

# Assessment of Forward Osmosis Membrane Technology for Saline Water Treatment and Desalination Application

M. Ahmad\*, M. Abdel-Jawad, S. Al-Haddad, and A. Al-Haji

Kuwait Institute for Scientific Research, Water Research Center, P.O. Box 24885, Safat 13109, Kuwait

## Abstract

The separation performance of Forward Osmosis (FO) membrane technology was investigated for saline water treatment and desalination. The main aim of this paper was to evaluate the viability of FO membrane system, on a laboratory bench-scale test unit using batch mode for saline water treatment and desalination applications. An intensive laboratory investigations have been carried out on a bench-scale laboratory test unit utilizing the commercially available spiral wound FO membranes made of cellulose triacetate (CTA). The influence parameters, including draw solution concentrations, flow-rate, and temperature upon water flux and recovery was assessed. Different sources of feed solutions (FS), including: deionized water, sodium chloride (NaCl) solutions, Arabian Gulf seawater and reverse osmosis (RO) brine were tested in this study. The salt concentrations of NaCl FS were 0.5, 3.5, and 7 wt%. The salt concentrations of Arabian Gulf seawater and RO brine were 4.5 and 5.6 wt%, respectively. Different salt concentrations of NaCl and Ammonium bicarbonate ( $\text{NH}_4\text{HCO}_3$ ) solutions were used and tested as draw solutions (DS). The salt concentrations of DS were ranging from 3.5 to 26% and 3.5 to 17.83% for NaCl and Ammonium bicarbonate, respectively. The tested flow rate of FS was ranged from 2 to 4 l/min. The examined temperature of the FS and DS was 15, 25, and 40°C. The results showed that the water flux increased with increasing DS osmotic pressure for all concentrations of both DS. Also, with higher concentration feeds, the water flux decreased for each DS due to less difference in osmotic pressures. It was found that water flux was proportional to FS and DS temperature, and this could be due to decrease in fluid viscosity which enhanced the diffusion rate of water through the membrane. Further research is required to investigate different types of commercially available FO membrane elements and DS in order to develop an effective and sustainable FO technology for saline water treatment and seawater desalination applications.

**Keywords:** Forward Osmosis Membrane, Desalination Technologies, Draw Solution, Osmotic Pressure, Concentration Polarization.

## 1. Introduction

Kuwait has been fully dependent on seawater desalination for the past six decades due to the lack of fresh natural water resources. Multi-Stage Flash (MSF) distillation process has successfully been utilized to supply drinking water in Kuwait over the aforementioned period [El-Sayed et al., 2010; MEW, 2010; Darwish et al., 2008; Awerbuch, 1997]. The conventional desalination technologies, such as MSF and Reverse Osmosis (RO) are the most frequently used worldwide [Spiegler and El-Sayed, 1994; Van et al., 2003].

Detailed on the aforementioned desalination technologies are described in the literatures [Cipollina et al., 2009; Spiegler and El-Sayed, 1994; Mulder, 1996; Buros, 2000]. However, the MSF and RO technologies have a number of serious limitations including: scaling and fouling problems, corrosion limitation, high capital cost, energy intensive, and low water recovery ratios [Ahmad, 2012; Spiegler and El-Sayed, 1994]. The escalation in the energy cost and technical problems as well as the environmental impact of the conventional desalination technologies have led the scientists to look at a number of promising non-conventional desalination technologies that may

\* Corresponding author

E-mail: [mahmed@kisir.edu.kw](mailto:mahmed@kisir.edu.kw)

© 2016 International Association for Sharing Knowledge and Sustainability

DOI: 10.5383/swes.8.02.004

be regarded as more efficient means of low-energy (i.e., low-cost) [Ge et al., 2013] and a more-reliable desalination system [Low, 2009] as well as less ecological impact [Ahmad, 2012]. Forward osmosis (FO) is an emerging technology that can be developed for seawater desalination in a more environmental-friendly process, with much higher water recovery ratio, and much lower energy consumption and cost than RO (Liu et al., 2009 ; McCutcheon et al., 2006; Chung et al., 2012). The RO process uses hydraulic pressure as the driving force to transport water across the membrane; while FO utilizes the natural osmotic pressure gradient of a much higher osmotic pressure solution by using artificial brine, i.e., the DS. The main characteristics of DS are as follows: osmotic pressure (  $\pi$  ), concentration (CDS), solubility, and diffusion coefficient (D).

**2. Theory**

The osmotic pressure (  $\pi$  ) for any solution can be determined by using Van't Hoff (1899) formula as described below.

$$f = cRT \tag{1}$$

where c is the molar concentration of the solute, R is the gas constant (L.bar/deg.mol), and T is the temperature on the absolute temperature scale (Kelvin). The relationship between osmotic and hydraulic pressures and water flux can be described by the following term (Achilli et al., 2009; Cath et al., 2006):

$$W = A (\Delta P - \Delta \pi) \tag{2}$$

where W is the water flux, A is the hydraulic permeability coefficient of the membrane,  $\Delta P$  is the difference in osmotic pressure on the two sides of the membrane, and  $\Delta \pi$  is the difference in hydrostatic pressure. Because of the concentration gradient across the membrane, a small amount of salt will be transferred from the DS to the FS across the membrane, leading to reduce the applied osmotic pressure across the membrane (Achilli et al., 2009). Theoretically, the salt permeability coefficient (B) of the FO membrane can be described by the following term (Lee et Al., 1981):

$$B = \frac{A(1 - R)(\Delta P - \Delta \pi)}{R} \tag{3}$$

where R is the salt rejection of the membrane and is determined by equation (4):

$$R = \left[ 1 - \left( \frac{C_P}{C_F} \right) \right] \times 100 \tag{4}$$

where Cp is the salt concentration of the DS, and Cf is the salt concentration of the FS.

In our study, during each test, the water flux was determined by the following term [Ng et al., 2006]:

$$\text{Water Flux} = \frac{\Delta \text{Weight}}{\text{Water density} \times \text{membrane surface area} \times \Delta \text{time}} \tag{5}$$

Based on the manufacturer's recommendation, the water flux, Liter per Meter Square Hour (LMH), can be determined by the expression as follows:

$$J = \frac{Vf_2 - Vf_1}{[t_2 - t_1]} \times \left( \frac{1}{A} \right) \tag{6}$$

Where Vf2 is volume of feed at time 2, Vf1 is volume of feed at time 1, t2 is time reading 2, t1 is time reading 1, A is membrane surface area, 0.5m2. Similarly, the permeate volume can be determined from the decrease in the initial volume of the FS over time. Thus, the FO system recovery would be calculated using Equation 7:

$$\text{Recovery} = \left( \frac{V_P}{V_F} \right) \times 100 \tag{7}$$

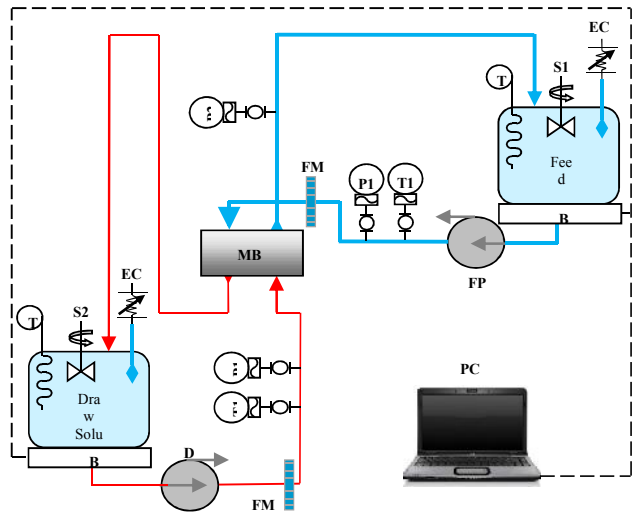
where VP= permeate volume, and VF = initial FS volume

**3. Objectives**

The main objectives of this study were as follows: (i) to investigate in a bench-scale laboratory arrangement the potential for the commercially available FO membrane element to be a viable, effective and sustainable technology for a wide range of saline water resources and salt concentrations; and (ii) to investigate different salt concentrations and sources of DS in order to produce the maximum water flux with minimum solute passage.

**4. Experimental Setup Description**

The laboratory bench-scale test unit was constructed and tested for investigating and verifying the performance of FO membrane process at different operating conditions to treat Arabian Gulf seawater and RO brine, as well as the aqueous solutions of sodium chloride at different salt concentrations. Fig 2 shows the equipment utilized for the FO test unit.



**Fig. 2. Schematic Diagram of a Forward Osmosis Bench-Scale Test Unit**

The experimental setup comprised of a membrane housing (MB), overhead stirrer assembly for feed (S1), overhead stirrer assembly for DS (S2), inlet pressure gauge indicator (P1), outlet pressure gauge indicator (P2), feed pump (FP), DS pump (DSP), digital recirculating bath for FS (T1), digital recirculating bath for DS (T2), portable conductivity meter for FS (EC1), portable

conductivity meter for DS (EC2), flow gauge indicator for feed (FM1), flow gauge indicator for DS (FM2), weighing scale for feed (B1), weighing scale for DS (B2), personnel computer (PC). The membrane housing vessel (AXEON, Model: 2521) is made of the Polyvinyl Chloride (PVC). FS was sent to the side ports and DS was sent to the end ports. The FS and DS cylindrical tanks (Tamco Model: 3001), with a capacity of 5 gall. The FS flow rate indicators (Blue-White, Model: F-45500L-8) is 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) is 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 pup) was used to circulate the DS. The temperature gauges (Wika, Model: TL50 series) were used to measure the temperature of the DS and FS.

## 5. Materials

An FO membrane element (Hydration Technology Innovations (HTI), OsMem 2521FO-MS-CTA-P-3H) is made of cellulose triacetate (CTA) and was utilized in this paper. HTI FO membrane elements are unique compared to other commercially available membrane elements, and it has been determined to be the best available FO membrane for seawater application and research (Tzahi et al., 2006).

## 6. Preparation of Feed Solutions and Draw Solution Samples

Four different sources of saline water were used and investigated individually as feed samples in this paper. Deionized water (DI), aqueous solutions of sodium chloride (NaCl), seawater, and RO brine were used as feed. Synthetic water using NaCl salts (Techno Pharmchem, Sodium chloride AR - 33127) were used and examined as FS and DS. The initial salt concentrations of the feed, using NaCl solute, were 0.5, 3.5, and 7 wt% by weight of NaCl salts. Different concentrations of NaCl solutions ranging from 3.5 to 26 wt% by weight of NaCl salt and Ammonium bicarbonate (NH<sub>4</sub>HCO<sub>3</sub>) (Techno Pharmchem, NH<sub>4</sub>HCO<sub>3</sub> AR - 38139) solutions ranging from 3.5 to 17.83 wt% by weight of NH<sub>4</sub>HCO<sub>3</sub> salt were used as DS. The feed samples using synthetic water were prepared by dissolving a predetermined mass of NaCl salt into a known mass of deionized water [produced by Ultra Violet (UV) water purification system, Direct-Q3, Trade Name: Direct-Q]. Additionally, two more sources of saline water were used and tested individually as feed samples in this study. These are Arabian Gulf (AG) seawater (4.9 wt%) and RO brine (5.6 wt%).

## 7. Physicochemical Analysis and Measuring Instruments

Physicochemical analysis was carried out following the standard procedure for all water streams, including FS and DS before and after the completion of the experiments. The physicochemical analysis of water samples included measurements of the temperature, total dissolved solids (TDS), electrical conductivity, pH, volume, and mass. When the source of the feed was either AG seawater or RO brine, full water chemistry analysis was conducted for each experiment.

A DR 5000 Spectrophotometer (Hach, DR 5000) and ion chromatography (Dionex 5000) systems were used to perform full chemical analysis.

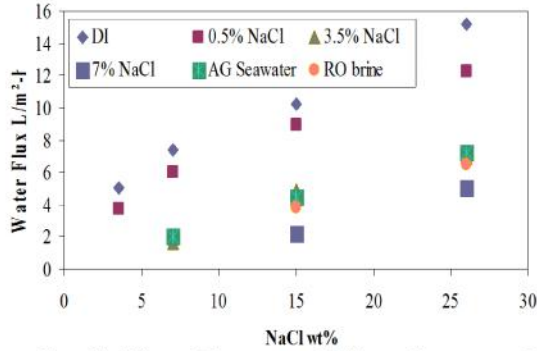
## 8. Experimental Procedure

These tests were carried out in batch mode. The FS and DS tanks were filled with a predetermined mass of feed sample and DS, which were 10 and 5 kg, respectively. For all tests, the temperature of the FS and DS was controlled through the operation of the recirculating bath. When the predetermined temperature of feed and DS reached the desired level, the feed pump was manually turned on, and then, simultaneously, the operational DS pump recirculated the FS and DS across a semi permeable membrane. The FS and DS pumps continuously delivered FS and DS from the collecting tank to the membrane housing through a flexible hose, as shown schematically in Fig 2. For all experiments, the affecting parameters, including salt concentrations of FS and DS, temperature, pressure, and flow rate were set at the predetermined values according to the test protocol of the experimental envelop. Apart from FS and DS concentrations, the predetermined values remained constant for the duration of the experiment. When the flowing FS and DS circulated around the membrane housing, the DS drew the water molecules from the feed sample through the FO membrane surface. Consequently, the feed level in the feed tank was gradually reduced; conversely, the DS 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. This is due to the water molecules leaving the feed behind and transported and mixed with the DS. The mass, volume, electrical conductivity, flow rate, pressure, and pH values were recorded every 5 min while carrying out the experiment. After running the experiment for a predetermined time, the operation of the FS and DS pumps was terminated, and simultaneously, the FS and DS were collected for laboratory analysis.

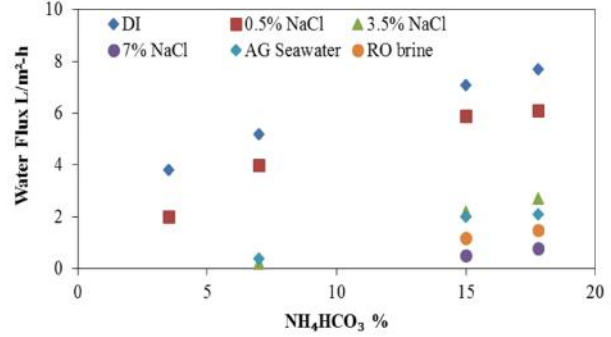
## 9. Results and Discussions

### 9.1 FO Flux and Water Recovery

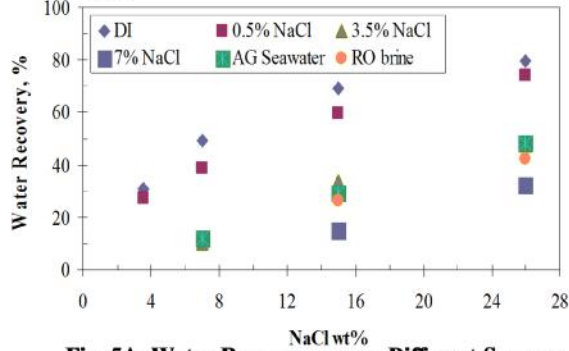
Figure. 2A and 4B shows that higher initial concentrations of NaCl and NH<sub>4</sub>HCO<sub>3</sub> DS could lead to increase in the water flux, and, Figure. 3A and 5B shows that higher initial concentrations of NaCl and NH<sub>4</sub>HCO<sub>3</sub> DS could lead to increase in the water recovery, and this is due to more osmotic pressure difference ( ). It was observed that rate of water permeate decreased with time with all feed concentrations as shown in Figure 3A and 6B. It is assumed that this decrease in flux could be due to internal concentration polarization (ICP). The DS that diffused into the porous support layer got diluted during the process and reduced the effective overall driving force. Table 1A and 1B shows the water flux and recovery at different salt concentration of FS and NaCl and NH<sub>4</sub>HCO<sub>3</sub> DS, respectively.



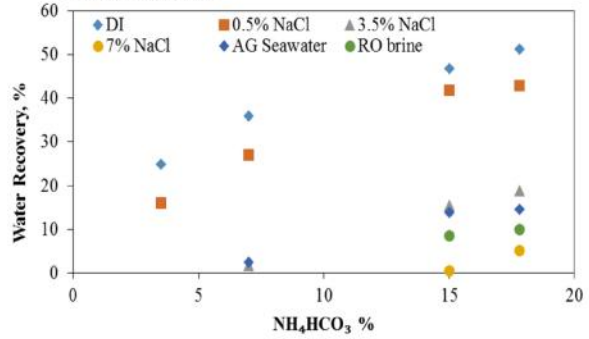
**Fig. 4A. Water Flux versus Different Sources and Salt Concentrations of NaCl Feed and NaCl Draw Solution.**



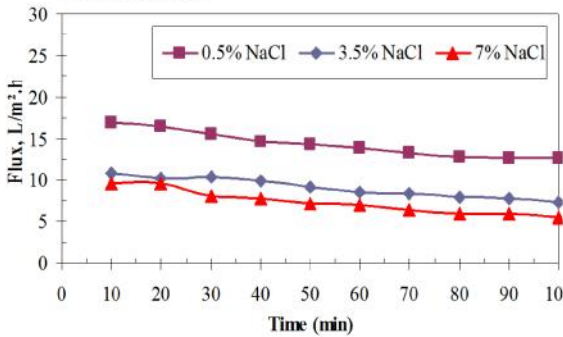
**Fig. 4B. Water Flux versus Different Sources and Salt Concentrations of NaCl Feed and  $\text{NH}_4\text{HCO}_3$  Draw Solution.**



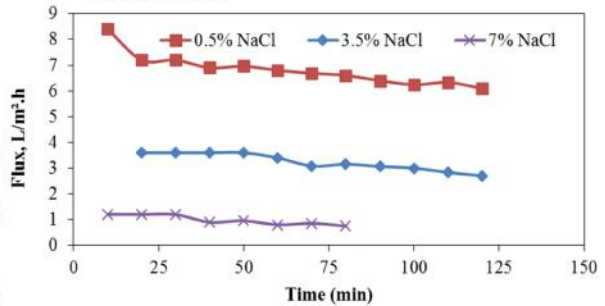
**Fig. 5A. Water Recovery versus Different Sources and Salt Concentrations of NaCl Feed and NaCl Draw Solution.**



**Fig. 5B. Water recovery versus different sources and salt concentrations of NaCl feed and  $\text{NH}_4\text{HCO}_3$  draw solution.**



**Fig. 6A. Water Flux Over Time for Various NaCl Feed Concentrations And 26% NaCl Draw Solution Concentration at 25°C.**



**Fig. 6B. Water Flux Over Time for Various NaCl Feed Concentrations And 17.83%  $\text{NH}_4\text{HCO}_3$  Draw Solution Concentration at 25°C.**

**Table 4A. Water Flux and Recovery for Different Feed and NaCl Draw Solutions**

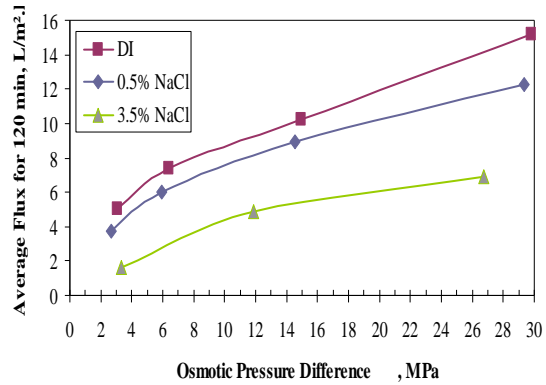
Feed	NaCl Solution, (wt%)	Draw	Water Flux at 25°C, l/m <sup>2</sup> .h	Water Recovery (%)
DI (~0 wt%)	3.5		5.0	30.6
	7.0		7.4	49.1
	15.0		10.2	69.0
	26.0		15.2	79.4
NaCl (0.5 wt%)	3.5		3.7	27.5
	7.0		6.0	38.8
	15.0		8.9	59.6
NaCl (3.5 wt%)	26.0		12.3	74.3
	7.0		1.6	10.1
	15.0		4.9	33.8
NaCl (7.0 wt%)	26.0		6.9	47.1
	15.0		2.2	14.8
NaCl (7.0 wt%)	26.0		5.0	32.3
	7.0		2.0	11.7
Seawater	15.0		4.5	29.2
	26.0		7.2	48.1
RO brine	15.0		3.8	26.4
	26.0		6.5	42.5

**Table 1B. Water Flux and Recovery for Different Feed and NH<sub>4</sub>HCO<sub>3</sub> Draw Solutions**

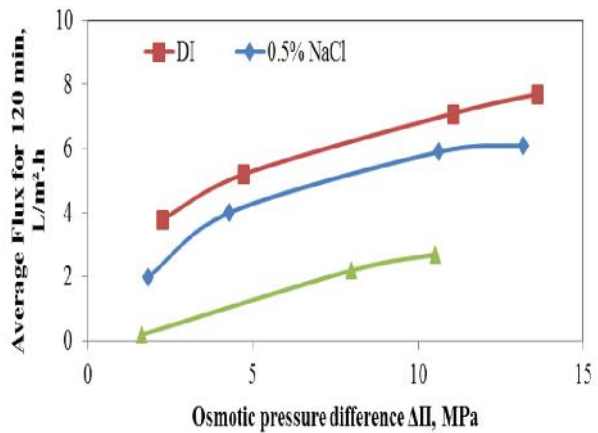
Feed	NH <sub>4</sub> HCO <sub>3</sub> Draw Solution, (wt%)	Draw	Water Flux at 25°C, l/m <sup>2</sup> .h	Water Recovery (%)
DI (~0 wt%)	3.5		3.8	25.0
	7.0		5.2	35.9
	15.0		7.1	46.9
NaCl (0.5 wt%)	17.8		7.7	51.3
	3.5		2.0	16.0
	7.0		4.0	27.0
NaCl (3.5 wt%)	15.0		5.9	41.9
	17.8		6.1	43.0
NaCl (7.0 wt%)	7.0		0.2	1.8
	15.0		2.2	15.5
	17.8		2.7	18.8
NaCl (7.0 wt%)	15.0		0.5	0.6
	17.8		0.8	5.1
Seawater	7.0		0.4	2.4
	15.0		2.0	13.8
RO brine	17.8		2.1	14.5
	15.0		1.2	8.6
	17.8		1.5	10.0

**9.2 Effect of DS Concentration**

Figure 5A and 5B shows the influence of salt concentrations of feed upon the average water flux, and it is obviously that the average flux was increased with decreasing the feed concentrations. Obviously, the average flux improvement was accompanied by an increase of the concentration of DS.



**Fig. 5A. Water Flux Over A Range Of Osmotic Pressure Differences For Various Feed Concentrations And 26% NaCl Draw Solution Concentration at 25°C.**



**Fig. 7B. Water Flux Over A Range Of Osmotic Pressure Differences For Various Feed Concentrations And 17.83% NH<sub>4</sub>HCO<sub>3</sub> Draw Solution Concentration at 25°C.**

Increasing the DS concentration would increase the driving force ( ) and could result in increased flux. The increase in flux must be linear with osmotic pressure difference, but it can be seen from Fig. 7A and 7B that it is nonlinear. This phenomenon may be due to ICP. Also Fig. 7A and 7B shows that an increase in the feed molarity would cause a reduction in water flux due to reduction in .

9.3 Effect of Temperature

The temperature of FS and DS were varied from 15 to 40°C in order to study the influence of temperature on flux. It was found that the permeate flux improved by increasing the FS and DS temperature as shown in Fig. 8A and 8B. This could have been the increase in temperature, resulting to a reduction in the solution viscosity and an increase in the diffusion rate. In the case of NH<sub>4</sub>HCO<sub>3</sub> DS, the increase in flux with temperature was not so significant and this may be due to loss of Ammonia at higher temperatures. In the case of NaCl DS, the flux was increased from 57 to 80% for samples with high osmotic pressure difference, as the temperature was increased from 15 to 40°C as shown in Table 5. Also, it can be seen that change in water flux due to rise in temperature was less with high concentration feeds which reduced the effective

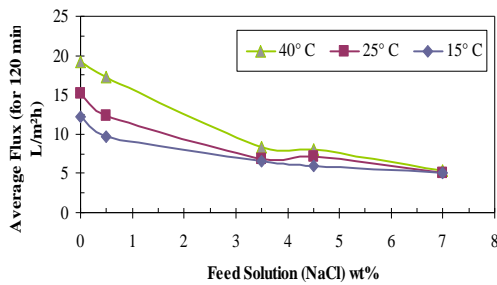


Fig. 6A. Water Flux Various Concentrations of NaCl Feed At Different Temperatures Using 26% NaCl Solution.

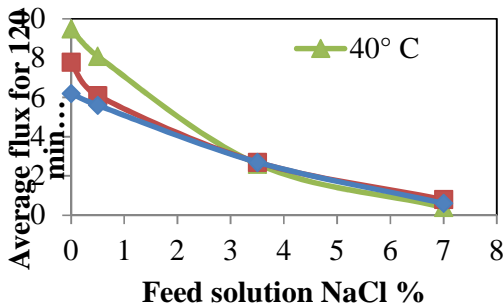


Fig. 6B. Water Flux Various Concentrations of NaCl Feed at Different Temperatures Using 17.83% NH<sub>4</sub>HCO<sub>3</sub> Solution.

Table 2 recapitulates the values of the three variables, attributed to the parameters as follows: salt concentration, temperature, and flow rate of FS and DS; whereas, the two responses were as follows: water flux and water recovery. The initial feed concentration was ranging from 0 (deionized water) up to 7 wt% of NaCl salts. Furthermore, feed samples using seawater were also covered in Table 5. The temperature was between 15 to 40°C. The running time was varied between 1 and 4 h.

Table 2. Water Flux for Different Feed Solutions at Different Temperatures Using 26 wt% by Weight of Dissolved NaCl Salt as Draw Solution.

Feed Solution	Temperature (°C)	Average flux at 120 min, (l/m².h)	Gain in flux, (%)
DI (~0 wt%)	15	12.2	0
	25	15.2	25
	40	19.2	57
NaCl (0.5 wt%)	15	9.6	0
	25	12.3	28
	40	17.3	80
NaCl (3.5 wt%)	15	6.6	0
	25	6.9	5
	40	8.4	27
NaCl (7.0 wt%)	15	4.5	0
	25	5.0	11
	40	5.3	18
Seawater	15	6.0	0
	25	7.2	20
	40	8.0	33

9.4 Effect on Major Components of Ionic Composition of Feed Samples

Tables 3 and 4 illustrate the major components of ionic composition of the feed samples, using seawater and RO brine, before and after each experiment, at different salt concentration of NaCl solutions used as draw solution.

Table 3. Major Physicochemical Analysis of Water Samples for the Feed Solution, Using Seawater, at Different Salt Concentrations, Using NaCl Solutions as Draw Solutions

Parameter	Unit (mg/l)	Feed Solution	FO Feed Residue after Testing with Following DS		
		Seawater	7% NaCl	15% NaCl	26% NaCl
TDS	mg/l	45,013	51,938	67,972	88,557
Ca <sup>2+</sup>	mg/l	825.3	993	1,326	1,704
Mg <sup>2+</sup>	mg/l	1,338.2	1,558	1,939	2,493
Na <sup>+</sup>	mg/l	1,2232	13,486	19,059	26,973
(SO <sub>4</sub> ) <sup>2-</sup>	mg/l	3,431	3,889	5,306	7,368
(HCO <sub>3</sub> ) <sup>-</sup>	mg/l as CaCO <sub>3</sub>	140.6	143.2	214.3	278.3
Cl <sup>-</sup>	mg/l	22,065	25,256	34,112	47,569
K <sup>+</sup>	mg/l	299	423	816.7	918.3
NO <sub>3</sub> <sup>3-</sup>	mg/l	3.87	4.5	5.67	6.12

Table 3 shows that the tested FO membrane was able to increase the TDS value of the FS using seawater from 45,013 ppm to 88,557 ppm by using aqueous solution with 26 wt% of NaCl salts as DS. Table 3 also shows that all concentrations of the major components of ionic composition of the FS were increased by increasing the concentration of the DS. Same observation applies with RO brine as shown in Table 4.

**Table 4. Major Physiochemical Analysis of Water Samples for the Feed Solution, Using RO Brine, at Different Salt Concentrations, Using NaCl Solutions as Draw Solutions**

Parameter	Unit (mg/l)	Feed Solution	FO Feed Residue after Testing with Following DS	
		RO Brine	15% NaCl	26% NaCl
TDS	mg/l	55,087	75,254	103,995
Ca <sup>2+</sup>	mg/l	1,076	1,466	2,015
Mg <sup>2+</sup>	mg/l	1,669	2,146	2,345
Na <sup>+</sup>	mg/l	16,274	23,400	35,214
(SO <sub>4</sub> ) <sup>2-</sup>	mg/l	3,300	5,600	8,000
(HCO <sub>3</sub> ) <sup>-</sup>	mg/l as CaCO <sub>3</sub>	178.6	237	283.5
Cl <sup>-</sup>	mg/l	28,607	39,547	55,213
K <sup>+</sup>	mg/l	508	840	984
NO <sub>3</sub> <sup>-</sup>	mg/l	6	6	7.34

### 10. Conclusion and Recommendations

The experimental results showed that the parameters as follows: FS and DS concentration, osmotic pressure difference ( ), and FS and DS temperature had significant influence on the separation performance of the FO membrane process in terms of water recovery and permeate flux. In general, the experimental investigation showed that the FO membrane system was feasible for concentrating RO retentate as well as high feed salinities. The experimental data can be used as a reference for designing a pilot plant using similar FO membrane configuration for further investigation. The experimental results were highly encouraging, and proved that the FO membrane system could be a powerful desalination unit for either desalting seawater or minimizing different concentrations of highly saline waters, including RO brine.

### References

- [1] Achilli, A., T.Y. Cath, and A.E. Childress. 2009. Power generation with pressure retarded osmosis: an experimental and theoretical investigation, *Journal of Membrane Science* **343**: 42–52.
- [2] Buros, O.K., 2000. *ABCs of desalting*, 2<sup>nd</sup> ed. S.I., International Desalination Association (IDA), Topsfield, Massachusetts, United States of America.
- [3] Cath, T.Y.; A.E. Childress; and M. Elimelech, 2006. Forward osmosis: principles, applications, and recent developments, *Journal of Membrane Science* **281** (2006) 70–87.
- [4] Chung, T.S., S. Zhang, K.Y. Wang, J.C. Su, and M. M. Ling, 2012. Forward osmosis processes: yesterday, today, and tomorrow. *Desalination* **287**: 78–81.
- [5] Lee, K. L., R. W. Baker, and H. K. Lonsdale, 1981. Membranes for power generation by pressure retarded osmosis, *Journal of Membrane Science*, **8**: 141–171.
- [6] Liu, L.; M. Wang; D. Wang; and C. Gao. 2009. Current patents of forward osmosis membrane process. *Recent Patents on Chemical Engineering* **2**: 76–82.
- [7] McCutcheon, J. R., R. L. McGinnis, and M. Elimelech, 2006. Desalination by ammonia–carbon dioxide forward osmosis: influence of draw and feed solution concentrations on process performance, *Journal of Membrane Science*, **278**: 114–123.
- [8] Spiegler, K.S., and Y.M. El-Sayed. 1994. *A Desalination Primer*. Italy: Balaban Desalination Publications, ISBN: 0866890343.
- [9] Tzahi Y. T. Y. Cath, A. E. Childress; M. Elimelech. 2006. Forward osmosis: principles, applications, and recent developments. *Journal of Membrane Science* **281**:70–87.
- [10] Van't Hoff, J. H. 1899. The role of osmotic pressure in the analogy between solutions and gases, *The Modern Theory of Solution*, Memoirs by Pfeffer, van't Hoff, Arrhenius, and Raoult, Edited by H.C. Jones. New York and London, Harper & Brothers Publishers pp. 11-42.