تطوير تقنيات التناضح المباشر لتطبيقات تحلية مياه البحر في دولة الكويت
DEVELOPMENT OF FORWARD OSMOSIS TECHNOLOGIES FOR SEAWATER DESALINATION APPLICATIONS IN THE STATE OF KUWAIT

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Abstract

The State of Kuwait is facing a truly difficult challenge of supplying freshwater in a sustainable way for domestic and for the development of various activities. This is due to lack of natural resources for freshwater and the increasing population growth rate associated with urban expansion as well as increasing growth in commercial, industrial, and agricultural activities. Accordingly, the Ministry of Electricity and Water (MEW) must rapidly expand their desalination facilities to alleviate the freshwater shortages and to meet the country’s freshwater needs. However, conventional desalination technologies (CDT) are prohibitively expensive and energy-intensive process and they are suffering from several technical challenges. Therefore, it is required to seek for innovative desalination technology that eliminates the disadvantages of the CDT. Over decades, the research studies have remarkably developed several promising membrane separation processes, including forward osmosis (FO). FO process requires further research and development to bring the technology into developing competitiveness on the commercial level. Therefore, the aim of this paper is to share the knowledge and experience gained from extensive laboratory and pilot scale projects executed by Kuwait Institute for Scientific Research (KISR) with aim of adapting and developing the FO membrane technologies for desalinating Arabian Gulf seawater (AGS). This paper will present the influence of the most effective operating parameters upon separation performance of FO membrane. Furthermore, it will present the efficiency of a commercial scale hollow fiber FO membrane for seawater desalination by utilizing an innovative pilot plant test unit. The experimental results showed that the FO pilot plant is capable of desalinating AGS at TDS of 42,000 ppm and producing freshwater at TDS of 100 ppm with a water recovery ratio of 30%. This gives a clear indication that the FO pilot plant is potentially capable of producing final product water that meets the drinking water quality in terms of TDS. The chemical analysis results of product water showed that the quality is within the accepted limits, and is comparable to and comply with international standards for drinking water. These tests provided clear conclusions that the proposed FO technology is viable for seawater desalination.

Keywords: Direct osmosis, innovative desalination technology, membrane separation process, hollow fiber membrane.

Introduction

The increasing demand for freshwater and scarcity of natural sources of freshwater in the State of Kuwait have led the country to depend on the Arabian Gulf seawater (AGS) as a main source to produce freshwater through conventional desalination processes. Multi-stage flash distillation (MSF) and reverse osmosis (RO) technologies are currently being utilized in the existing desalination plants of the Ministry of Electricity and Water (MEW) of Kuwait [MEW, 2015]. However, these processes are prohibitively expensive and energy intensive. Additionally, these technologies provide low water recovery and produce high levels of brine discharged to the sea [Ahmad, 2012]. Furthermore, these systems are sensitive to the corrosion and scaling problems as well as fouling [Ge et al., 2013; Stone et al., 2013; Mulder, 1996]. Therefore, research and development in innovative non-conventional desalination technologies is substantially needed to improve the process reliability and sustainability as well as eliminate the limitations of MSF and RO technologies.

The research studies shows that the forward osmosis (FO) membrane process has high potential for seawater desalination applications and can be one of sustainable solutions for seawater desalination in near future [Wang et al., 2015; Cath, 2010]. A schematic diagram of the FO concept for seawater desalination is shown in Fig. 1. FO system is driven by a natural osmotic pressure generated by highly concentrated solution/agent known as draw solution (DS). The DS must have a higher salt concentration than that in the feed solution (FS) which creates a driving force in order to withdraw freshwater molecules from undesired solutes, dissolved in FS, through a semi-permeable FO membrane as shown in Fig. 1.

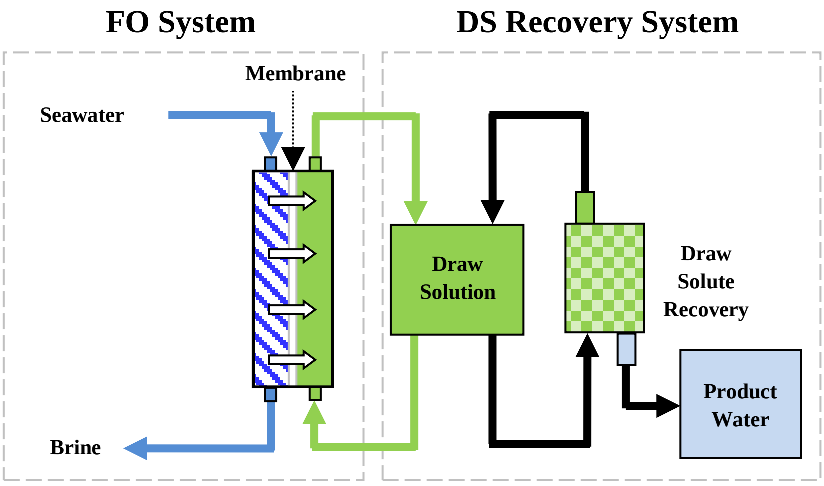

*Figure 1***.** A simplified schematic diagram of FO technology [Cath et al., 2006].

Previous studies have compared FO with conventional RO and reported that FO system consumes between 20 and 30% less energy (McGinnis and Elimelech, 2007), generates less brine discharge to the surrounding environment (Cath et al., 2006), has low fouling potential and high physical cleaning efficiency (Mi and Elimelech, 2010a; Husnain et al., 2015a), and higher boron rejection (Nicoll, 2013). Despite the advantages of the FO system in the desalination applications, the FO process is not well developed and has not yet reached a maturity level for commercial applications. The main problem that limits the widespread application of the FO system is to determine the most viable DS recovery system that is potentially capable of continuously and constantly generating high osmotic pressure required for maintaining the water flux at desired levels in the FO process, and at the same time to produce high-quality water with a total elimination of the DS residue in the final product water [Su et al., 2013]. The researchers worldwide are focusing on research activities that eliminate the aforementioned limitations of FO. Accordingly, researchers in Gulf Cooperation Council (GCC) are also conducting researches in optimizing the FO process parameters for desalinating high saline water with low water production cost. Since the FO technology has not been investigated in the State of Kuwait, Kuwait Institute for Scientific Research (KISR) in collaboration with well-known international FO developers are conducting research studies on FO technology at laboratory and pilot scale levels to take lead in the development and innovation in this area of research. These studies are vital to investigate the FO system for desalinating the AGS under the prevailing conditions of Kuwait for a better understanding and filling some of the existing gaps of know-how in recovering DS and product water from the diluted DS of the FO system at a reasonable cost and reasonable reliability with the least harm to the environment. The outcome of these studies will eventually benefit MEW when the proposed FO system is well developed and reaches a maturity level for large-scale commercial applications to supply freshwater in Kuwait. Therefore, this paper will provide the main findings of studies conducted by KISR on FO technology at laboratory and pilot-scale levels.

FO Theory

The most important equations, which are involved in this study, are described in this article. According to Van't Hoff (1899), the osmotic pressure (π) for any aqueous solutions can be mathematically determined by using the following equation:

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

Where c is the molar concentration of the solute, R is the gas constant (0.082 L.bar/deg.mol), and T is the temperature on the absolute temperature scale (Kelvin).

For each experiment, the water flux was mathematically calculated from the decrease in the weight of the FS over running time [Ng et al., 2006] and, hence, the water flux is determined by the following term:

$$\text{Water Flux} = \frac{\Delta \text{Weight}}{\text{Water density} \times \text{membrane surface area} \times \Delta \text{ time}} \tag{2}$$

Based on the recommendation of the FO developer, the water flux, Liter per Meter Square Hour (LMH), can be analytically determined by using the following expression:

$$\text{J} = \frac{\text{Vf}_2 \text{ - Vf}_1}{[\text{t}_2 \text{ - t}_1]} \times \left(\frac{1}{A}\right) \tag{3}$$

Where Vf_2 represents a volume of FS at time 2, Vf_1 represents volume of FS at time 1, t_2 is time reading 2, t_1 is time reading 1, and A is membrane surface area, $0.5m^2$.

Similarly, the permeate volume was theoretically determined from the decrease in the initial volume of the FS over running time. Thus, the water recovery ration of the FO system was calculated by the following term:

$$\text{Recovery} = \left(\frac{V_P}{V_F}\right) \times 100 \tag{4}$$

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

Materials and Methods

Laboratory Test Unit

The test unit consisted of two loops, i.e. DS and FS loops, as shown in Fig.2. The main parts of the test unit, including all necessary accessories and auxiliaries as well as the measuring instruments, as per the design were identified. As shown in Figure 3, the experimental setup comprised of an FO membrane housing (MB), overhead stirrer assembly for FS (S1), overhead stirrer assembly for DS (S2), inlet pressure gauge indicator (P1), outlet pressure gauge indicator (P2), FS pump (FP), DS pump (DSP), digital recirculating bath for FS (T1), digital recirculating bath for DS (T2), portable electrical conductivity meter for FS (EC1), portable electrical conductivity meter for DS (EC2), portable pH meter for FS (pH1), portable pH meter for DS (pH2), flow gauge indicator for FS (FM1), flow gauge indicator for DS (FM2), weighing scale for FS (B1), weighing scale for DS (B2), personnel computer (PC).

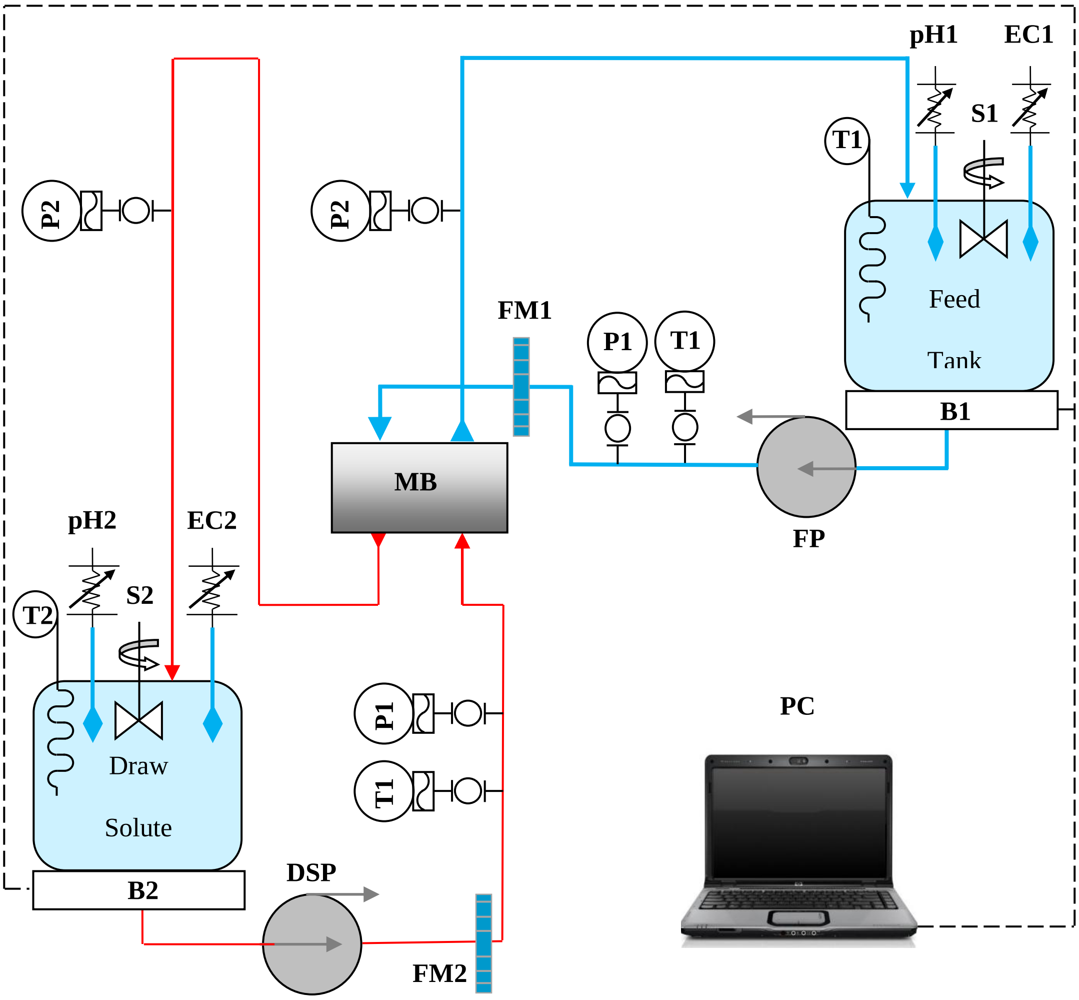

Figure 2. Schematic diagram of the Laboratory-scale Test Unit.

Materials used in Laboratory Scale Investigations

Sodium chloride (NaCl) has been utilized to prepare the FS and DS for the laboratory studies. The NaCl used was analytical reagent grade with 99.9% purity (Techno Pharmchem, Sodium chloride AR – 33127). Deionized water (DI), NaCl solutions, AGS, and RO brine were used as FS. A commercially available semi permeable spiral wound FO membrane element from Hydration Technology Innovations (HTI, OsMem 2521FO-MS-CTA-P-3H), which is made of Cellulose tri acetate (CTA), was used in the laboratory scale study. These membranes are considered to be unique, innovative and experimentally proved to be the best commercially available FO membrane for seawater desalination applications [Tzahi et al., 2006; Cath et al., 2006]. The RO brine was obtained from the seawater reverse osmosis (SWRO) unit installed at Desalination Research Plant (DRP).

Experimental Procedure used in Laboratory Scale Investigations

The laboratory scale tests were performed in batch mode. The FS and DS reservoirs were filled with a predetermined mass of FS and DS, which were 10 and 5 kg, respectively. The temperature of the FS and DS was set into a predetermined level by means of a recirculating cooling/heating bath. The FS and DS pumps recirculated FS and DS from the reservoirs to the membrane housing. The affecting parameters, such as concentrations, temperature, pressure, and flow rate of FS and DS, were set at the predetermined values according to the experimental envelop. As the FS and DS circulate inside the membrane housing, due to osmotic pressure gradient, DS extracts water from the FS. As a result, the FS level in the FS reservoir was gradually reduced and vice versa. Accordingly, the FS conductivity in the FS reservoir was gradually increased, whereas the DS conductivity in the DS reservoir was gradually decreased.. The operating parameters were monitored and recorded every 5 min while performing the experiment. After running the test 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.

Pilot Scale Test Unit

The FO pilot plant test unit with a capacity of 10 m^3/d was constructed by Trevi Systems Inc., USA for desalinating AGS as shown in Plate 1 and Figure 3.

Plate 1. FO Pilot Plant at DRP

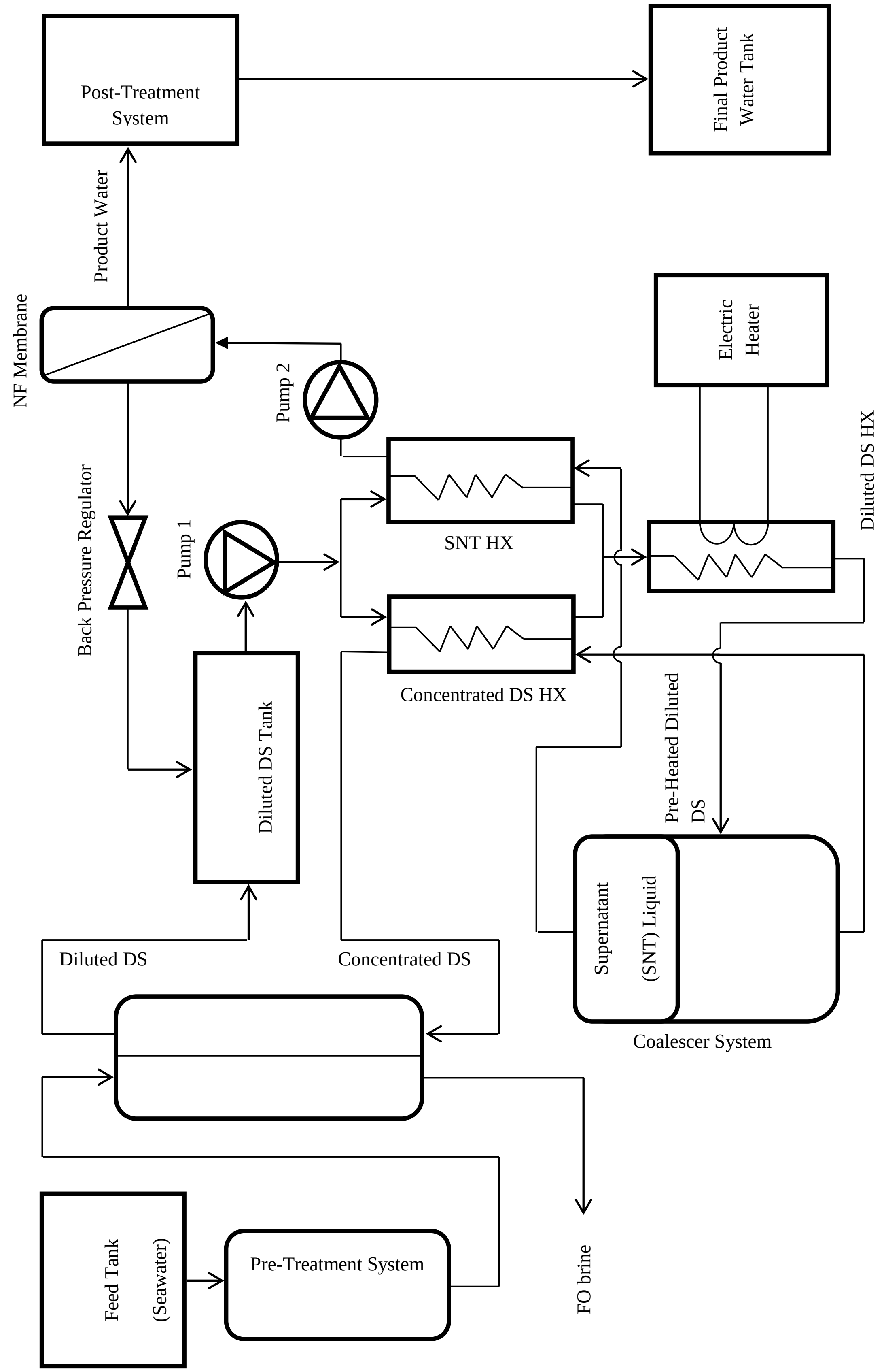

Figure 3. Schematic Diagram of the Pilot-Scale Test Unit.

The pilot plant is supplied with full-scale hollow fiber FO membranes that were recently being developed by Toyobo Co. This pilot plant will utilise the integration of thermal and membrane separation concepts by utilizing a coalescer system and Nanofiltration (NF) membrane technology as draw solution regeneration process.

Materials used in Pilot Scale Investigations

The Trevi Systems' FO System is designed for continuous operation. The FO pilot plant is an hybrid unit of four stage processes: (1) pre-treatment system and anti-scalant dosing, (2) water permeation through the FO membrane and dilution of the polymer draw solution in the shell side, (3) electrically heated coalescer system for polymer draw solution recovery, and (4) the post treatment system for removing any traces of polymer from the final product water. The pre-treatment side consists of feed pump, cartridge filters, anti-scalant dosing, pH, temperature and conductivity sensors. The FO membrane part consists of DS pump, various valves and sensors and the FO Membrane Module. The draw solution recovery part of the system consists of three heat exchangers, coalescer tank, heater loop, and various sensors and automated valves. The post-treatment system consists of supernatant pump, nano filters, product water polishing tanks, and assorted automated valves and sensors. The membrane used was recently developed hollow fibre FO membrane made of cellulose triacetate and with 230 micron bore diameter. The polymer draw solution used was ethylene oxide-propylene oxide copolymer patented by Trevi systems Inc. and the coalescer temperature was set at 85°C. The feed used was AGS obtained from beach well located at DRP in Doha, Kuwait.

Experimental Procedure used in Pilot Scale Investigations

The FS, which is actual seawater seawater obtained from beach well is passed to the bore side of the membrane at pressure less than 2 bar. The DS which is heated to 85 degree Celsius is passed to the DS heat exchanger and then passed to the shell side of the FO membrane. As the FS and concentrated DS flows through the bore side and shell side of the semi-permeable membrane respectively, the membrane allows only pure molecular water to pass through it. Due to the power of osmosis gradient, pure water is drawn through the membrane from the FS into the DS, thus, leaving a highly concentrated brine fluid on the FS side and a DS that has been infused with and diluted by the pure water that has left the FS. This diluted DS is then fed to the DS recovery systems consisting of coalescer and heat exchangers, where the diluted DS is separated in to supernatant water and concentrated DS. The concentrated DS is again fed back to the FO membrane system for drawing more water and the process continues. The supernatant water is then passed though the post treatment system and heat exchangers and final product water is produced.

Results and Discussions

Laboratory Scale Results

The water flux and recovery at different salt concentration of FS and DS using NaCl is shown in Figures 4. It is obvious from the figures that higher DS concentrations resulted in increased water flux and water recovery. As the DS concentration is increased with respect to the FS, the osmotic pressure gradient increases and this resulted in higher flux and recovery. Also, the figure shows the effect of FS concentration upon water flux and water recovery. The increase in FS concentration will result in low water flus and water recovery and this is due to the lower osmotic pressure gradient. In order to illustrate this, curves presenting FO membrane performance on FS using DI water is shown in the figures.

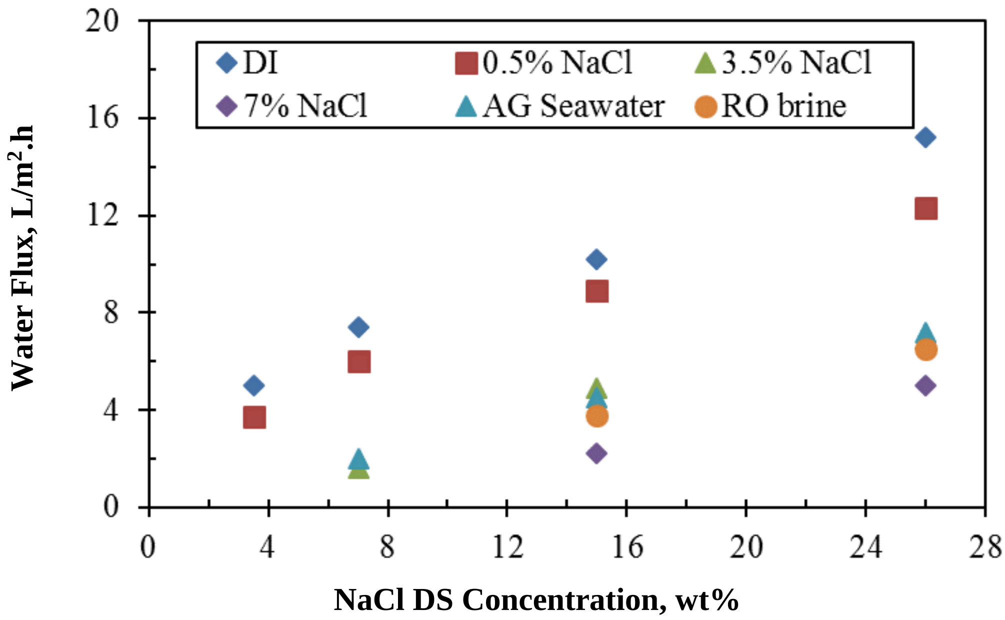

Figure 4. Water Flux obtained for various FS and NaCl DS concentrations

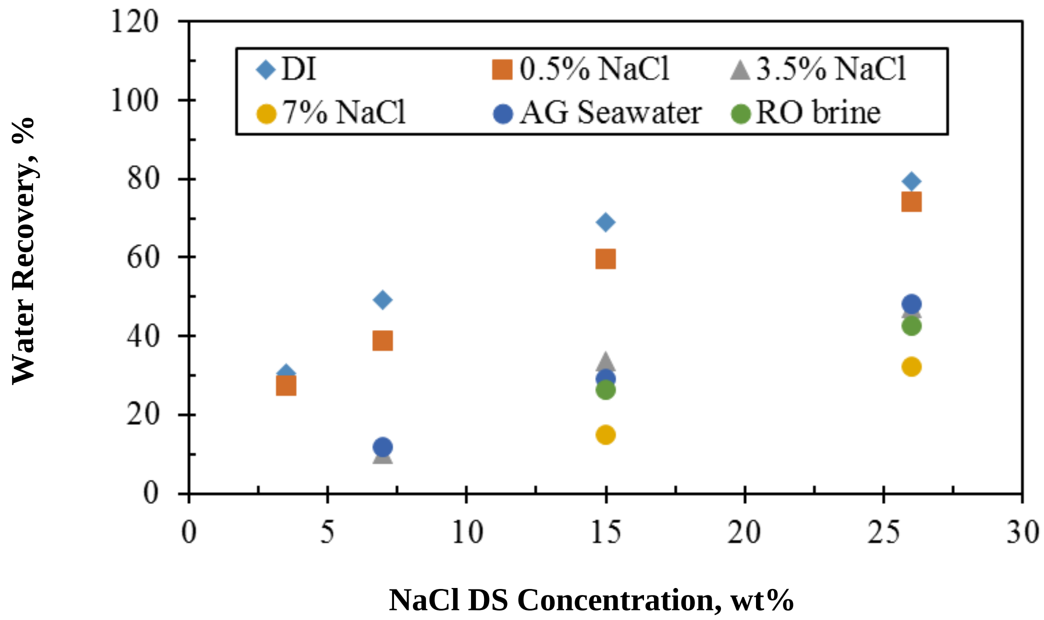

Figure 5. Water Recovery obtained for various FS and NaCl DS concentrations

Thus, by using NaCl DS at concentration of 15 wt% , the experimental data showed that the water recovery ratios of around 34% and 26% can be achieved for AGS and RO brine, respectively. Also, as shown in Figure 5 as the NaCl Ds was increased from 15 to 26%, the water recovery ratios reached around 48% and 43% for AGS and RO brine, respectively. As for low FS concentrations, by using NaCl DS of 15 wt%, the experimental results showed that the water recovery ratios can reach around 69% and 60% for DI and low saline water (having a TDS value similar to that of brackish-water and municipal wastewater), respectively. By increasing the initial DS concentration from 15 to 26 wt%, water recovery ratios could reach around 79% and 74% for DI water and 0.5 wt% NaCl FS, respectively.

The laboratory experimental studies showed that water flux was decreased with running time with all feed concentrations as shown in Figure 6. The two main reasons behind this are: (i) the DS that diffused into the porous support layer got diluted during the FO process and as a result reduced the effective overall driving force. Accordingly, the osmotic pressure difference (ΔΠ) is reduced over the time of the experiment; and (ii) water flux was affected by the internal concentration polarization (ICP).

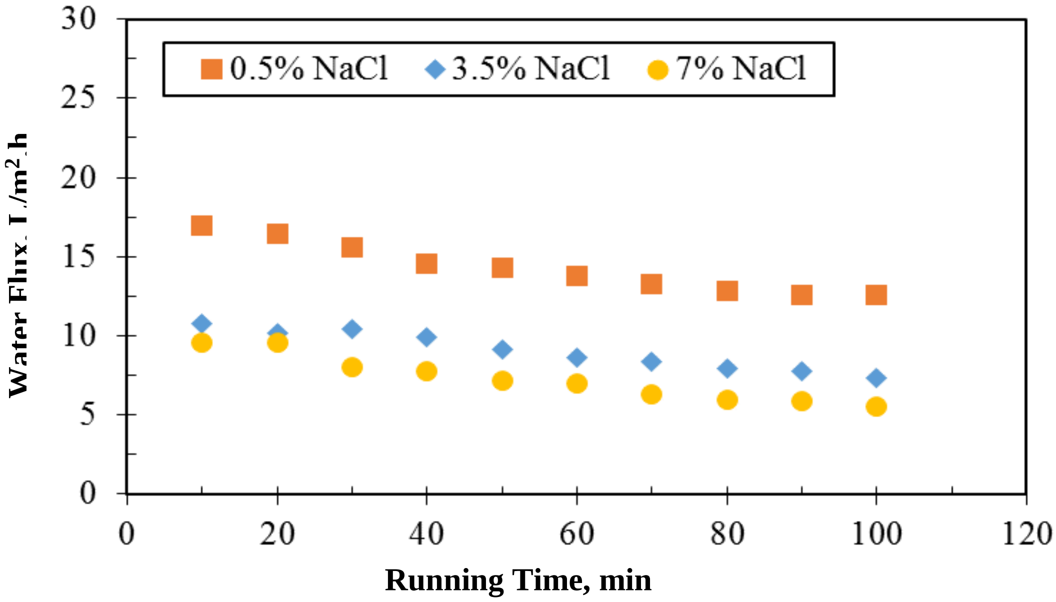

Figure 6. Water flux vs running time for various NaCl FS concentrations and using 26% NaCl DS at 25°C.

The effect of FS and DS temperature upon the water flux is shown in Figure 7. The FS and DS temperatures were varied from 15 to 40°C in order to determine the influence of temperature on the water flux.

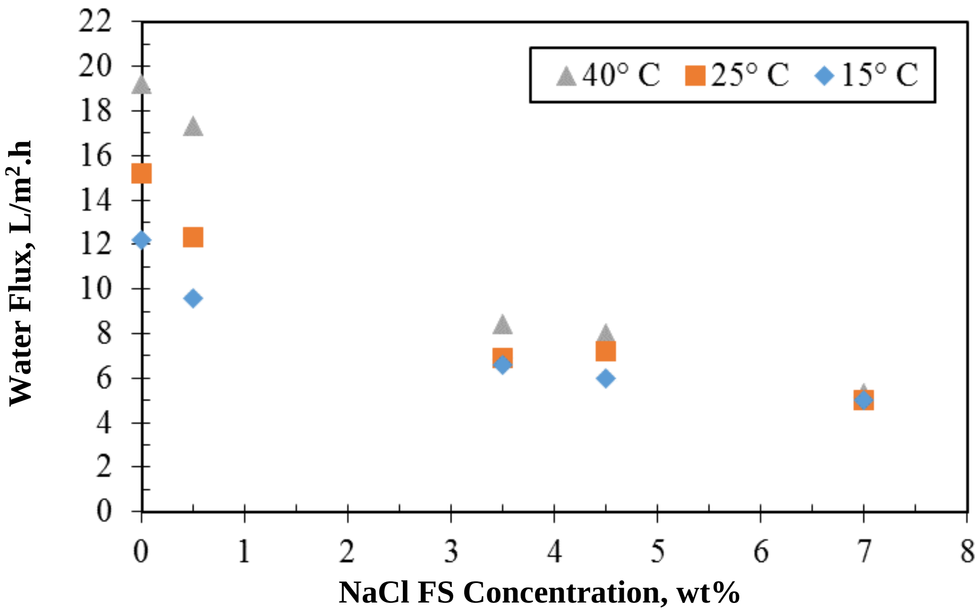

Figure 7. Effect of temperature upon water flux for various FS concentrations and using 26% NaCl DS.

The study showed that the water flux is proportionate to the FS and DS temperature. The increased water flux with increase in temperature could be resulted from the reduction in solution viscosity, which consequently increased the diffusion rate. The figure shows that the water flux was increased from 15.2 to 19.2 $l/m^2.h$ for DI feed as the temperature was increased from 25 to 40°C.

Tables 1 and 2 shows the major ionic composition of the AGS and RO brine, before and after each test, at different NaCl DS concentrations, respectively. It is obvious from Table 1 that the tested FO membrane was capable of significantly increasing the TDS value of AGS from 45,013 ppm to 88,557 ppm by using NaCl DS of 26 wt%. Similar trends was observed with RO brine FS also as shown in Table 2. These data's shows the potential of using FO technology for Zero Liquid Discharge (ZLD) applications.

Table 1
Major Ionic Composition of AGS FS at the start and end of the experiment Using NaCl DS

Parameter	Unit	AGS	NaCl DS Concentration		
			7 wt%	15 wt%	26 wt%
TDS	mg/l	45,013	51,938	67,972	88,557
Ca^{2+}	mg/l	825.3	993	1,326	1,704
Mg^{2+}	mg/l	1,338.2	1,558	1,939	2,493
Na^{+}	mg/l	1,2232	13,486	19,059	26,973
$(SO_4)^{2-}$	mg/l	3,431	3,889	5,306	7,368
$(HCO_3)^{-}$	mg/l as $CaCO_3$	140.6	143.2	214.3	278.3
Cl^{-}	mg/l	22,065	25,256	34,112	47,569
K^{+}	mg/l	299	423	816.7	918.3
NO^{3-}	mg/l	3.87	4.5	5.67	6.12

Table 2
Major Ionic Composition of RO brine FS at the start and end of the experiment Using NaCl DS.

Parameter	Unit	RO Brine	NaCl DS Concentration	
			15 wt%	26 wt%
TDS	mg/l	55,087	75,254	103,995
Ca^{2+}	mg/l	1,076	1,466	2,015
Mg^{2+}	mg/l	1,669	2,146	2,345
Na^{+}	mg/l	16,274	23,400	35,214
$(SO_4)^{2-}$	mg/l	3,300	5,600	8,000
$(HCO_3)^{-}$	mg/l as $CaCO_3$	178.6	237	283.5
Cl^{-}	mg/l	28,607	39,547	55,213
K^{+}	mg/l	508	840	984
NO^{3-}	mg/l	6	6	7.34

Pilot Scale Results

The laboratory results provided scientific data on the potential of using FO technology for AGS desalination applications. In order to assess the efficiency of the innovative hollow fiber FO membrane for AGS desalination by utilizing a pilot plant test unit and to check the stability of FO pilot plant for commercial applications under the prevailing conditions of Kuwait, an operating envelope was prepared as shown in Table 3. The pilot plant tests are currently ongoing as per the operating envelope. This section will give a brief overview on the data obtained so far on the performance of the FO pilot plant.

Table 3
Overview of the Logic of the Experimental Envelop of the Pilot Plant.

<table>
<tr><th colspan="3">Parameter</th><th></th><th>Reasoning</th></tr>
<tr><td colspan="3">FS Temperature, °C</td><td>RT</td><td>Beach well seawater with a steady temperature around 25°C will be investigated.</td></tr>
<tr><td colspan="3">FS Flow-rate, L/min</td><td>12-16</td><td>Testing the effect of FS flow-rate upon the performance indicators.</td></tr>
<tr><td colspan="3">DS Flow-rate, L/min</td><td>8-18</td><td>Testing the effect of DS flow-rate upon the performance indicators.</td></tr>
<tr><td>Source of FS</td><td colspan="2">Arabian Gulf Seawater, ppm</td><td>42,000</td><td>Testing with actual Arabian Gulf seawater conditions for usual design cases of commercial plants.</td></tr>
<tr><td rowspan="3">Source of DS</td><td rowspan="3">Polyalkylene Glycol (PAG)</td><td rowspan="3">Grade</td><td>A</td><td rowspan="3">Testing the effect of three different DS upon water recovery ratio and permeate quality.</td></tr>
<tr><td>B</td></tr>
<tr><td>C</td></tr>
<tr><td colspan="3" rowspan="3">DS Temperature, °C (Coalescer)</td><td>75</td><td rowspan="3">Testing the effect of the temperature in the coalescer upon supernatant quality and thermal energy consumption.</td></tr>
<tr><td>80</td></tr>
<tr><td>85</td></tr>
<tr><td colspan="3" rowspan="2">Bore Diameter of the Hollow Fiber Membrane, µm</td><td>135</td><td rowspan="2">Testing the effect of bore diameter of the hollow fiber membrane upon water recovery ratio and permeate quality.</td></tr>
<tr><td>235</td></tr>
</table>

The DS flow rate was varied from 8 to 18 liter per minute while keeping the FS flowrate constant. The DS is distributed to the shell side of the membrane through a centre tube in the membrane module as shown in Figure 8. The DS then flows radially through the membrane and the concentration of the DS will be the highest at the area near to the centre tube. As it flows radially through the membrane it gets diluted and will be of less concentration as it reaches the area far to the centre tube. So, with increasing flow rate of DS it is possible to have less DS concentration gradient across the membrane and this results in higher water flux and product flow rate as shown in Figure 9. It was observed that the effect of flow rates upon product water flow rate and water recovery is not linear and this could be due to the limited capacity of the heat exchanger and coaelescer used in the current system.

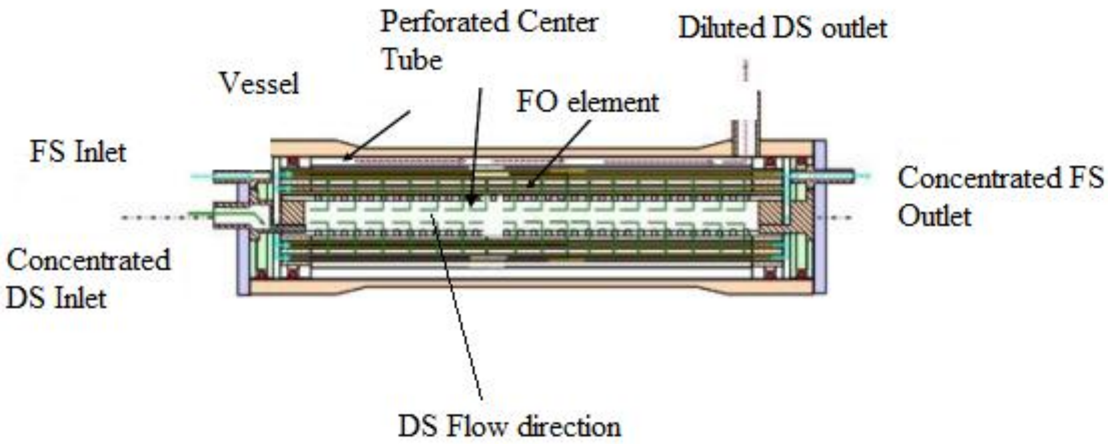

Figure 8. Schematic diagram of the configuration of the TOYOBO FO membrane module.

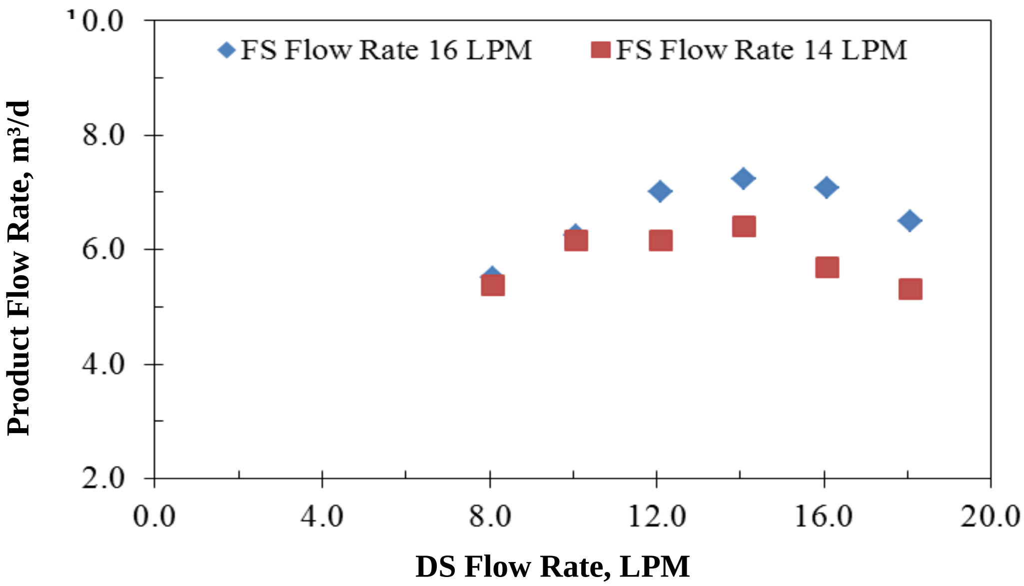

Figure 9. Effect of DS Flow Rate upon Product Water Flow rate at different FS Flow rates

In the case of FS flow rate, the pilot plant was tested at two flow rates, 16 and 14 lpm. It is clear from the Table 4 that higher FS flow rates are recommended to increase the product flow rate. The FS is distributed to the bore side of the membrane and it flows in axial direction as shown in Figure 8. As the FS flows from the inlet to the outlet side, the concentrated DS near the centre tube draws more water from FS, and as it reaches the outlet will be highly concentrated. It is assumed that when the FS flow rate is increased the concentration gradient of FS between the inlet and outlet will be less than at lower FS flow rates.

Table 4
Effect of FS Flow Rate upon Product Water Flow rate and Water Recovery

DS Flow Rate, LPM	Product Capacity , m³/d		Recovery Ratio %	
	FS Flow Rate 14 LPM	FS Flow Rate 16 LPM	FS Flow Rate 14 LPM	FS Flow Rate 16 LPM
8.1	5.3	5.5	26.1	23.7
10.1	6.0	6.3	30.2	28.8
12.1	6.2	7.0	31.2	30.1
14.1	6.4	7.2	31.3	31.1
16.1	5.7	7.1	27.9	29.9
18.1	5.4	6.5	28.1	28.9

Table 5 show the physiochemical analysis of all the three streams of water from the pilot plant, namely, FS, product and brine. The samples were collected in 1-liter polyethylene (PE) bottles, which were washed with deionized water prior to use. The samples were then tested in DRP laboratory for various physiochemical parameters. The pH, conductivity and Total Dissolved Solids (TDS) were measured by pH, conductivity and TDS meters, respectively. The other parameters such as calcium, magnesium, chloride and sulphate were estimated by Ion Chromatography System (ICS), whereas, boron and sodium is estimated by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). The parameters such as nitrate, copper, chromium, iron, silica, phosphate and fluoride are estimated by spectrophotometer (DR-6000). All analysis was done in triplicate and average values were taken for analysis.

Table 5
Physiochemical Analysis of FS, FO Product and FO Brine Samples Collected from FO Pilot Plant

Parameter	Unit	AGS Feed	FO Product	FO Brine
pH		7.4	7.2	7.3
Conductivity	mS/cm	55.4	0.29	76.5
TDS	ppm	35801	143	49518
Calcium	mg/L	824	6.16	1288
Magnesium	mg/L	1154	5.83	1720
Sulfate	mg/L	3600	0	4600
Chloride	mg/L	26000	38	37000
Sodium	mg/L	14,800	65	20,100
Alkalinity	mg/L	120	4.3	160
Boron	mg/L	2.75	0.24	2.9
Nitrate	mg/L	3.5	0.7	4.3
Copper	mg/L	<0.05	<0.05	<0.05
Chromium	mg/L	<0.05	<0.05	<0.05
Iron	mg/L	<0.05	<0.05	<0.05
Silica	mg/L	16.2	0.724	25.7
Phosphate	mg/L	0.15	0.11	0.3
Fluoride	mg/L	4.3	0.13	5.5

It is very important to state that FO pilot plant was able to reduce the TDS from 35801 ppm to 143 ppm in a single stage process using single hollow fibre FO membrane. The TDS of FO product is low taking it in to account that the TDS of RO first stage product at DRP is around 390 ppm. The FO pilot plant was operated continuously for 30 days under the optimum flow conditions for FS and DS shown in Table 4, i. e FS flow rate at 14 LPM and DS flow rate at 16 LPM. It was observed that the performance of the pilot plant was stable during the 30 days continuous operation as shown by TDS and water recovery percentage values in Figure 10. There was no significant change in TDS and water recovery percentage values during the observation period.

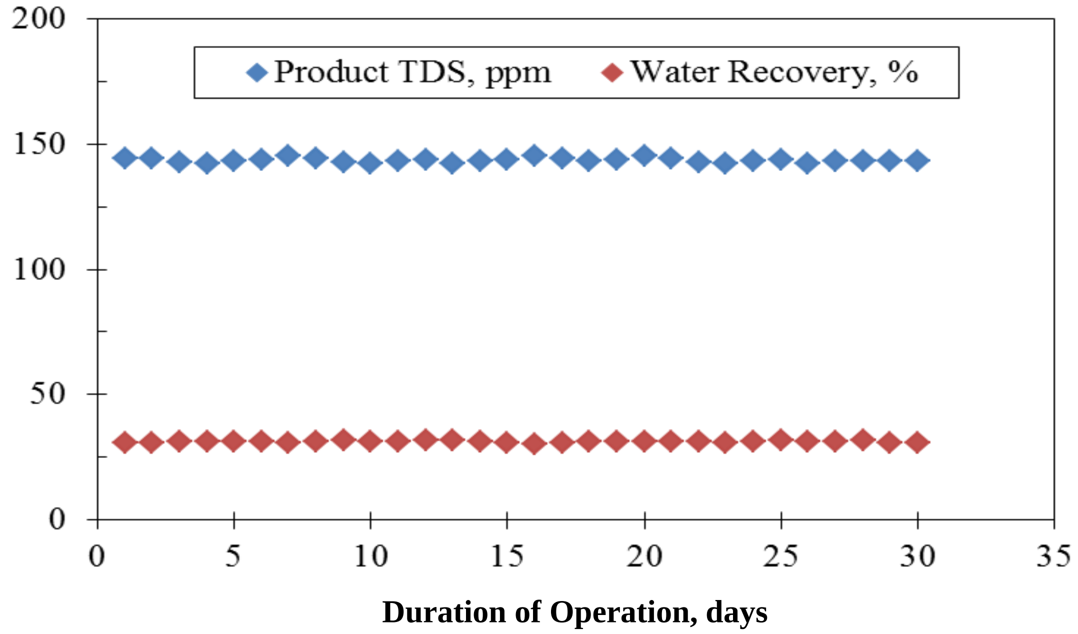

Figure 10. Product TDs and FO pilot plant Water Recovery Distribution over a period of 30 days continuous operation

The preliminary calculation of thermal energy required by the FO pilot plant is approximately 2 ~2.5 kWh/m^3, which is much lower than that the conventional desalination processes of MSF (38 kWh/m^3 thermal energy) and MED/TVC (38 kWh/m^3 thermal energy). In order to proceed to the semi-commercialization of FO pilot plant a detailed monitoring and analysis of water quality, FO performance stability and actual total energy consumption should be carried out for a longer period of time. The on-going operation of the FO pilot plant at DRP for a period of one year will provide a series of data or trends to confirm the performance reliability of FO technology for AGS desalination.

Conclusion

This paper evaluated the feasibility of FO technology for AGS desalination at laboratory and pilot scale levels. The laboratory scale studies proved that the investigated FO membrane elements with NaCl DS were potentially capable for extracting freshwater from different sources and salinities of aqueous solutions. The experimental data obtained in the laboratory scale studies can be used as a reference for designing a pilot plant test unit for further research and development using NaCl as DS. The values of water quality parameters obtained from the FO pilot plant are promising and proved that FO technology can be considered as an alternative desalination process to conventional desalination technologies. It was presented that single stage FO desalination may produce the product water of high quality. The FO pilot plant over a continuous operation of 30 days was capable to produce product water of TDS ≈ 100 to 150 ppm at water recovery ratio of ≈ 30%. The results of the pilot scale study demonstrate the potential of using FO process for sea water desalination and will lead the research community to accelerating the technical and economical evaluation of FO desalination systems. However, detailed techno-economic analysis is also recommended to be taken into consideration in future study to estimate the actual energy consumption of the investigated FO process and compare the results obtained to the conventional desalination technologies such as MSF and RO.

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