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Evaluation of the separation performance of thin film composite forward osmosis membrane using sodium chloride draw solution for Arabian Gulf seawater desalination

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ABSTRACT

This study investigated the forward osmosis (FO) performance of commercially available thin film composite (TFC) spiral wound membrane using an inorganic-based draw solution (DS) on a bench-scale laboratory test unit. The effect of feed solution (FS) and DS concentrations, flow rate and temperature of FS and DS on FO performance has been systematically investigated. The FS used were 0.5 to 7.0 wt% NaCl solutions, Arabian Gulf seawater (AGS) (TDS ~ 45,000 ppm), reverse osmosis (RO) brine (TDS ~ 56,000 ppm) and deionized water. The DS used were 7 to 26 wt% NaCl. The flux behavior with respect to increase in DS concentration was nonlinear due to internal concentration polarization and the dilutions of DS by permeate. It was observed that flow rate has less influence on water flux and recovery, whereas, FS and DS temperature have positive influence on water flux and recovery. The FO performance results for the selected membrane proved to be encouraging in terms of water flux and recovery. Using 26% NaCl DS, water recovery of 37.6 and 33.8% was achieved for the tested TFC membrane using AGS and RO brine as feed solutions, respectively. Overall, this study demonstrated that the TFC membrane can be considered highly efficient for seawater desalination and most importantly, for high product water recovery from brine.

Keywords: Forward osmosis; Thin-film composite membrane; Draw solution; Osmotic pressure; Seawater desalination.

1. Introduction

The continuous increase of world population and the endless freshwater demand is expected to increase fourfold in the next 25 years [1]. The increase of freshwater demand is mainly due to population growth, climate change, agricultural and industrial growth, and improved living standard [2]. There are a number of ways to control the water shortage in an economical way, such as the development of new membrane technologies and recycling of wastewater. The membrane technologies play a major role in seawater desalination and waste water recycling when compared to thermal process [3,4]. The number of desalination plants present in 150 countries is approximately 23,000 and about 53% of these desalination plants are located in the Middle East [5]. The State of Kuwait and the Gulf Cooperation Council (GCC) countries are mainly depending on seawater desalination as the major source of freshwater [6,7]. Currently, the multi stage flash (MSF) and reverse osmosis (RO) are the most widely used desalination methods [8]. MSF is a thermal distillation process that is commonly used for desalinated water production around the world. However, the process is usually coupled with power generation plants and suffers from high capital and operating costs, and low recovery ratios compared to RO [4,9,10]. RO has become increasingly popular as an alternative seawater desalination technology, as it is currently producing freshwater at lower cost compared to the conventional thermal

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desalination systems, as a result of the ongoing continuous improvements in RO technologies [11,12]. Nevertheless, RO still has a number of challenges, such as significant concentration polarization, scaling and fouling, requirement of a high hydraulic pressure to overcome the osmotic pressure generated by seawater, limited water recovery ratio (which is between 30–50%) [8].

Forward osmosis (FO) technology is one of the non conventional desalination technologies that have received extensive attention during the last decade as an emerging process for seawater desalination [13,14]. The RO process uses hydraulic pressure as the driving force to transport water through the membrane; whereas, FO takes advantage of naturally induced freshwater transport across a semi-permeable membrane from feed solution (FS) at a lower salt concentration to the aqueous solution at higher salt concentration, known as draw solution (DS). Ideally, the semi-permeable membrane allows only freshwater to pass through the membrane leaving all organic and inorganic salts behind. The DS has higher osmotic pressure than FS, to induce freshwater flow across the membrane; and thus, FO does not rely on a high pressure pump as in a pressure-driven membrane process (i.e., RO) to transport a net water flow across the membrane [8]. Therefore, FO requires less energy in comparison to RO. However, in contrast to RO, the product water of FO technology is unfortunately not a freshwater that can immediately be used as drinking water. The product of FO is diluted DS, i.e., a mixture of DS and freshwater. Therefore, a regeneration stage must be utilized to recover DS and freshwater [15].

Previous and current studies have compared FO with RO technology and reported the advantages as follows: FO requires between 20–30% less consumption energy [16]; it has much higher permeate recovery ratio (recovery ratio at least 75%) [17] and discharges lower volume of brine to the environment [18]; it has low fouling potential and high cleaning efficiency [19,20]; and higher boron rejection [21]. Forward osmosis has a wide range of applications, namely, desalination of seawater, brine concentration, wastewater treatment, food industries, fruit juice concentration, and separation of oil-water mixture [2,22,23].

The thin film composite (TFC) membrane is used widely in academic and research studies for seawater desalination. TFC is an ultra thin layer (100–500 nm thick) on the supporting membrane and fabricated by cross-link polymerization process using diamine and acid chlorides. The selectivity of TFC layer depends on the nature of diamine, acid chloride, and additives added in the TFC fabrication process [24,25]. The TFC layer performs the actual separation process, and the support layer provides the mechanical strength. The selectivity of ions and permeability rate has attracted researchers to investigate and develop TFC membranes for seawater desalination [26–30].

After the inauguration of the first FO desalination plant in Oman [21], researchers in GCC are interested in optimizing the FO process parameters for desalinating high saline water with low water production cost. In our previous study, we have reported the investigation of cellulose triacetate spiral wound forward osmosis membrane for desalination process [31]. It was found that water flux increased with increasing DS osmotic pressure, and the water flux is dependent on the temperatures of FS and DS. The results were encouraging and provided a platform to continue the research work for the development of a new membrane for Arabian Gulf seawater (AGS) desalination [32,33].

On the other hand, desalinating high saline brine using the already established membrane and thermal desalination technologies is still a major challenge in terms of its technical feasibility and expenses. ZLD systems are being considered for such an application. ZLD process consists of thermal or thermal and membrane integrated technologies for brine concentration. The integration of these processes is to reduce the brine disposal problem and generate revenue by extracting valuable minerals from brine. In addition, ZLD system is potentially capable of recovering 95–99% high purity water [34,35]. Although ZLD is proven process for brine concentration, the capital and operating costs often exceed the cost of the desalination facilities [36,39]. Martinetti et al. in 2009 [34] reported that the ZLD cost can be reduced by integrating FO membrane technology to reduce the brine volumes. The FO membrane system has a potential to be utilized as a pre-concentrator system for a ZLD process. Thus the reject brine of any desalination plant can be further concentrated by means of the FO system prior delivering to the ZLD process for final treatment. The implementation of the FO system in ZLD may reduce the capital and operational costs of ZLD by reducing the volume of the waste stream to a minimum level. This means that the RO brine, as an example, can be further desalted by feeding it to the FO membrane system to yield further amount of product water with the aim of increasing the overall permeate water recovery ratio, and simultaneously, concentrating the RO retentate as much as possible.

The main objective of this paper is to examine the viability of FO technology to desalinate AGS on bench-scale level using TFC FO membrane and sodium chloride (NaCl) DS. The NaCl DS regeneration stage is not considered in this study. In addition, an attempt was made to assess the feasibility of using TFC FO membrane for brine concentration towards ZLD application.

2. Material and methods

2.1. Materials and instruments

A spiral wound TFC FO membrane element from Hydration Technology Innovations (HTI), was used in this study. The HTI FO membranes are unique compared to other commercially available semipermeable membranes, and it has been determined to be the best available membrane for FO applications and research [40]. The NaCl used was analytical reagent grade from Techno Pharmchem, AR –33127 with 99.9% purity. The membrane housing vessel (AXEON, Model: 2521) is made of the Polyvinyl Chloride (PVC). The FS and DS cylindrical tanks (Tamco Model: 3001), are with a capacity of 20 L. The FS flow rate indicators (Blue-White, Model: F-45500L-8) are made of polysulfone and stainless steel wetted materials. The DS flow indicator (King Instrument's, Model: 7510-2-1-2A08) is made of acrylic and stainless steel wetted materials. The pressure gauges (Wika, Model: 233.53) are made of SS wetted materials. The FS pump (AMT, 300 series self-priming pumps) was used to circulate the FS. The DS pump (MP pumps,

FRX, Model: 75-SP) was used to circulate the DS. The temperature gauges (Wika, Model: TI.50 series) were used to measure the temperature of the DS and FS.

2.2. Preparation of FS and DS

Four different sources of saline water were used and tested individually as FS in this experimental study. The FSs were deionized water (DI), NaCl solutions with concentrations ranging from 0.5 to 7.0 wt%, AGS, and RO brine. Different concentrations of NaCl solutions ranging from 3.5 to 26 wt% by weight of NaCl salt were used as DS. Table 1 shows the characteristics of NaCl in aqueous solutions.

The NaCl solutions were prepared by dissolving a predetermined mass of NaCl salt into a known mass of DI produced by Ultra Violet (UV) water purification system (Millipore, Direct-Q3). AGS and RO brine were collected from the feed stream and reject brine discharge of the Kadhmah Bottled Water (KBW) plant, respectively. The KBW plant represents one of the main research projects of the Water Research Center (WRC) of the Kuwait Institute for Scientific Research (KISR), located at the Doha Research Plant (DRP) in Kuwait. The KBW plant consists of two series of RO membrane units using the series product staging method. Table 2 shows the detailed characterization of AGS and RO brine.

2.3. Experimental setup and process description

The experimental setup, as shown in Fig. 1, comprised of a membrane housing, overhead stirrers for FS and DS, inlet and outlet pressure gauge indicators, FS and DS pumps, digital recirculating baths for FS and DS temperature control, electrical conductivity meters for FS and DS, flow gauge indicators for FS and DS, weighing scale for FS and DS, and, personnel computer (PC).

The experiments were carried out in batch mode. The FS and DS tanks were filled with a predetermined volume of FS and DS, which were 10 and 5 L, respectively. The predetermined temperature of the FS and DS was controlled through the operation of the recirculating bath. The temperatures of FS and DS were varied from 15°C to 40°C. When the predetermined temperature of FS and DS reached the desired level, the FS pump and DS pump recirculated the FS and DS respectively, across the membrane. The flow rates were varied from 2 to 4 L/min. During the circulation, the DS drew water molecules from the FS through the FO membrane. Consequently, the level in the feed tank was gradually reduced; whereas, the level in the DS tank was gradually increased. At the same time, the feed salinity in the feed tank was gradually increased, and simultaneously, the salinity of the DS in the DS tank was gradually decreased. The mass, volume, electrical conductivity, flow rate, pressure, and pH values were recorded every 10 min while carrying out the experiment. After running the experiment for the predetermined time, the FS and DS pumps were terminated, and the FS and DS samples were collected for laboratory analysis. All the experiments were conducted in triplicate and mean values were reported.

MB: Membrane housing, S1: Overhead stirrer assembly for feed solution, S2: Overhead stirrer assembly for draw solution, P1: Inlet pressure gauge indicator, P2: Outlet pressure gauge indicator, FP: Feed solution pump, DSP: Draw solution pump, B1: Weighing scale for feed solution, B2: Weighing scale for draw solution, C1: Digital recirculating bath for feed solution temperature control, C2: Digital recirculating bath for draw solution temperature control, EC1:

Table 1
Characteristics of NaCl in aqueous solutions

C (NaCl g/l)	π (KPa)	μ (mPa × s)	ρ (g/l)	D (10^{-9}m²/s)
0.0	0	0.892	997	1.51
2.5	189	0.895	999	1.497
5.0	380	0.898	1000	1.485
20	1550	0.918	1011	1.472
35	2763	0.939	1021	1.490
60	4882	0.976	1037	1.556

C: Concentration, π: Osmotic pressure, μ: Viscosity, ρ: Density, D: Diffusion coefficient

Table 2
Major physiochemical analysis of AGS and RO brine

Parameter	Feed solution	
	AGS	RO brine
TDS, mg/l	45013	55087
Ca^{2+}, mg/l	825.3	1076
Mg^{2+}, mg/l	1338.2	1669
Na^{+}, mg/l	12232	16274
$(SO_4)^{2-}$, mg/l	3431	4300
$(HCO_3)^{-}$, mg/l as $CaCO_3$	140.6	178.6
Cl^{-}, mg/l	22065	28607
K^{+}, mg/l	299	508
NO^{3-}, mg/l	3.87	6

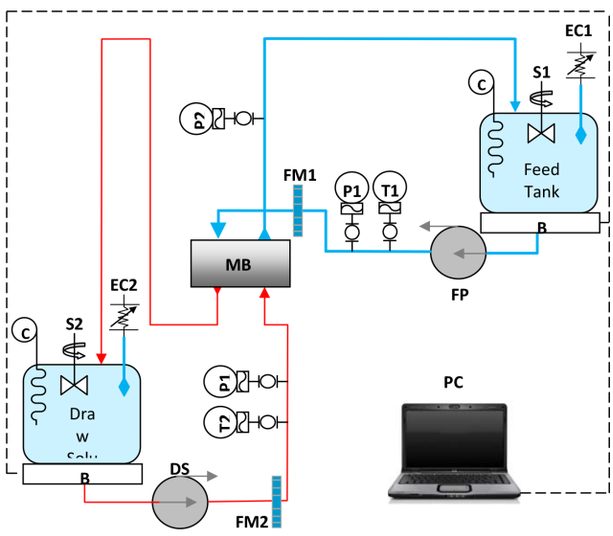

Fig. 1. Schematic diagram of a FO bench-scale test unit.

Portable conductivity meter for feed solution, EC2: Portable conductivity meter for draw solution, FM1: Flow gauge indicator for feed solution, FM2: Flow gauge indicator for draw solution, PC: Personnel computer, T1: Temperature sensor for feed solution, T2: Temperature sensor for draw solution.

In the FO bench-scale test unit, water permeates through the membrane from the FS side to the DS side. The water flux was calculated from the volume change of the FS over time. The water flux, (LMH), was determined by the expression as follows:

$$J = \frac{Vf_2 - Vf_1}{\left[t_2 - t_1\right]} \times \left(\frac{1}{A}\right) \quad (1)$$

where Vf_2 is volume of FS at time 2, Vf_1 is volume of FS at time 1, t_2 is time reading 2, t_1 is time reading 1, and A is membrane surface area, 0.37 m².

The permeate volume was determined from the decrease in the initial volume of the FS over time. Thus, the FO system recovery was calculated as flows:

$$\text{Recovery} = \left(\frac{V_P}{V_F}\right) \times 100 \quad (2)$$

where V_P= permeate volume, and V_F= initial FS volume

3. Results and discussions

3.1. Influence of FS and naCl DS concentrations

Figs. 2 and 3 show significant increase in water flux and permeate water recovery ratio, respectively, when DS concentration was increased. The increase in DS concentration increased the osmotic pressure difference (ΔΠ) and resulted in higher water flux and recovery. By maintaining the DS concentration constant (e.g., 26 wt% of NaCl), the water flux and water recovery ratio was decreased when FS concentration was increased. This decrease in water flux and water recovery ratio is due to internal concentration polarization (ICP) [41,42]. Figs. 2 and 3 suggest that by increasing the concentration of DS, several advantages can be rendered to the FO system, for instance, a significant increase in production rate and a dramatic fall in the volume of the residual liquid of FO brine. The water flux was increased 61% when the NaCl DS concentration was increased from 7.0 to 26.0 wt% in the case of DI water feed. In the case of AGS feed, the increase in water flux was 3.9 times when NaCl DS concentration was increased from 7.0 to 26.0 wt%. In other words, the permeate water recovery ratio of around 38% was achieved when NaCl DS at concentration of 26 wt% was used for AGS feed. Even with limitation of ICP (which is substantially lowering the driving force), the experimental results of the water flux rates obtained could still be comparable to standard RO system for desalinating AGS. The water recovery ratios obtained were 23.8 and 38% while using 15 and 26% NaCl DS respectively.

A fall in the rate of water permeate was observed during the tests, and this trend was observed for all investigated FS concentrations. The reduction in water flux with time as shown in Fig. 4 could be due to the decrease in osmotic pressure difference between FS and DS as a result of increase in

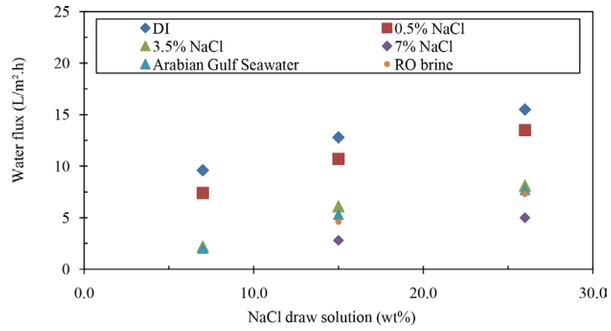

Fig. 2. Effect of NaCl DS concentration on the permeate water flux at various FS concentrations using TFC membrane.

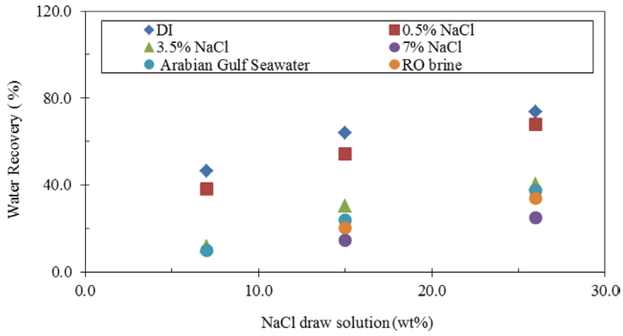

Fig. 3. Effect of NaCl DS concentration on the water recovery ratio at various FS concentrations using TFC membrane.

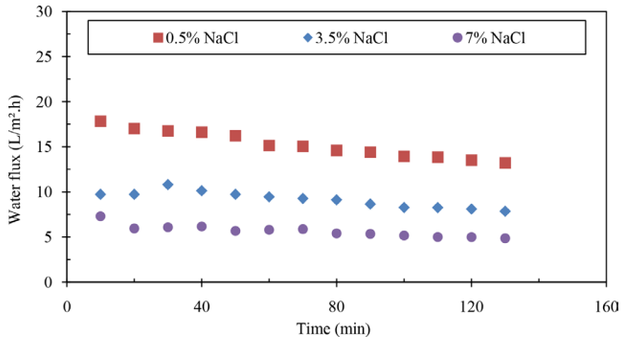

Fig. 4. Water flux versus running time for different feed concentrations using TFC membrane and 26% NaCl DS.

FS concentration with time as shown in as shown in Table 3. It can be observed that with 0.5 wt% NaCl FS, the FS concentration was increased from 0.46 to 1.01 wt%; whereas, the 26 wt% NaCl DS concentration was reduced from 25.57 to 10.47 wt%. Similar trend was observed with 3.5 and 7 wt% NaCl FSs while using 26 wt% NaCl DS. The reason behind this could be the ICP that progressively reduced the flux rate as reported in other investigations [41,42]. This gives a clear indication and explanation why the observed trend of permeate volumes were decreased with respect to time. By increasing the FS concentration, the water flux was reduced because of an increase in the osmotic pressure

Table 3
The variation in FS and NaCl DS Concentrations during the experiments using TFC membrane

Time (min)	Concentration (wt%)					
	0.5% NaCl FS & 26% NaCl DS		3.5% NaCl FS & 26% NaCl DS		7% NaCl FS & 26% NaCl DS	
	0.5% NaCl FS	26 % NaCl DS	3.5% NaCl FS	26 % NaCl DS	7% NaCl FS	26 % NaCl DS
0	0.46	25.57	3.46	25.82	6.74	25.55
3	0.47	23.83	3.28	24.41	6.78	24.77
10	0.50	21.12	3.41	22.74	6.95	23.96
20	0.53	19.02	3.52	21.36	7.12	23.22
30	0.55	17.56	3.65	20.11	7.29	22.52
40	0.58	16.27	3.78	19.00	7.47	21.82
50	0.61	15.16	3.92	17.93	7.62	21.12
60	0.65	14.18	4.06	17.15	7.71	20.46
70	0.69	13.44	4.19	16.46	7.87	19.75
80	0.73	12.73	4.36	15.72	8.02	19.32
90	0.77	12.17	4.47	15.30	8.16	18.84
100	0.83	11.63	4.61	14.81	8.31	18.43
110	0.88	11.20	4.74	14.38	8.45	18.04
120	0.94	10.82	4.88	14.03	8.59	17.67
130	1.01	10.47	5.02	13.71	8.72	17.34

Table 4
Effect of NaCl DS concentrations and corresponding osmotic pressure difference on the permeate water flux for various FS using TFC membrane

NaCl draw solution (wt%)	DI feed		0.5% NaCl feed		3.5% NaCl feed	
	ΔΠ, (MPa)	Water flux (L/m²·h)	ΔΠ, (MPa)	Water flux (L/m²·h)	ΔΠ, (MPa)	Water flux (L/m²·h)
7	6.38	9.6	5.95	7.4	3.30	2.2
15	14.96	12.8	14.53	10.7	11.88	6.1
26	29.79	15.5	29.36	13.5	26.71	8.1

of the FS, which led to a drastic reduction in the driving force (ΔΠ) for driving freshwater from FS into DS side in FO system, as demonstrated and reported by Phuntsho et al. [43] . This would explain the observed lower water flux and water recovery in the case of high FS concentrations in Figs. 2 and 3 respectively.

The osmotic pressure difference of different FS and DS concentration combinations and, the resulting water flux are tabulated in Table 4. A clear tendency of increasing water flux with rising ΔΠ can be observed. It can be clearly seen that the water flux was found to be inversely proportional to the FS concentration. The effect of feed concentration on water flux and water recovery percentage is very important parameter in seawater desalination and RO brine concentration. The water flux and water recovery values will help in assessing the pure water production cost as well as in calculating volume of brine discharge back to sea. The increase in the water recovery ratio will benefit mineral extraction process from concentrated brine.

3.2. Influence of FS and NaCl DS Temperatures

The temperatures of FS and DS were varied from 15°C to 40°C in order to study the effect of temperature on water flux and water recovery ratio. Fig. 5 shows the relationship between average water flux and DS concentration at different temperatures for the TFC membrane. The water flux is dramatically improved by increasing the operating temperatures of FS and DS. This may be related to the decrease in the solution viscosity achieved by increasing the operating temperature, which has led to a significant increase in the diffusion rate and increase of osmotic pressure at higher temperature [22,44–46]. In the case of experiments with high ΔΠ, the average water flux was significantly increased from 10.8 to 21.9 L/m²·h, as the operating temperature was changed from 15 to 40°C. The operating temperature reduced the severity of concentrative ECP on the water flux and ultimately enhanced permeate flux at higher DS concentrations [46]. It was observed that the operating temperature could not improve the water flux, when the ΔΠ is decreased due to increase in FS concentration. The FS and DS temperatures were seen to be the predominant factor for improving water flux, in the case of low FS concentrations, and were ineffective, in the case of higher salt concentrations of FS [44–46]. In addition, at low temperature the positive and negative charged ions will come together and form ion pairs. The pairing of charged ions leads to decrease in the osmotic pressure for the low temperature and directly impact the water flux [44].

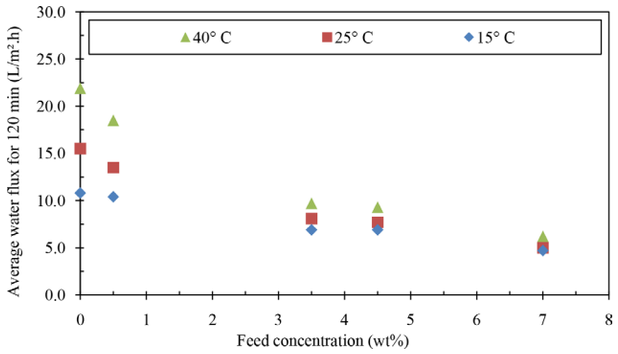

Fig. 5. Water flux obtained at different operating temperatures for various feed solution concentrations using 26% NaCl DS and TFC membrane.

Table 5
Effect of FS concentration on the water flux at different operating temperatures using 26% NaCl DS and TFC membrane

Feed solution	Temperature (°C)	Average flux at 120 min (L/m²·h)	Gain in flux (%)
DI (~0 wt %)	15	10.8	0
	25	15.5	44
	40	21.9	103
NaCl (0.5 wt %)	15	10.4	0
	25	13.5	30
	40	18.5	78
NaCl (3.5 wt %)	15	6.9	0
	25	8.1	17
	40	9.7	41
NaCl (7.0 wt %)	15	4.7	0
	25	5.0	6
	40	6.2	32
AGS (4.5 wt %)	15	6.9	0
	25	7.7	12
	40	*9.3*	*35*

Table 6
Effect of FS concentration on the water recovery ratio at different operating temperatures using 26% NaCl DS and TFC membrane

Feed solution	Temperature (°C)	Water recovery at 120 min (%)	Gain in water recovery (%)
DI (~0 wt %)	15	54.7	0
	25	73.6	35
	40	85.9	57
NaCl (0.5 wt %)	15	52.3	0
	25	68.0	30
	40	72.2	38
NaCl (3.5 wt %)	15	35.3	0
	25	40.4	14
	40	48.1	36
NaCl (7.0 wt %)	15	23.4	0
	25	25.0	7
	40	31.8	36
AGS (4.5 wt %)	15	31.4	0
	25	37.6	20
	40	46.8	49

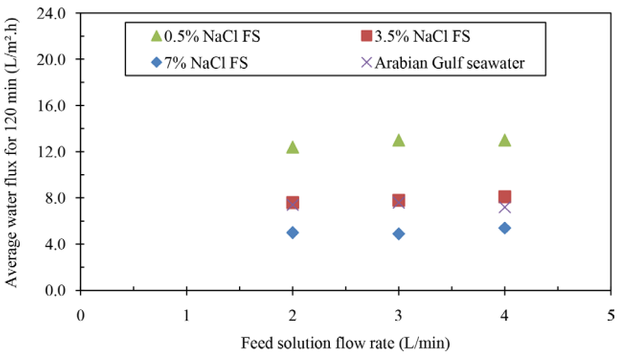

Fig 6. Effect of flow-rate on the average water flux for various FS concentrations using 26% NaCl DS and TFC membrane.

Table 5 shows the influences of salt concentration and temperature of FS and DS upon the water flux and gain percentage in the water flux. Table 6 shows the influences of salt concentration and temperature of FS and DS upon the water recovery and gain percentage in the water recovery. In the case of experiments with high ΔΠ, the water recovery was significantly increased from 54.7 to 85.9 percentages, as the operating temperature was changed from 15 to 40°C. However, for experiments with low ΔΠ, the water recovery increase was from 23.4 to 31.8 percentages only and this is due to an increase in FS concentration.

3.3. Influence of FS and naCl DS flow rates

The influence of flow rate (between 2 and 4 L/min) on average permeate water flux and water recovery ratio was investigated. The measured water fluxes from these experiments are presented in Fig. 6. It was observed that FS and DS flow circulation had limited effect on membrane flux as a result of significantly shorter flow path of feed water in the tested spiral wound membrane [47]. Fig. 7 shows the effect of flow rate on water recovery using TFC membrane and 26 wt% NaCl DS. As with water flux, water recovery was also identical for all tested flow rates. It is worthwhile to mention the fact that the difference in flow rate (ΔQ) of FS and DS was kept constant as per membrane manufacturer instruction to prevent membrane failure. Also, similar pressures (~2.5 psi) were maintained on feed side to prevent membrane damage. The Reynolds number was 1896 for both channels and the flow was laminar. However, further studies on the effect of flow rate of FS and DS at different ΔQ and ΔP are recommended in order to provide a clear picture on the influence of the flow rate upon the water flux and recovery.

3.4. Assessment of TFC-FO membrane and naCl DS for zero liquid discharge (ZLD) application

Based on the data obtained from the experimental study using RO brine as FS, the assessment of the FO membrane and NaCl DS for ZLD application was studied. The concentrated residual feed samples were collected at the end of the tests and chemical analysis was performed. It is observed that the FO membrane system can be utilized as a pre-concentrator system for a ZLD process. The reject brine of any desalination plant can be further concentrated by means of the FO system prior delivering to the ZLD process for final treatment. Table 7 shows a summary of the experimental data and physiochemical analysis of AGS FS and concentrated residual AGS FS samples collected at the end of the tests which were performed using different concentrations of NaCl DS. The permeate water flux values were 2.0, 5.3, and 7.7 L/m²·h, by using NaCl DS of 7, 15, 26 wt%, respectively; while the permeate water recovery ratios were 9.7, 23.8, and 37.6%, respectively. According to simple mass balance calculations, the total concentration ratios were 90.3, 76.2, and 62.4%, respectively. The average TDS value of the AGS FS fed to the FO process was 45013 ppm; whereas, the residual liquids of FS were concentrated with average TDS values of 49560, 59750, and 68150 ppm, by using NaCl DS of 7,15,26 wt%, respectively. With regard to ionic rejection, the average hardness ion values of Ca^{2+}, Mg^{2+}, and $(SO_4)^{2-}$ for the tested AGS were 825, 1338, and 3431 mg/L, respectively. The TFC FO membrane system over a single stage was able to concentrate these ions up to 980, 1468, and 3500 mg/L, respectively, by using NaCl DS concentration of 7 wt%. By using NaCl DS with concentration of 15wt%, the TFC FO membrane system was capable to concentrate the Ca^{2+}, Mg^{2+}, and $(SO_4)^{2-}$ hardness ions up to 1007, 1665, and 3700 mg/L, respectively. While using the NaCl DS with concentration of 26 wt%, the TFC FO membrane system was capable to concentrate the Ca^{2+}, Mg^{2+}, and $(SO_4)^{2-}$ hardness ions up to 1142, 1989, and 5500 mg/L, respectively. The ionic concentrations Na^+ and Cl^- in the tested AGS were 12232 and 22065 mg/L, respectively. The ionic concentrations of Na^+ were increased to 12680, 14399 and 17524 mg/L, for 7, 15 and 26 wt% NaCl DS concentrations, respectively, over the single stages of FO system. Additionally, the ionic concentrations of Cl^- were also increased to 24350, 27675 and 33591 mg/L, for 7, 15 and 26 wt% NaCl DS concentrations respectively, over the single stage of FO process. In general, the ionic rejection ratios were found to be proportional to the DS concentrations. The ionic concentrations of the residual liquids, on the other hand, are reduced as the DS concentration increased. This was due to the increase in the osmotic driving force, which was achieved by increasing the DS concentration.

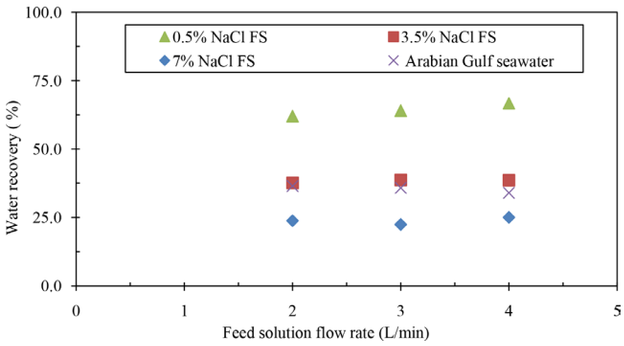

Fig 7. Effect of flow-rate on the water recovery ratio for various FS concentrations using 26% NaCl DS and TFC membrane.

Table 8 illustrates a summary of the experimental results and chemical analysis of RO brine FS and concentrated residual RO brine FS samples collected at the end of the tests which were performed using different concentrations of NaCl DS.

The permeate water flux values were 4.6 and 7.3 L/ m²·h, by using NaCl DS of 15 and 26 wt%, respectively; while the permeate water recovery ratios were 20.2 and 33.8%, respectively. According to the mass balance calculations, the total concentration ratios were found to be equivalent to 79.8 and 66.2%, respectively. The TFC FO membrane tested was able to increase the TDS value of RO brine from 55087 ppm up

Table 7
Major inorganic composition of concentrated residual AGS FS using various NaCl DS concentrations and TFC membrane

Parameter	AGS FS	NaCl DS concentrations		
		7% NaCl	15% NaCl	26% NaCl
J_w, L/m²·h	–	2.0	5.3	7.7
R_w, %	–	9.7	23.8	37.6
TDS, mg/l	45013	49560	59750	68150
Ca^{2+}, mg/l	825	980	1007	1142
Mg^{2+}, mg/l	1338	1468	1665	1989
Na^+, mg/l	12232	12680	14399	17524
$(SO_4)^{2-}$, mg/l	3431	3500	3700	5500
$(HCO_3)^-$, mg/l as $CaCO_3$	140.6	139.6	165.6	220.8
Cl^-, mg/l	22065	24350	27675	33591
K^+, mg/l	299	420	500	850
NO^{3-}, mg/l	3.87	4.3	5	4.6

J_w: permeate water flux; R_w: permeate water recovery ratio.

Table 8
Major inorganic composition of concentrated residual RO brine FS using various NaCl DS concentrations and TFC membrane

Parameter	RO brine FS	NaCl DS concentrations	
		15% NaCl	26% NaCl
J_w, L/m²·h	–	4.6	7.3
R_w, %	–	20.2	33.8
TDS, mg/l	55087	70150	73520
Ca^{2+}, mg/l	1076	1130	1350
Mg^{2+}, mg/l	1669	1935	2228
Na^{+}, mg/l	16274	17073	20041
$(SO_4)^{2-}$, mg/l	4300	5400	5600
$(HCO_3)^{-}$, mg/l as $CaCO_3$	178.6	220	230.7
Cl^{-}, mg/l	28607	32404	37901
K^{+}, mg/l	508	850	850
NO^{3-}, mg/l	6	6.5	7

to 70150 and 73520 ppm, by using 15 and 26 wt% NaCl DS respectively, over a single stage of FO system. This investigation clearly indicated that the overall concentration ratio was significantly decreased as the DS concentration increased. The results proved that the investigated FO system was able to concentrate the RO brine by a considerable amount while simultaneously extracting a considerable amount of freshwater. This freshwater can easily be further desalted by feeding it to seawater RO membranes to obtain a final product water to drinking water standards.

As for the ionic composition, the average hardness ion values of Ca^{2+}, Mg^{2+}, and $(SO_4)^{2-}$ for the RO brine fed to the feed stage were 1076, 1669, and 4300 mg/L, respectively. The TFC FO system over a single stage was able to increase the hardness ions up to 1130, 1935, and 5400 mg/L, for Ca^{2+}, Mg^{2+}, and $(SO_4)^{2-}$, respectively, in the case of the NaCl DS of 15 wt%. By increasing the NaCl DS concentration from 15 to 26 wt%, then the aforementioned divalent ions were increased to 1350, 2228, and 5600 mg/L, respectively. The RO brine contains monovalent ions, i.e., Na^{+} and Cl^{-}, with ionic concentration of 16274 and 28607 mg/L, respectively. The Na^{+} and Cl^{-} ions were dramatically increased to 17073 and 32404 mg/L, respectively, in the case of NaCl DS of 15 wt% over a single stage. By increasing the NaCl DS concentration from 15 to 26 wt%, Na^{+} and Cl^{-} monovalent ions were increased to 20041 and 37901 mg/L, respectively. In general, the ionic concentrations of the residual liquid were found to be proportional to the DS concentration, which was leading to an increase in the osmotic driving force.

The results suggested that the commercial plant using the tested TFC FO membrane with NaCl DS could be technically designed and constructed with a wider range of DS concentrations for RO brine concentrations. This would include higher operating limits of DS concentration to yield a substantial amount of freshwater, and at the same time, to achieve a considerable reduction in the volume of the residual liquid. Accordingly, this treatment option would eventually lead to a significant decrease in the capital costs of ZLD. However, designing commercial plants with higher DS concentrations might be limited by a significant increase in the power consumption of the regeneration stage in order to be able to yield freshwater and concentrate the DS.

4. Conclusion

The performance of commercial TFC FO membrane was assessed for desalinating and concentrating different types of saline water including DI water, NaCl solutions, AGS, and RO brine and different NaCl DS concentrations. The permeate flow increased with increase in DS concentrations as a result of increase in its osmotic pressure. The flux behavior with respect to increase in DS concentration was non-linear due to internal concentration polarization and the dilutions of DS by permeate. It was observed that for the selected spiral wound TFC-FO configuration, the water flux was identical for varying flow rates. This is due to short area available for feed flow in spiral wound module in FO configuration. The FO permeation values for the seawater or even brine was in the range of 7–8 L/m² h and demonstrated the feasibility of using selected TFC-FO membrane for concentrating RO retentate as well as highly saline feed solutions towards ZLD applications.

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