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Nanofiltration separation of highly concentrated multivalent electrolyte draw solution; a pilot plant study

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ABSTRACT

Nanofiltration membrane system is proposed for the regeneration of draw solution in a two-stage forward osmosis (FO) process. Pilot plant experiments were carried out on two types of multivalent electrolyte draw solutions, $MgSO_4$ and $MgCl_2$. Two commercial size NF90-4040 Filmtec Nanofiltration (NF) membranes were packed in a high-pressure vessel for the regeneration of draw solution. The concentrations of the draw solution used were between 20 and 118 g/L. The impact of feed concentration, flow rate and feed pressure on the performance of NF membrane was investigated. Both metal salts have shown a high rejection rate by the NF membrane. The rejection rate to the $MgSO_4$ was slightly higher than that to the $MgCl_2$. Experimental results showed that NF rejection rate and permeate flow rate increased with increasing the feed pressure and flow rate but decreased with increasing the concentration of feed solution. However, this was achieved at the expense of higher power consumption. In general, the efficiency of NF system for the regeneration of draw solution was higher at lower feed concentration. This suggests that NF separation method is probably more suitable for the regeneration of low concentration draw solution which is generated from brackish water FO treatment plants. Furthermore, NF application in the regeneration of high-concentration draw solution is not yet feasible due to the limitations in the NF process such operating feed pressure and rejection rate.

Keywords: Draw solution regeneration; Nanofiltration; Electrolyte rejection; Seawater desalination; Membrane desalination

1. Introduction

Although the concept of nanofiltration (NF) separation is a relatively new, it has found wide applications in food industries, pharmaceutical and water and wastewater treatment [1–5]. NF membranes have been in the market for more than two decades now. They gained popularity in the last few years due to the rapid advance in membrane technology. Today, NF membranes are made of different materials including aromatic polyamides [6,7], polyacrylonitrile [8], polysulfones [6], or polyphenyleneoxide [9] and are available with different permeabilities to provide water flux between 10 and 100 L/m^2 h at a low pressure of 10 bar. High fluxes, low feed pressure and fouling propensity of NF membrane reduce power consumption of the filtration process [1]. These distinguished

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features made NF process the preferable separation technique in many manufacturing industries [3–5].

NF is, commonly, considered as an intermediate process between ultrafiltration (UF), reverse osmosis (RO) membrane filtration processes. Due to the loose structure of the membrane, it offers higher membrane flux than RO membranes. Compared with microfiltration (MF) and ultrafiltration (UF) membrane filtration processes, NF process exhibits higher retention capacity to organic matters, synthetic dyes, antibiotics and all viruses. With molecular weight cut-offs (MWCO) between 200 and 2,000 Dalton, NF membrane is capable of retaining most of the divalent and multivalent ions in the aqueous solution [1,3]. The separation mechanisms of NF membrane is a coupling of steric (sieving) effects and electric (Donnan) effects which take place at the external solution–membrane surface interface [10]. Uncharged molecules and colloids transport to the membrane surface by convection and diffusion due to the pressure and chemical gradients, respectively. Sieving effect is the only separation mechanism which is responsible for the retention of uncharged solutes such as some organic substances. For the charged particles, the separation mechanism takes place at the membrane–solution interface due to the electrostatic interaction (Donnan effects) between membrane and charged particles. Sieving and electric effects are effectively the separation mechanisms of divalent ions in the draw solution such as $MgSO_4$ and $MgCl_2$ [1,10].

NF membrane rejection rate to divalent ions, such as $MgSO_4$, is more than 98% [11,12]. Furthermore, NF process has lower retention to monovalent ions and requires less energy demands than RO for operation. These unique features make NF process a suitable technology for the regeneration of multivalent draw solution. Practically, forward osmosis (FO) process takes place prior to the NF process in a dual-stage membrane filtration system for saline water treatment [11]. A divalent or multivalent metal salt is applied as the draw agent of the FO process. Freshwater transports from seawater to the draw solution due to the osmotic pressure gradient across the membrane. Diluted draw solution is normally treated by thermal or membrane processes for freshwater extraction and draw solution recycling and reuse. The type of membrane used for the regeneration of draw solution depends mainly on the draw solution type and concentration. Therefore, NF membrane was proposed for the regeneration of large molecular weight draw solution such as $MgSO_4$ and $MgCl_2$ [11,12]. During the FO process, monovalent ions, mainly Na^+ and Cl^-, are diffused from the feed to the draw solution and contaminating the draw solution. These ions are partially rejected by the NF membrane because of their low molecular weight. Therefore, they can be removed from the regenerated draw solution, but further treatment may be required for the removal of any ions in the permeate solution if their concentration is undesirably high.

The attractiveness of NF membranes is not only due to their high rejection of macromolecules and some small molecules, but also due to their unique performance which only allows mostly monovalent ions to pass through the membrane. As such, this is a useful feature to remove monovalent ions from the feed solution. High fluxes, low feed pressure and fouling propensity of NF membrane reduce power consumption of the filtration process. Therefore, NF is more energy efficient than the RO process.

During the filtration process, the performance of NF membranes is affected by a number of operating parameters such as feed flow rate, feed pressure and feed concentration. Variation in these operating parameters will affect the performance of NF process in terms of permeate water quality, power consumption and recovery rate. Previous studies evaluated the performance of NF membrane in the treatment of feed concentrations between 2 and 25 g/L and NF rejection rates were measured at different feed pressures and flow rates [13–16]. For seawater desalination, high-concentration draw solution is usually applied for freshwater extraction from seawater. The diluted draw solution is regenerated by membrane treatment for recycling and reuse. The data available on the performance of NF membrane at high feed concentrations are rather scarce. Furthermore, there are no pilot plant tests that have carried out to investigate the performance of NF membrane at high feed concentration. In the current study, a pilot plant study was carried out to evaluate performance and efficiency of NF membranes in regenerating a diluted multivalent draw solution. Two 4 inch Filmtec NF90-4040 membrane modules were packed in a high-pressure vessel. Two divalent draw solutions, $MgCl_2$ and $MgSO_4$, were evaluated for the NF treatment at feed concentrations varied from 34–118 g/L to 12–35 g/L, respectively. The impact of feed pressure, flow rate and concentration on the NF performance was investigated and the potential of NF process for the regeneration of draw solution was evaluated.

2. Experimental work

2.1. Membrane and feed solution

Two NF membranes type NF90-4040 were procured from Desal supplier, the UK. NF90-4040 is a thin-film composite membrane made of aromatic polyamide, material and finished with polysulphone coating. With an active area equals to 7.6 m^2, the spiral wound module provides high water permeability and rejection rate to multivalent ions, nitrate, iron and organic compounds. The rejection rate of NF90-4040 to $MgSO_4$ is more than 97% (concentration of feed solution 2,000 ppm). Furthermore, the membrane can tolerate feed pressure up to 41 bar and feed pH between 2 and 11. Water and salt permeability coefficients, Aw and B, respectively, of NF90-4040 membrane were estimated using the following formula:

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

$$B = \frac{(1 - R_j)}{R_j} J_w \tag{2}$$

In Eq. (1), J_w is the membrane flux (L/m^2 h), A_w is the water permeability coefficient (L/m^2 h bar), ΔP is pressure difference across the membrane (bar) and $\Delta\pi$ is the osmotic pressure of the feed solution (bar). In Eq. (2), B is solute permeability coefficient (m/d) and R_j is the membrane rejection rate (%). A_w and B factors of NF90-4040 membrane were 10 L/m^2 h bar and 0.0309 m/d, respectively. More information about the NF90-4040 membrane can be found in Table 1.

A laboratory grade magnesium sulphate heptahydrate ($MgSO_4 \cdot 7H_2O$) and magnesium chloride ($MgCl_2$), purity more than 99%, were ordered from Sigma-Aldrich Company, the UK. Chemicals were dissolved in deionized (DI) water (conductivity less than 5 μs) using mechanical stirrer (Fig. 1) to make the feed solution of the NF membrane system. The feed solution kept in a 260-L storage tank. Different $MgSO_4$ and $MgCl_2$ concentrations were used as the NF feed solution. These concentrations represent the diluted draw solution generated from seawater and brackish water FO desalination process. Table 2 shows the concentrations of diluted draw solutions from the FO process for seawater and brackish water desalination. After leaving the FO membrane system, the diluted draw solution goes to an NF system for regeneration and reuse. The upper and lower ranges of feed and draw concentrations are presented in Table 3 [17,18].

Table 1
Characteristic of nanofiltration Filmtec membrane NF90-4050

Characteristics	Value
Membrane type	Polyamide thin-film composite
Maximum operating pressure	41 bar
Maximum operating temperature	40°C
Free chlorine tolerance	<0.1 ppm
pH range, continuous operation	2–11
pH range, short-term cleaning (30 min)	1–12
Maximum feed flow	1.4 m^3/h
Maximum feed silt density index	SDI 5
Membrane active area	7.6 m^2

2.2. Experimental set-up

The pilot plant was designed at Surrey University, the UK and manufactured by Axium Process Ltd, the UK. A schematic diagram of the pilot plant is shown in Fig. 1. Two Filmtec membranes type NF90-4040 are packed in a high-pressure vessel which can stand a maximum pressure of 69 bar (1,000 psi). The feed solution has the capacity of 260 L and provided with an overhead mechanical stirrer and connected. A variable-speed high-pressure pump is connected to the feed tank and can deliver up to 60 bar hydraulic pressure.

The plant is provided with a needle valve mounted on the NF concentrated brine line to adjust the feed pressure (Fig. 1). The temperature and pressure of the feed and concentrate flows were measured by a number of gauges mounted on designated pipes. Two rotameters were provided to measure the flow rates of permeate and concentrated brine. However, it was found that rotameters were not very accurate; hence, the flow rates were measured manually by collecting the volumes of permeate or concentrate over certain time intervals. It should be noted here that permeate and concentrate flows were recycled back to the feed tank. NF membranes were washed with DI water at the end of each experiment to ensure the removal of any salt ions trapped on the membrane surface.

2.3. Testing procedure

Samples from the feed and concentrate streams were collected and analysed for salt concentration measurement. Conductivities were measured using a conductivity meter type Multi Seven, Mettler Toledo, Switzerland. All samples were measured at room temperature, 25°C. The impact of feed concentration, flow rate and pressure on the NF performance was evaluated in separate experiments, and NF membrane cleaned with DI water after each experiment. Furthermore, a separate experiment was carried out to evaluate the rejection rate of NF90-4040 membrane over time using 68 g/L $MgSO_4$ as the feed solution.

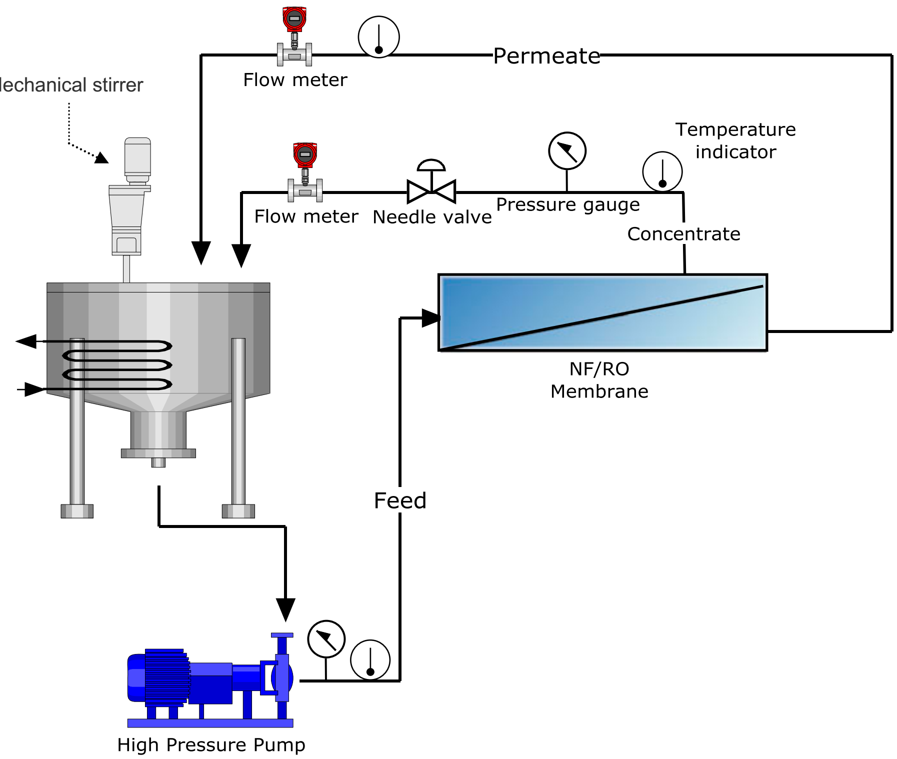

Fig. 1. Schematic diagram of the pilot plant.

Table 2
NF feed concentrations and osmotic pressures

$MgSO_4$ concentration (g/l)	Osmotic pressure (bar)	$MgCl_2$ concentration (g/l)	Osmotic pressure (bar)
118	23	35	27
112	21.1	29	22.2
72	13.5	22	15.5
44	8.7	16	11.1
38	7.5	12	7.9
34	6.8		

Table 3
Operating parameters of FO and diluted draw solution concentration

Draw solution	Concentration (g/L)	Feed solution	Concentration (g/L)	%recovery rate	NF feed concentration (g/L)
$MgSO_4$	174.5	SW	35	45	118
	38.5	BW	5	15	34
$MgCl_2$	62.5	SW	35	SW osmotic equilibrium	35
	20.9	BW	1.5	70	12

At 25 L/min feed flow rate and 38.5 bar feed pressure, NF rejection rate to $MgSO_4$ solution was 97.4% after 1 min, but it stabilized after 40 min and reached 99% after 60 min (Fig. 2). Accordingly, it was recommended that tests should be carried out for about 45–60 min before any results are taken.

3. Results and discussion

3.1. Effect of feed concentration

To investigate the impact of feed concentration on the rejection rate of NF membrane, $MgSO_4$ and $MgCl_2$ were used as the feed solutions of the NF system. Membrane recovery rate, $\%R$, was calculated from the following equation:

$$\%R = \frac{Q_p}{Q_f} \times 100 \quad (3)$$

where $\%R$ is the recovery rate, Q_p is permeate flow and Q_f is feed flow. The membrane rejection rate, $\%R_j$, is the ratio of ions concentration in the permeate to ions concentration in the feed solution as following:

$$\%R_j = 1 - \frac{C_p}{C_f} \quad (4)$$

where C_p and C_f represent permeate and feed concentrations (mg/L), respectively. Four $MgSO_4$ concentrations 34, 44, 72 and 112 g/L and three $MgCl_2$ concentrations 22, 29 and 35 g/L were investigated as the feed solutions of NF system. The impact of increasing the feed concentrations on the rejection rate of NF membrane is shown in Fig. 3(a). The experimental results show that salt retention by NF membrane decreased with increasing the feed concentration of $MgSO_4$ and $MgCl_2$. This was due to the lower membrane flux (Fig. 3(b)) and the higher salt diffusion across the membrane at higher feed concentrations. Typically, increasing feed concentration results in a higher feed osmotic pressure hence lower permeate flow as shown in Eq. (1).

Salt diffusion across the membrane, J_s (kg/m^2 h), also increases with increasing the feed concentration the following [19]:

$$J_s = B(C_m - C_p) \quad (5)$$

where B is the salt diffusion coefficient (m/d), C_m is the salt concentration at the membrane surface (mg/L) and C_p is the salt concentration in the permeate flow (mg/L). The coupled effect of lower

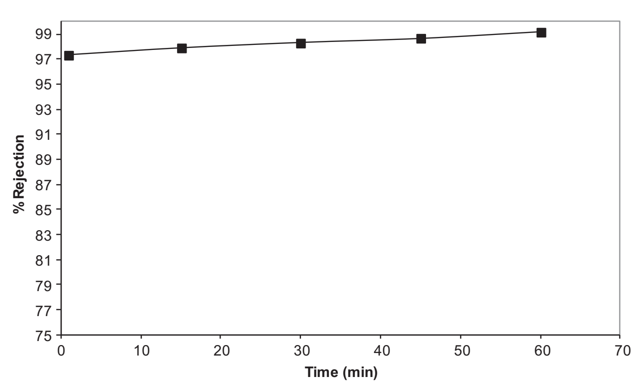

Fig. 2. MSO_4 rejection rate with time; testing parameters: feed concentration 61 g/l $MgSO_4$, feed pressure 38.5 bar, flow rate 25 l/min.

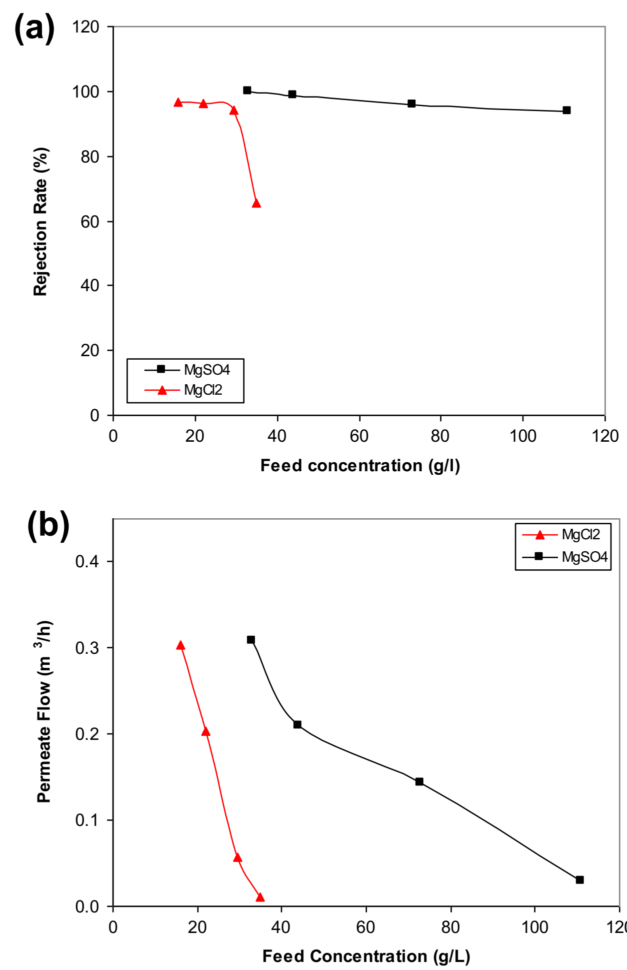

Fig. 3. Impact of feed concentration on the NF performance (a) rejection rate and (b) permeate flow; feed flow rate 13 L/min and feed pressure 35 bar.

membrane flux and higher salt diffusion caused by higher feed concentration resulted in a lower NF rejection rate. The pilot plant results show that $MgSO_4$ rejection rate decreased from 99.8 to 93.6%, when the feed concentration increased from 33 to 112 g/L (Fig. 3). $MgCl_2$ rejection rate, however, was lower than $MgSO_4$ even though it was at lower concentrations in the feed solution. NF rejection rate to $MgCl_2$ was over 96.6% at 16 g/L feed solution and then decreased to 96% at 22 g/L and dropped to about 65.5% at 35 g/L feed concentration (Fig. 3(a)). In general, NF membranes have higher rejection to $MgSO_4$ than $MgCl_2$; this is attributed to the higher electrostatic repulsion forces between the membrane and the 2–2 $MgSO_4$ salt [20,21]. The higher the rejection rate, the better the regeneration process is. In fact, higher membrane rejection rate is highly desirable to minimize the losses of draw solution in the regeneration process. However, using $MgSO_4$ in the draw solution has a major drawback because of its low osmotic pressure (Table 1). Therefore, high draw solution concentrations are required, especially for the desalination of seawater. The osmotic pressures of $MgSO_4$ and $MgCl_2$ were calculated at different feed concentrations using OLI Stream Analyzer 2.0, OLI System Inc, (Fig. 4). $MgSO_4$ and $MgCl_2$ osmotic pressures were around 10 bar at, respectively, 55 g/L and 15 g/L feed concentrations. This indicates that $MgSO_4$ draw solution should be 3.5 times more concentrated than $MgCl_2$ draw solution to provide the same osmotic driving force in the FO membrane. However, the main advantage of using $MgSO_4$ is the relatively high rejection rate by NF membrane (Fig. 3(a)).

Permeate TDS is another important parameter because it affects the product water quality. Fig. 5(a) shows the TDS of NF permeate for both $MgSO_4$ and $MgCl_2$ feed solutions. In general, the permeate TDS was rather high and it requires further treatment to bring it down to an acceptable level. This observation holds for most of the $MgSO_4$ and $MgCl_2$ feed concentrations. However, experimental results show that the TDS of permeate was about 66 mg/L, when 34 g/L $MgSO_4$ was the feed solution of the NF membrane system. As matter of fact, the osmotic pressure of 34 g/L MgSO4 feed solution is 6.8 bar (Table 1); this feed concentration resembles the concentration of diluted draw solution generated from the FO treatment of brackish water. However, at 112 g/L $MgSO_4$ feed solution, the permeate TDS increased to 7,000 mg/L. In such cases, a further membrane treatment is recommended to reduce the permeate concentration on the desirable level.

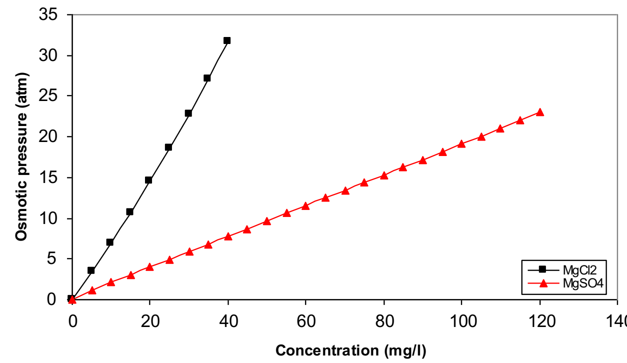

Fig. 4. Osmotic pressure of $MgSO_4$ and $MgCl_2$ as a function of feed concentration.

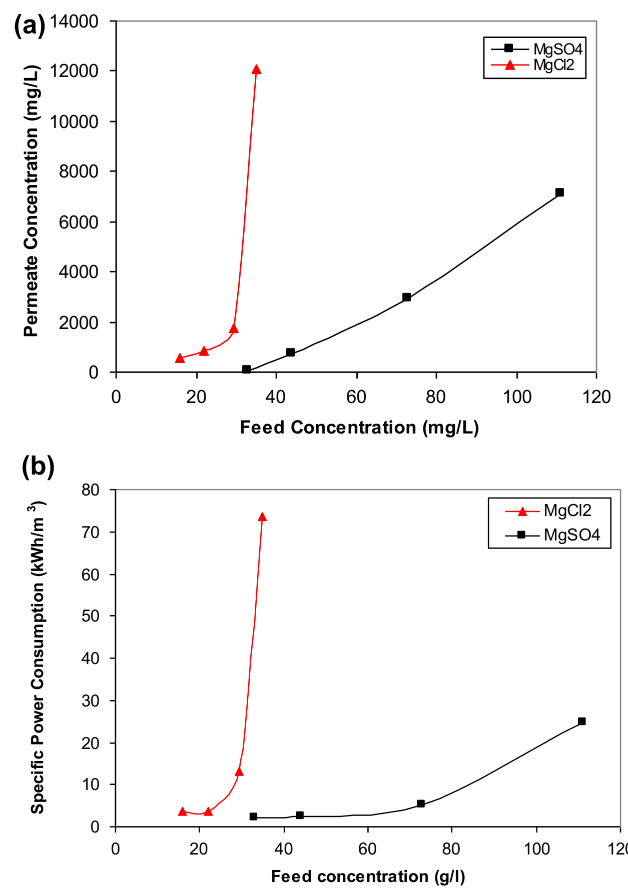

Fig. 5. Permeate concentration at different feed concentrations (a) permeate TDS and (b) specific power consumption; feed flow rate 13 L/min and feed pressure 35 bar.

Finally, the impact of feed concentration on the power consumption of NF process is illustrated in Fig. 5(b). The specific power consumption, E_s (kWh/m^3), was calculated from the following equation:

$$E_s = \frac{P_f \times Q_f}{Q_p \times \eta} \quad (6)$$

where P_f is the feed pressure (bar), Q_f is the feed flow rate (m^3/h) and η is the pump efficiency which is assumed 0.8 in the current study. In Eq. (6), Q_p/Q_f is the recovery rate of the membrane, hence E_s can also described as function of membrane recovery. As such, lower E_s can be achieved by increasing the membrane recovery rate. E_s of NF process increased with increasing the concentration of feed solution due to the higher osmotic pressure and the concentration polarization effect at the NF membrane surface [13]. The lowest E_s was in case of using 33 g/L $MgSO_4$ feed concentration, whereas the highest E_s was in case of using 35 g/L $MgCl_2$ feed concentration. The highest power consumption required for the treatment of 35 g/L $MgCl_2$ feed solution was attributed to its higher osmotic pressure which was about 27 bar. At 35 g/L $MgCl_2$ feed concentration, the recovery rate of NF membrane was as low as 1.3% and this resulted in a very high E_s value. However, the results show that E_s was significantly high, especially at high feed concentrations which make NF regeneration process a less attractive option.

3.2. Effect of feed pressure

Most of the commercial NF membranes are designed to operate at maximum feed pressure around 40 bar. The impact of feed pressure on the performance of NF90-4040 is illustrated in Fig. 6. $MgSO_4$ and $MgCl_2$ were the feed solutions of the NF membrane system to be regenerated for reuse in the FO membrane.

In general, NF rejection rate to $MgSO_4$ and $MgCl_2$ increased with increasing the feed pressure from 30 to 45 bar (Fig. 6(a)). NF rejection rate to 118 g/L feed concentration increased from 91.8 to 97.8%, when the feed pressure increased from 35 to 45 bar. Practically, membrane flux increased with increasing the feed pressure and diluted ions concentration of the permeate flow (Fig. 6(b)). For example, at 118 g/L $MgSO_4$ feed concentration, there was 57% increase in the permeate fluxwhen the feed pressure increased from 35 to 45 bar. Results in Fig. 6(a) also show that rejection rate decreased with increasing the concentration of feed solution; hence it was lower at 118 g/L than 72 g/L $MgSO_4$ feed concentration. Furthermore, the lowest NF rejection rate was about 68% for 35 g/L $MgCl_2$ feed solution and 35 bar feed pressure. However, NF rejection rate to $MgCl_2$ increased to 95%, when the feed pressure increased to 45 bar. Apparently, $MgSO_4$ solution is more suitable for the NF treatment than $MgCl_2$ solution.

The impact of increasing the feed pressure on the permeate quality is illustrated in Fig. 6(c). Permeate TDS decreased with an increase in the feed pressure; this observation applied on $MgSO_4$ and $MgCl_2$ draw solutions and it is attributed to the higher membrane flux at elevated feed pressures (Fig. 6(b)). Results also show that the permeate TDS was higher, when $MgCl_2$ was the feed solution of the NF membrane. Primarily, this was due to the lower NF membrane rejection rate to $MgCl_2$. On the other hand, it is important to consider the practical operating feed pressure of NF system which should not exceed 45 bar in this case. For example, at 118 g/L $MgSO_4$ feed concentration, the permeate TDS was 9,620 and 2,577 mg/L at 35 bar and 45 bar feed pressures, respectively. Whilst permeate TDS for 35 g/L $MgCl_2$ feed solution was 11,226 mg/L and 1,692 mg/L at 35 and 45 bar feed pressures, respectively. These results indicate that at high feed concentrations, (i) permeate TDS was relatively high and further treatment is required to reduce its concentration to the desirable level (ii) NF membrane should be operated at the maximum design feed pressure for the regeneration of highly concentrated draw solutions. In a long term, this will affect the NF performance due to the higher membrane compaction. At lower feed concentration, the TDS of permeate was relatively acceptable provided that NF system operating at maximum feed pressure. For example, the concentration of permeate was about 490 mg/L at 72 g/L $MgSO_4$ feed solution and 45 bar feed pressure. Therefore, NF membrane treatment is probably more suitable for low concentration feed solution which consists of a solution of large molecular weight such as $MgSO_4$. Alternatively, further membrane treatment is probably required to reduce the TDS of permeate flow at high feed concentrations.

Clearly, permeate TDS can be reduced by increasing the feed pressure, hence the impact of using high feed pressures on power consumption should be investigated. Fig. 6(d) shows the impact feed pressure on the specific power consumption, E_s (kWh/m^3), of the NF membrane system. E_s, in general decreased with increasing the feed pressure due to the higher permeate flow as shown in Eq. (6). Interestingly, E_s reached a staggering value of 135 kWh/m^3, when 35 g/L $MgCl_2$ feed solution was treated by the NF membrane at 35 bar feed pressure. E_s, however, decreased to 23.3 kW/m^3, when the feed pressure increased to 45 bar. The lowest E_s was achieved, when $MgSO_4$ was the feed solution. This was probably due to the lower osmotic pressure of $MgSO_4$ compared to $MgCl_2$ feed solution (Table 4) which required less

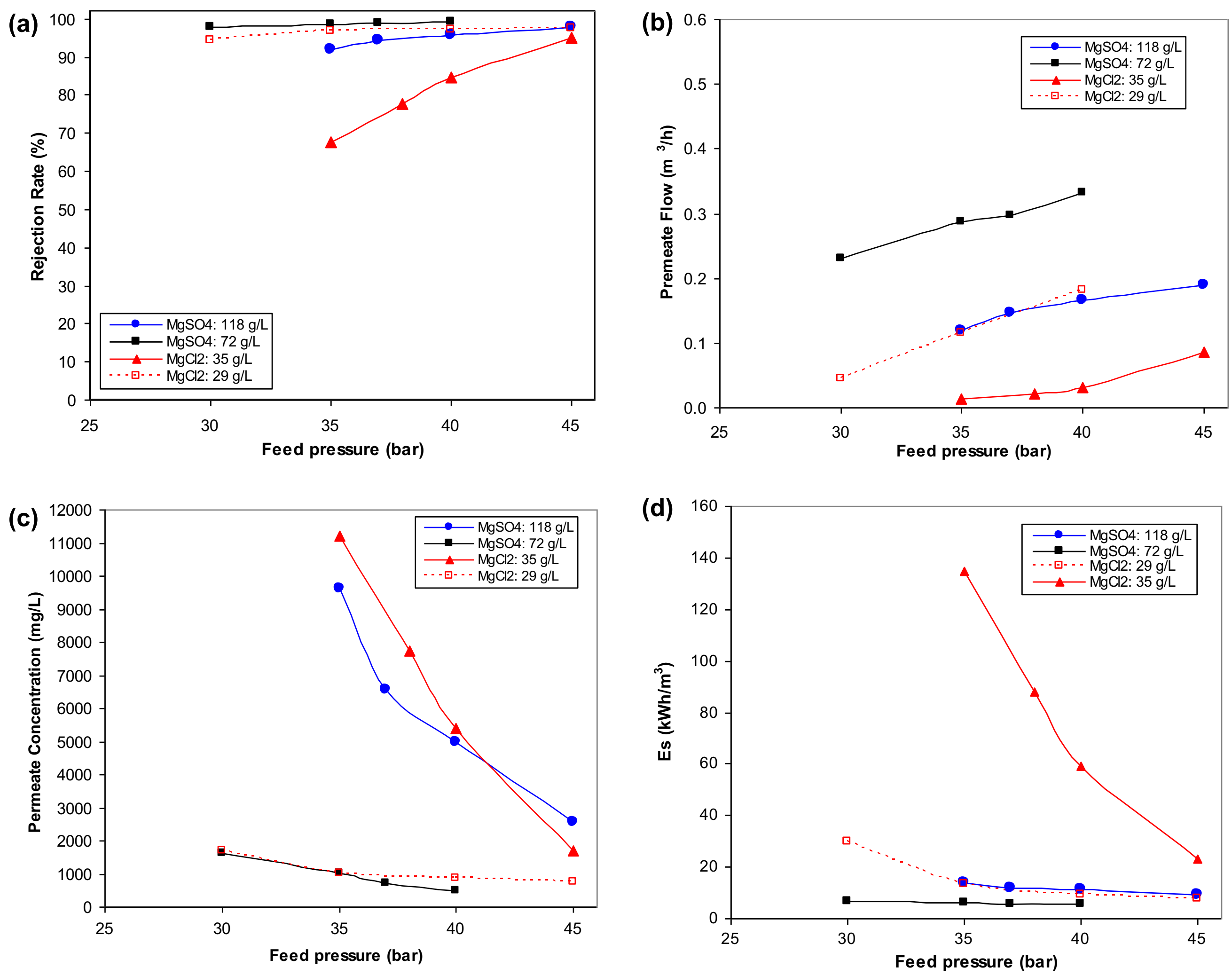

Fig. 6. Effect of feed pressure on the performance of NF membrane (a) rejection rate, (b) permeate flow, (c) permeate concentration and (d) specific power consumption; feed flow rate 29 L/min.

energy for treatment. In general, the results show that E_s of NF treatment was relatively high to be economically justifiable, especially at high feed concentrations. Furthermore, NF membrane is not appropriate method for the regeneration of $MgCl_2$ due to the high power consumption and relatively low rejection rate. Nevertheless, NF membrane could be suitable for the regeneration of low feed concentrations from brackish water FO treatment process.

3.3. Effect of feed flow rate

One of the important operating parameters in NF treatment is the flow rate of feed solution. In the current study, flow rates between 13 and 30 L/min were tested and their impact on the NF performance was investigated (Fig. 7). The impact of feed flow rate on the NF rejection rate is shown in Fig. 7(a). Using high feed flow rates resulted in an increase in the NF rejection rate. In cross-flow filtration processes, the higher the feed flow rate, the lower the concentration polarization is [22,23]. Consequently, the solute accumulation at the membrane surface decreased at higher feed flow rates and resulted in lower salt diffusion across the membrane. For example, NF rejection rate to 72 g/L $MgSO_4$ feed solution was 96% and 98.6 at 13 and 30 L/min feed flow rates, respectively. However, experimental results show that NF rejection rate to 22 g/L $mgCl_2$ feed solution decreased from 98.1 to 97.1%, when the feed flow rate increased from 22 to 30 L/min. This was probably due to an improper membrane cleaning after use which resulted in an unexpected error. Furthermore, NF rejection rate to $MgSO_4$ feed solution was higher than that to $MgCl_2$

Table 4
Characteristics and specific power consumption of the $MgSO_4$ and $MgCl_2$ feed solutions

Feed solution	Feed concentration (mg/L)	Osmotic pressure (bar)	Feed pressure (bar)	E_s (kWh/m^3)
$MgSO_4$	118	23	35	13.8
			37	12.0
			40	11.1
			45	9.1
$MgSO_4$	71	13.7	30	6.5
			35	6.1
			37	5.7
			40	5.6
$MgCl_2$	35	27.2	35	135.0
			38	87.8
			40	59.2
			45	23.3
$MgCl_2$	29	21.67	30	29.9
			35	13.3
			40	9.5
			45	7.6

despite the higher $MgSO_4$ feed concentrations. The reason for that was investigated by previous workers [20,21] and was attributed to the higher electrostatic repulsion force of NF membrane to $MgSO_4$.

Using high feed flow rates was demonstrated to be advantageous to increase permeate flow rate (Fig. 7(b)). Permeate flow rate increased by 1.4–3.8 times as feed flow rate increased from 13 to 30 L/min. An increase in the permeate flow rate was in the following order 112 g/L $MgSO_4$ feed solution followed by 72 g/L $MgSO_4$, 22 g/L $MgCl_2$ and 16 g/L $MgCl_2$ feed solutions, respectively. The reason for that was due to the higher concentration polarization at the solution–membrane surface at higher feed concentrations. Therefore, increasing feed flow rates reduced the effect of concentration polarization as the feed flow velocity increased [24,25]. At 112 g/L $MgSO_4$ feed solution, for example, the permeate flow rate increased from 0.054 to 0.208 m^3/h, when the feed flow rate increased from 13 to 28 L/min, respectively. Based on these results, it is recommended to use high feed flow rates for the treatment of high-concentration feed solution by the NF process in order to reduce the impact of concentration polarization phenomenon.

Since increasing the flow rate of feed solution reduces the impact of concentration polarization, it would be affecting the quality of permeate solution [24,25]. Fig. 7(c) shows the impact of feed flow rate on the TDS of permeate. In most cases, the TDS of permeate decreased with increasing the flow rate of feed solution. This suggests increasing the flow rate of feed solution reduced the impact of concentration polarization at the feed solution–membrane interface, hence increased the permeate flow rate across the membrane. As shown in Fig. 7(c), the TDS of permeate decreased from 2,920 to 1,010 mg/L, when the feed flow rate of 72 g/L $MgSO_4$ feed solution increased from 13 to 30 L/min. Results also show that TDS of permeate was higher at higher feed concentration due to more severe concentration polarization at the membrane surface which promoted salt diffusion to the permeate side. But it should be noted that lower NF rejection rate to $MgCl_2$ resulted in a moderately high permeate concentration despite the relatively low feed concentrations compared to the $MgSO_4$ feed solutions. The experimental results suggest using high flow rate velocities is implicitly important to increase the permeate flow rate and reduces its TDS. However, using high flow rates would affect the power consumption of the NF process. Despite the lower permeate TDS at higher feed flow rates, the TDS of permeate solution was still high and requires further treatment before it can be used for human applications.

Fig. 7(d) shows the impact of feed flow rate on the specific power consumption, E_s, of the NF process. E_s increased with increasing the flow rate of feed solution for all feed solutions investigated here. For 72 g/L $MgSO_4$ feed solution, E_s increases from 5.26 to 6.1 kWh/m^3, when the feed flow rate increased from 13 to 30 L/min. The lowest E_s was about 2.47 kWh/m^3 and attributed to the regeneration of 16 g/L $MgCl_2$ feed solution at 13 L/min flow rate.

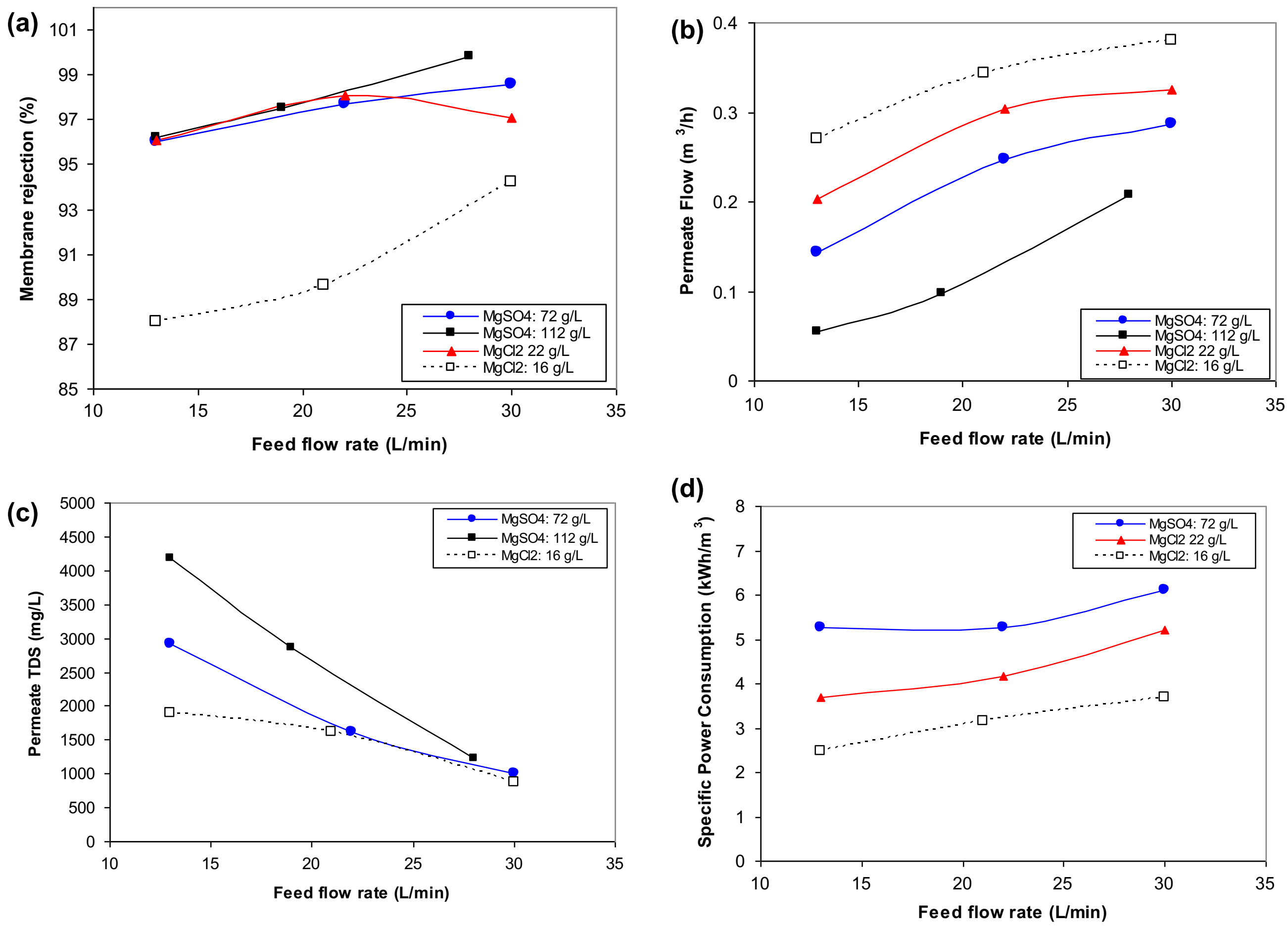

Fig. 7. Impact of flow rate on the NF performance (a) rejection rate, (b) permeate flow, (c) permeate TDS and (d) specific power consumption; feed pressure 35 bar.

Unfortunately, the permeate TDS at such low feed flow rate was 1,892 mg/L, i.e. twice the concentration of permeate at 30 L/min flow rate.

Generally, NF membrane can be used for the regeneration of low salinity draw solution such as brackish water desalination or for the concentration of brackish brine. For seawater desalination, further membrane treatment would be required to reduce the concentration of permeate solution. The TDS of feed solution can be reduced by increasing the feed pressure or flow rate but that would be on the expense of higher power consumption. It is also preferable to use 2–2 metal salt such as $MgSO_4$ because of its high rejection by the NF membrane.

4. Conclusion

In the present study, the feasibility of using NF membrane for the regeneration of divalent draw solutions was evaluated. A commercial size NF90-4040 membrane was applied for the regeneration of different concentrations $MgSO_4$ and $MgCl_2$ draw solutions. Pilot plant results showed that the NF process was a less reliable technique for the treatment of $MgSO_4$ and $MgCl_2$ draw solutions, especially at high feed concentrations. The efficiency of the NF process decreased with increasing the feed concentration, especially in terms of power consumption and permeate concentration. However, the efficiency of the NF process increased with increasing the flow rate of feed solution, but that was on the expense of higher power consumption. Alternatively, increasing feed pressure was found to have the same effect of increasing the feed flow rate on the performance of NF process. Unfortunately, using elevated feed pressures increased the power consumption of the NF process. However, it should be noted that high feed flow rates and feed pressure are recommended for the treatment of relatively high-concentration feed solutions despite the higher power consumption. In such case, a third stage membrane treatment is required for the adjustment of permeate concentrations. In general, NF process was more efficient in the regeneration of 2–2 feed solution than 2–1 feed solution. Furthermore, NF is more efficient for the treatment of low feed concentrations such as that used in the FO treatment of brackish waters.

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