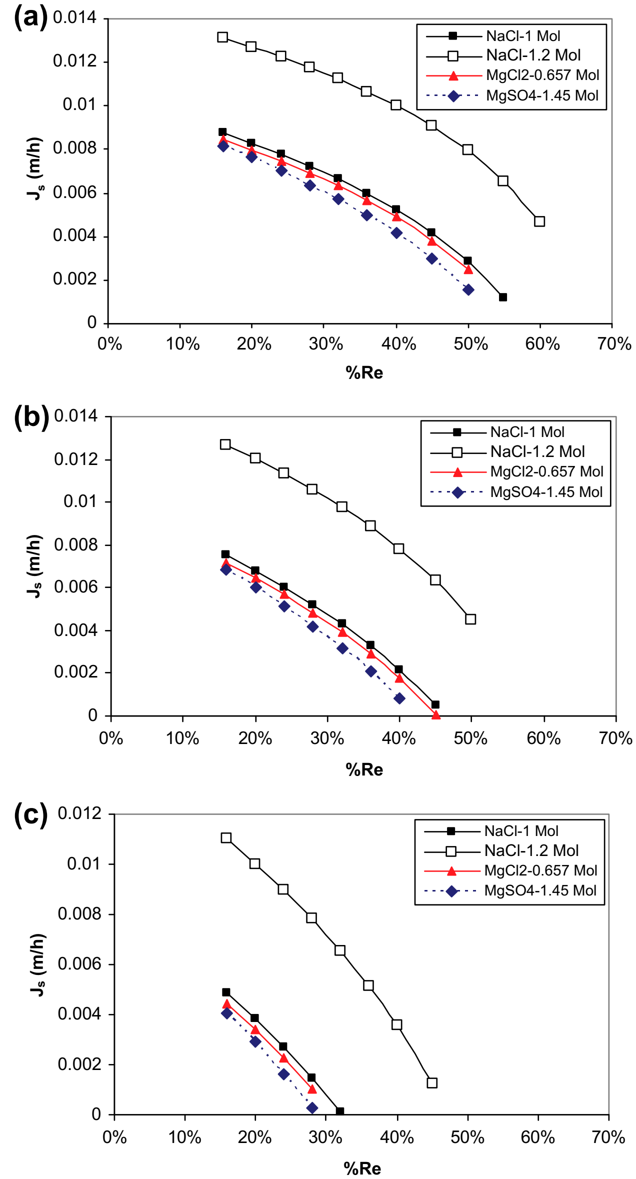


Fig. 3. Solute flux across the FO at different membrane recovery rates (a) seawater salinity 32,000 mg/L (b) seawater salinity 38,000 mg/L, and (c) seawater salinity 45,000 mg/L.

due to the higher concentrative concentration polarization on the feed side of the membrane caused by the high solvent transport towards the membrane surface. Salt diffusion from the feed to the draw solution side of the FO membrane was found to be higher at lower feed salinities (Fig. 3(a)). For example, salt diffusion at 1.2 mol draw solution was 0.013 and 0.011 m/h, respectively at 32,000 mg/L and 45,000 mg/L feed salinities (Fig. 3(a) and (c)). This trend was observed for a number of seawater and draw solution concentrations. Practically, it was due to the higher membrane flux which caused a severe concentration polarization and resulted in a higher solute accumulation at the membrane surface [10,11]. As shown in Fig. 3(a), $J_w$ was 0.013 and 0.0087 m/h at 1.2 and 1 mol NaCl, respectively. Interestingly, the differences in salt diffusion between 1 mol NaCl, 0.657 $MgCl_2$ and 1.45 $MgSO_4$ were insignificant because of the equal osmotic pressure generated by these draw solution concentrations (Fig. 3(a)–(c)).

### 3.2. Performance of FO process for brackish water desalination

Three inorganic solutes were used as the draw solution in the FO membrane, that is NaCl, $MgCl_2$, and $MgSO_4$. Two brackish water salinities, 1.5 and 3 g/L, were evaluated as the feed solution of the FO membrane. The concentration of draw solutions was 0.33, 0.22, and 0.32 for NaCl, $MgCl_2$, and $MgSO_4$, respectively, which give an equal osmotic pressure about 15 bar. Based on the osmotic pressure of these draw solution, up to 80% recovery rate can be achieved. Typically, the recovery rate of brackish water in the conventional desalination plant is around 75%. However, in the FO process, a higher recovery rate can be reached as there is no hydraulic pressure is involved, and hence, in this study, an FO recovery rate between 40 and 80% was evaluated. The results show a gradual decrease in the membrane flux with increasing the FO recovery rates from 40 to 80%. This observation applies on all osmotic agents and that was mainly due to the decrease in the osmotic pressure across the membrane at higher FO recovery rates as shown in Fig. 4(a) and (c). The results also show that the water flux across the membrane was higher at lower feed concentration or at 1.5 g/L feed concentration. Obviously, this was due to the lower osmotic pressure driving force across the FO membrane at higher feed concentration (3 g/L) (Fig. 4(a) and (c). It should be mentioned here that the water flux in case of NaCl draw solution was slightly lower than that at $MgCl_2$ and $MgSO_4$ draw solutions and that was mainly because of the lower membrane rejection rate to NaCl compared with $MgCl_2$ and $MgSO_4$. Finally, the solute flux from the feed to the draw solution side of the FO membrane is shown in Fig. 4(b). The results show a higher solute flux at 3 g/L feed TDS than at 1.5 g/L feed TDS because of the higher concentration. Solute flux across the membrane also increased with increasing the recovery rate of the FO membrane. Typically, the internal concentration polarization increases with increasing the recovery rate, and hence, a higher solute flux occurred.

In the FO-BWRO system, the feed to the second-stage BWRO membrane is the diluted draw solution from the first stage FO process. Practically, the concentration of BWRO feed solution affects the process performance in terms of energy consumption and permeate quality as will be explained in the following section. Fig. 5 shows the concentration of draw solution out, $C_{ds\text{-}out}$, at different FO recovery rates. After leaving the FO membrane, the concentration of diluted draw solution, $C_{ds\text{-}out}$ (mg/L), was in the following order; $MgSO_4$ > $MgCl_2$ > NaCl. Apparently, this was due to the higher initial concentration of $MgSO_4$ compared with $MgCl_2$ and NaCl draw solutions. In general, $MgSO_4$ solution exhibits lower osmotic pressure than $MgCl_2$ and NaCl, and therefore, a higher concentration (mg/L) of $MgSO_4$ is required to generate an osmotic pressure equal to that from $MgCl_2$ and NaCl draw solutions.

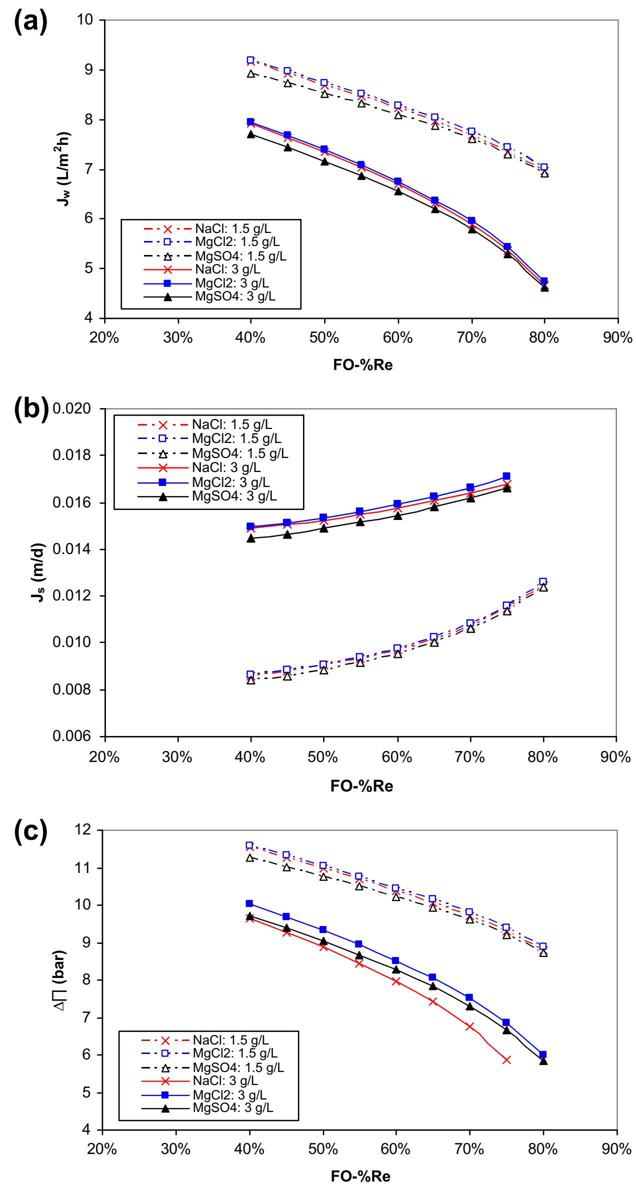


Fig. 4. FO performance at different recovery rates (a) impact on the membrane flux, (b) impact on the solute flux, and (c) impact on the osmotic pressure difference across the membrane.

### 3.3. Performance of RO, BWRO and NF membrane

A Filmtec seawater RO membrane type SW30HRLE 400i was used for the draw solution

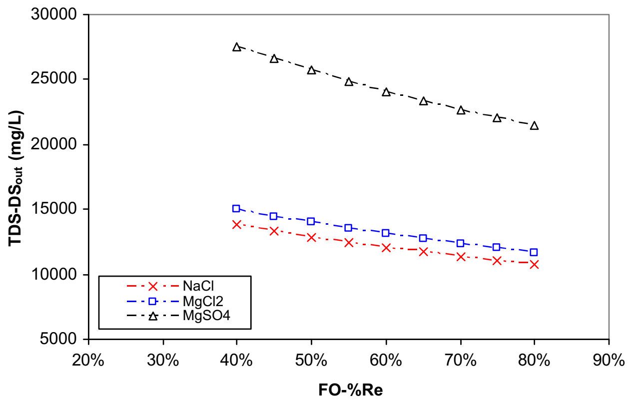


Fig. 5. The concentration of draw solution leaving the FO membrane at different FO recovery rates.

regeneration and fresh water extraction in seawater desalination. For the brackish water desalination, a Filmtec BWRO membrane type BW30-400 was used for the draw solution regeneration and freshwater extraction. In addition to the BWRO membrane BW30-400, a Filmtec NF membrane type NF90-400 was used for $MgSO_4$ draw solution regeneration and freshwater extraction. Pretreatment of sea water/brackish water is required upon using RO/BWRO membrane directly for desalination. However, in the FO-BWRO system, the feed water of BWRO membrane does not need a further treatment as FO process works as a pretreatment for the BWRO. Normally, conventional pretreatment of sea water yields SDI around three, while in case of FO pretreatment, the SDI can be as low as one. In matter of fact, this is one advantage of the FO membrane treatment to reducing the fouling propensity in the second-stage RO membrane. The specific power consumption and permeate concentration of the desalinated sea water, TDS 35 g/L, are shown in Fig. 6(a) and (b). The results show a decrease in the RO-specific power consumption at higher FO recovery rates (Fig. 6(a)). The lowest power consumption achieved was in the conventional RO process without the FO treatment followed by 0.657 mol $MgCl_2$ and 1 mol NaCl in the FO–RO system, respectively. Using 1 mol NaCl draw solution resulted in a slightly more concentrated feed solution to the RO membrane and hence increased the power consumption of RO process. Power consumption, however, decreased with increasing the recovery rate of RO system. Interestingly, the power consumption difference between the RO and the FO–RO system decreased with increasing the recovery rate of RO membrane especially in case of 0.657 mol $MgCl_2$ draw solution. These results underline the importance of draw solution in the FO

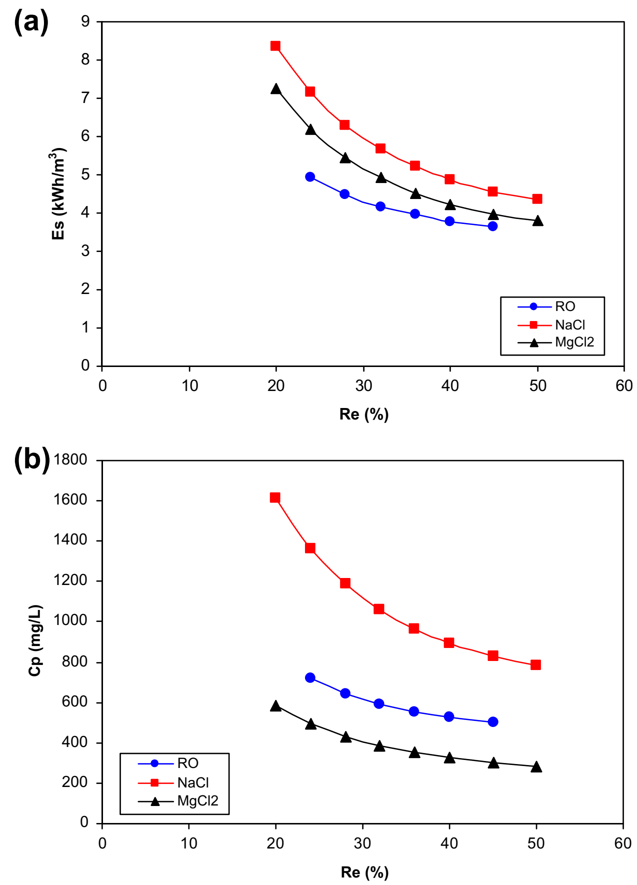


Fig. 6. RO membrane performance for seawater desalination: (a) specific power consumption in the RO, and (b) permeate TDS (feed TDS 35 g/L).

process which plays a significant role in improving the process performance. Benefiting from the high purity draw solution, the FO–RO system is able to reach high recovery rates which cannot be achieved in the conventional RO membrane system for seawater desalination. Most of the conventional RO desalination plants operate on recovery rates less than 50%. However, a recovery rate over 50% can be achieved in the FO–RO system without causing major fouling problems in the RO system. For example, 50% recovery rate was achieved in the 0.657 mol $MgCl_2$ and 1 mol NaCl FO–RO process compared to 45% in the conventional RO process (Fig. 6(a)). The other advantage of the FO–RO system is the high permeate water quality (Fig. 6(b)). 0.657 mol $MgCl_2$ exhibited the lowest permeate concentration followed by the conventional RO process and 1 mol NaCl, respectively. This was due to the higher RO rejection rate to $MgCl_2$ than to NaCl which constitutes 80% of the seawater solution. Finally, the permeate concentration in RO systems decreased with increasing the recovery rate and that was due to the higher dilution of permeate concentration in the FO membrane at higher recovery rates.

In case of brackish water, a Filmtec BW30-400 membrane was used for water desalination. Unlike sea water, brine disposal in the brackish water treatment is problematic especially in case of inland desalination. Therefore, it is preferable to achieve high recovery rates in the brackish water desalination process. Depending on the feed salinity and composition, a recovery rate of 75% or higher could be reached in the brackish water desalination process. For 3 g/L feed concentration, the higher recovery rate that could be achieved by the BWRO membrane was 70% while in the FO-BWRO system was about 75%. Higher recovery rate could also be achieved by the FO-BWRO system depending on the feed concentration. Fig. 7(a) shows the power consumption in the BWRO system at different draw solutions. The results show that the power consumption was lower in the conventional BWRO system than in the FO-BWRO system. In case of FO-BWRO system, the lowest power consumption was archived by 0.32 mol $MgSO_4$ followed by 0.22 mol $MgCl_2$ and 0.33 mol NaCl draw solutions, respectively. However, the lowest achievable specific power consumption was upon using NF Filmtec membrane NF90-400 for the regeneration of $MgSO_4$ draw solution in the FO-BWRO system (Fig. 7(a)). This was due to the high NF membrane permeability compared with the BWRO membrane, 9.9 L/$m^2$ h bar and 3.3 L/$m^2$ h bar, respectively. NF90-400 membrane rejection rate to $MgSO_4$ is >97% which makes it suitable for the regeneration of draw solution [14]. It should be mentioned here that the power consumption of the regeneration system increased slightly with increasing the recovery rate (Fig. 7(a)). For BWRO and FO-BWRO systems, lowest power consumption was achieved at 65% recovery rate while in the FO–NF system was at 60%. The reason for that is because of the feed pressure increase with increasing the recovery rate of BWRO/NF membrane system (Fig. 7(b)). As the recovery rate increases, the brine concentration, and hence its osmotic pressure, also increases, and hence, a higher feed pressure is required to overcome the osmotic pressure of the feed solution. The lowest feed pressure was in the conventional BWRO system because of the lower feed concentration (Fig. 7(b)). In case of FO-BWRO system, the lowest feed pressure was in case of 0.32 mol $MgSO_4$ draw solution followed by 0.22 mol $MgCl_2$ and 0.33 mol NaCl draw solutions, respectively. Nevertheless, more than 31% energy reduction was achieved when NF membrane was used for the regen-

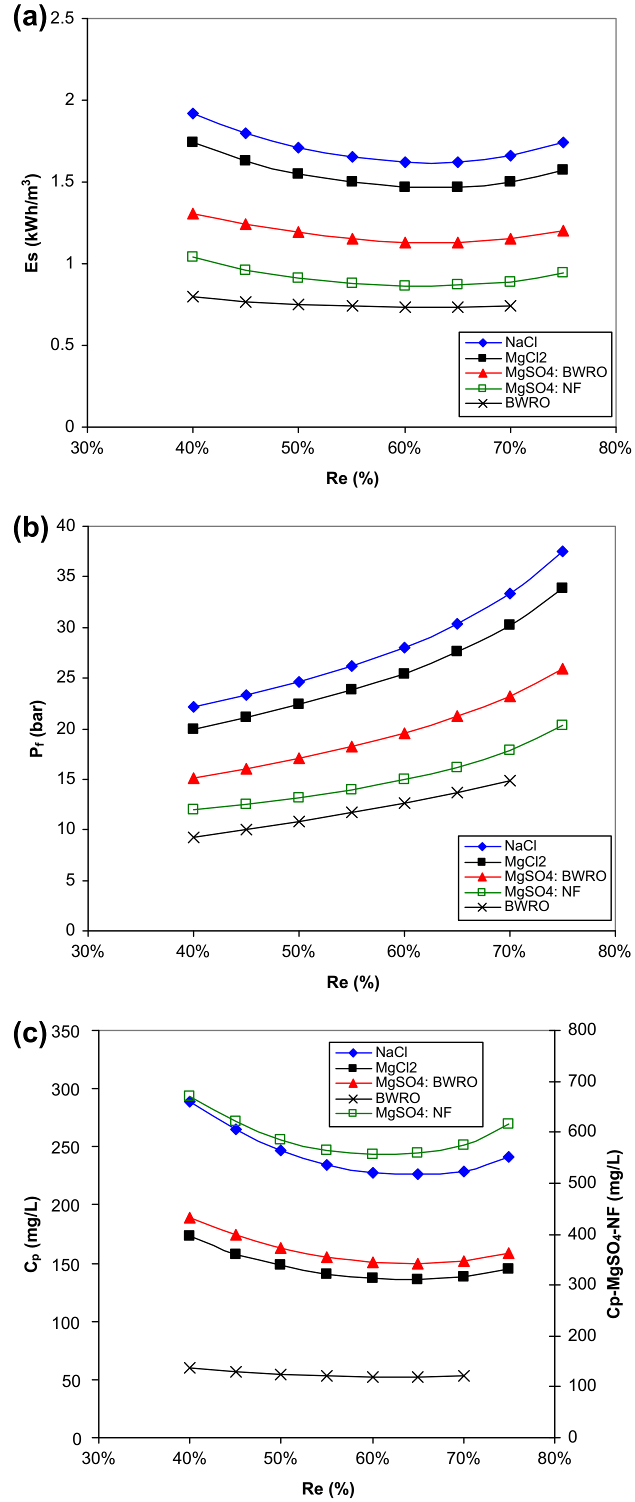


Fig. 7. Performance of BWRO and NF membranes for draw solution regeneration and fresh water extraction: (a) feed pressure, (b) specific power consumption, and (c) permeate TDS.

eration of $MgSO_4$ in the FO–NF system (Fig. 7(b)). Unfortunately, the major drawback of using NF membrane for draw solution regeneration is the high permeate concentration because of its low rejection rate to solutes (~97% to $MgSO_4$). Fig. 7(c) shows that at 75% recovery rate, the permeate concentration of the FO–NF system was 615 mg/L compared to 159 mg/L for the FO-BWRO system (0.32 M $MgSO_4$ draw solution). An additional membrane treatment is often required for the FO–NF permeate if it is meant to be used as a drinking water. Permeate concentration from the conventional BWRO system, on the other hand, was only 53 mg/L at 70% recovery rate because of the high rejection rate of the BWRO membranes.

Although FO–RO/BWRO system is less efficient in terms of power consumption and permeate quality compared to the conventional RO/BWRO system, it has a number of advantages such as higher recovery rate, lower RO/BWRO membrane fouling and less antiscalants use. It should be mentioned here that high recovery rate is particularly important in inland desalination plant in which brine management and disposal is a major problem. This problem can be alleviated by increasing the recovery rate of the desalination process if the FO–RO/BWRO system is applied. The high power consumption of the FO–RO/BWRO system can be resolved by using a combination of an engineered osmotic agent and a suitable regeneration membrane process such as NF process which can considerably reduce the power consumption. Using NF process, however, will adversely affect the permeate quality but that is not a major problem if the end-use of the product water is for domestic and human applications other than drinking water. It is also important to select a proper draw solution in order to reduce the cost of desalination by improving the FO and RO filtration processes.

## 4. Cost of FO–RO desalination system

The cost and number of FO elements required for the FO-BWRO system are shown in Table 2. The values in Table 2 are based on HTI, USA, FO membranes using 0.22 M MgCl2 as the draw solution. Three feed concentrations were evaluated in this study; 1.5, 3, and 5 g/L. The cost of HTI FO membrane type 8040FO-FS-P is about 1,719 USD/element. These membranes are made of cellulose tri-acetate with total active area of 16.5 $m^2$. The results in Table 2 and Fig. 8 show the number of FO membrane required for brackish water treatment increases with increasing the feed salinity from 1.5 to 5 g/L. This was due to the decrease in the osmotic pressure difference and hence the net driving force across the FO membrane at higher feed salinity (Fig. 4(c)). The cost of FO membrane increased with increasing the feed salinity as shown in Fig. 8. However, the difference in number of FO elements and cost between 1.5 and 5 g/L feed concentration increased with increasing the recovery rate of FO membrane (Fig. 8). This was mainly due to the reduction in the osmotic pressure driving force across the FO membrane (Fig. 4(c)). Increasing FO recovery rate would increase the concentrative concentration polarization at the feed side of the membrane, and hence, water flux decreases. For example, at 40% recovery rate, the cost of FO membrane increased by 34% when the feed concentration increased from 1.5 to 5 g/L while it increased by 65% at 75% recovery rate. However, it should noted here that the expected FO membrane life is longer than the conventional RO membrane due to the lower fouling propensity and membrane compaction problems. Unfortunately, the cost of FO membrane is rather high now, but it is expected to drop down in the near future which will makes the FO process more competitive to the conventional RO process.

Table 2
Number and cost of FO and RO membranes in the FO–RO system for desalination different seawater TDS

| | 1.5 g/L feed | | | 3 g/L feed | | | 5 g/L feed | | |
|---|---|---|---|---|---|---|---|---|---|
| (% Re | A ($m^2$) | No Elm. | Cost USD × $10^6$ | A ($m^2$) | No Elm. | Cost USD × $10^6$ | A ($m^2$) | No Elm. | Cost USD × $10^6$ |
| 40 | 136,041 | 8,245 | 14.17 | 157,116 | 9,522 | 16.37 | 20,650 | 1,252 | 21.5 |
| 45 | 139,408 | 8,449 | 14.52 | 162,853 | 9,870 | 16.97 | 21,885 | 1,326 | 22.8 |
| 50 | 142,947 | 8,663 | 14.89 | 169,246 | 10,257 | 17.63 | 23,374 | 1,417 | 24.4 |
| 55 | 146,735 | 8,893 | 15.29 | 176,565 | 10,701 | 18.39 | 25,248 | 1,530 | 26.3 |
| 60 | 150,886 | 9,145 | 15.72 | 185,236 | 11,226 | 19.30 | 27,739 | 1,681 | 28.9 |
| 65 | 155,581 | 9,429 | 16.21 | 195,979 | 11,878 | 20.42 | 31,308 | 1897 | 32.6 |
| 70 | 161,120 | 9,765 | 16.79 | 210,115 | 12,734 | 21.89 | 37,036 | 2,245 | 38.6 |
| 75 | 168,059 | 10,185 | 17.51 | 230,388 | 13,963 | 24.00 | 48,160 | 2,919 | 50.2 |

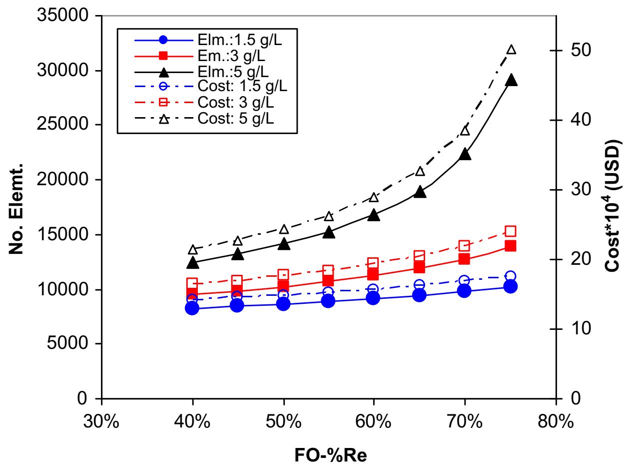


Fig. 8. Number and cost of FO element at different FO recovery rates and feed concentrations.

## 5. Conclusion

This study investigated the effect of draw solution on the performance of FO–RO and FO-BWRO systems, respectively, for seawater and brackish water desalination. For seawater and brackish water desalination, water flux decreased with increasing the recovery rate of FO process. This trend was also observed in the solutes flux across the FO membrane for seawater desalination. However, for brackish water desalination, solutes flux increased with increasing the FO recovery rates. In general, power consumption of seawater desalination was lower in the conventional RO process than in the FO–RO system. However, the difference of power consumption between the RO and the FO–RO system decreased with increasing the RO recovery rate. Interestingly, a higher recovery rate can be reached in the RO with FO pretreatment than in the conventional RO process. In case of brackish water desalination, the power consumption in the conventional BWRO process was lower than that in the FO-BWRO system, but the recovery rates of the conventional BWRO process were lower than that can be achieved by the FO-BWRO system. Using FO–NF system was able to reduce the cost of brackish water desalination due to the higher permeability of NF compared to BWRO membrane but that was on the cost of the permeate water TDS. The results from this study also showed that the energy requirements of FO desalination are affected by the type of draw solution, and hence, more research and experimental work need to be done in that area. One advantage of the FO-BWRO process is the high recovery rate which is a key parameter in inland brackish water desalination due to the increasing concerns about brine disposal. The cost of membrane was found to increase with increasing the feed TDS because of the lower membrane flux. Finally, more experimental work required to demonstrate the feasibility of FO-RO/BWRO desalination due to the constraints in ROSA and other software used in this study.

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