*Desalination and Water Treatment*
www.deswater.com
doi: 10.5004/dwt.2020.25526

# A comparative study of two different forward osmosis membranes tested using pilot-plant system for Arabian gulf seawater desalination

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**ABSTRACT**

A pilot-scale forward osmosis (FO) desalination system of capacity 10 m$^3$/d was successfully established at Doha desalination research plant (DRP) of Kuwait Institute for Scientific Research (KISR), during October, 2016. The pilot-plant system has access to evaluate the performance of different FO membranes developed by world leading manufacturers and also the efficiency of different draw solutions (DS). The current study was aimed at evaluating the performance of two different hollow fiber FO membranes with different bore diameters of 135 and 230 µm, respectively. The DS consisted of high osmotic polyelectrolyte thermoresponsive polymer; whereas the feed solution (FS) was Arabian Gulf seawater supplied from the beach well of DRP, to demonstrate the direct application of pilot-plant FO system for desalination application. The FS was passed through the bore side and polymer DS was passed through the shell side of the membrane. The DS which was diluted due to the water permeated through the membrane as a result osmotic pressure difference was sent to the coalescer at 85°C, where the diluted polymer DS was separated into supernatant water and concentrated polymer DS. The membrane performance was evaluated in terms of FO flux, salt rejection and water recovery. The membrane with 230 µm has observed highest performance during FO operation with water recovery of around 30% and by reducing the total dissolved solids from 40,000 to 130 ppm. The high performance associated with 230 µm membrane is attributed to the more diffusion of the highly concentrated DS towards membrane lumen side. Such diffusion resulted in high osmotic pressure difference which is considered as the driving force across the membrane. Additionally, less pressure-drop experienced by the 230 µm membrane between its bore side and outer shell side could be the reason for its high-water recovery. The results of this study demonstrated the potential of using FO membrane with larger bore diameter with controlled flow rate to attain high performance in the thermal-based FO seawater desalination.

*Keywords:* Forward osmosis; Polymer draw solution; Hollow fiber membrane; Bore diameter; Arabian Gulf seawater desalination

## 1. Introduction

The State of Kuwait depends 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) desalination technologies are currently being utilized in the existing desalination plants of the Ministry of Electricity and Water (MEW) of Kuwait. MSF desalination plants continue to dominate due to their proven high operational reliability and the convenience of their integration with existing power plants (Ettouney and Wilf 2009). The proportion of desalination capacity supplied by RO is increasing due to its better economics when compared with MSF process. However, in general, these processes are prohibitively expensive and energy intensive. Additionally, these technologies provide low water recovery and discharge high levels of brine to the environment (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 and Mulder 1996). Therefore, focus on commercializing non-conventional desalination technologies developed by recent researches and developments in seawater desalination technologies is substantially needed to eliminate the limitations of MSF and RO technologies.

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Presented at the 13th Gulf Water Conference – Water in the GCC: Challenges and Innovative Solutions. 12–14 March 2019, Kuwait

1944-3994/1944-3986 

The research studies shows that the forward osmosis (FO) membrane process has high potential for seawater desalination applications and can be one of the sustainable solutions for seawater desalination in near future (Wang et al. 2015 and Cath 2010). The absence of high pressure pumps in FO can lower energy consumption in seawater desalination process compared with RO (Hartanto et al. 2016). FO is driven by the osmotic pressure gradient between two solutions and eliminates the requirement for high hydraulic pressure. In FO process, water naturally infuses through a semipermeable membrane from the feed solution at a lower osmotic pressure to the draw solution at a higher osmotic pressure. A regeneration process removes water from the diluted draw solution and re-concentrates the draw solution for reuse.

The advantages of FO over conventional RO such as 20% and 30% less energy requirement, less brine discharge to the surrounding environment, low fouling potential and high physical cleaning efficiency, and higher boron rejection has been reported in literatures (Hartanto et al. 2016, Cath et al. 2006, McGinnis and Elimelech 2007, Mi and Elimelech 2010, Husnain et al. 2015 and Nicoll 2013). In spite of these advantages of FO process in seawater desalination applications, the FO process has not yet reached commercial level applications. The key fact that limits the extensive use of the FO desalination process is the development of a viable draw solution (DS) and DS recovery system that is possibly capable of continuously and constantly producing high osmotic pressure vital for keeping the water flux at desired levels in the FO process, and at the same time to produce high-quality water with total rejection of DS residue in the final product water (Coday et al. 2014). Thus, the establishment of effective DS and DS regeneration system with energy-saving still remains as a major challenge for FO seawater desalination applications (Linares et al. 2014, Lutchmiah et al. 2014 and Lou et al. 2014). Hence, a breakthrough in FO technology is necessary to solve the aforementioned limitations by focusing on areas, such as FO membrane development, exploration of an innovative DS and DS recovery system, in order to compete with the existing technologies.

The researchers worldwide are still conducting researches in developing ideal DS and DS recovery system for desalinating high saline water with low water production cost. The three main requirements that are considered to be ideal for DS are, namely, higher osmotic pressure for high water flux, simple and low-cost regeneration, and least possible reverse solute flux (Ge et al. 2013 and Chekli et al. 2012). Conventional inorganic DS that generates high water flux has higher reverse solute flux due to its small molecular size (McCutcheon et al. 2005 and Achilli et al. 2010). As a result, polymers with relatively high molecular weight have been examined as FO draw solutes and observed that it reduces reverse flux and can be regenerated using ultrafiltration and membrane distillation (Ge et al. 2012). Draw solutes based on thermoresponsive compounds have attracted FO developers due to their unique response to temperature (Ling et al. 2011, Noh et al. 2012 and Han et al. 2013). Trevi Systems Inc. (TSI) have developed thermoresponsive polymer DS and subsequent thermal DS recovery system for seawater desalination application. Thermally responsive draw solutes are attracting researchers due to its simplicity, the absence of using extra chemicals and, most of all, the possibility of using less expensive and clean energy sources such as solar thermal energy and low-grade industrial waste heat (Cai et al. 2015). The thermo-responsive draw solutes are generally lower critical solution temperature (LCST) materials. The LCST materials are miscible with water at higher concentrations at temperatures below the phase transition temperature and can withdraw water from feed solutions (Nakayama et al. 2014). The diluted LCST materials exhibits liquid–liquid (L–L) phase separation from water at a temperature higher than the phase transition temperature. The phase transition temperature of LCST materials can be reduced by altering the chemical structure. Thus, the energy requirement for the separation of draw solutes can be greatly reduced by using a LCST material with a low-phase transition temperature (Kim et al. 2011).

TSI has developed a FO pilot-plant hybridised with thermal separation system (FO-TS) for seawater desalination using the thermos-responsive polymer. The energy requirement of the FO-TS system is 87.5% less than the conventional RO by using solar energy or waste heat (Carmignani et al. 2012). Compared with FO-RO hybrid system, FO-TS technology is insensitive to the osmotic pressure as it can be operated with higher DS concentrations. However, a post-treatment system using conventional membrane processes, such as nano-filtration (NF) or brackish water (BW) RO membrane may still be required to polish the final product water. Pilot-level studies on thermally responsive organic compounds are greatly required as there is no significant information and data on the viability and efficiency of the aforementioned FO technology for seawater desalination (Cai and Hu 2016). Furthermore, testing and analysis of a full-scale FO module on a pilot scale is essential to design a commercial-scale FO pilot plant (Kim and Park 2011). The performance of large-scale commercialized spiral-wound FO membranes has been reported (Lutchmiah et al. 2014 and Kim and Park 2011),whereas limited studies have been reported for FO HF (Shibuya et al. 2016).

The FO technology has not been investigated in the State of Kuwait for seawater desalination applications. Accordingly, Kuwait Institute for Scientific Research (KISR) in collaboration with international FO developers are conducting 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 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 reliability with less harm to the environment. Therefore, this paper will provide the initial findings of ongoing pilot-scale study conducted by KISR on FO technology for seawater desalination application using commercially available hollow fiber (HF) FO membranes and thermoresponsive polymer DS developed by TOYOBO Co., Ltd. and TSI, respectively. The study is on-going and shows the primary results.

## 2. Materials and methods

### *2.1. 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. This pilot plant utilizes the integration of thermal and membrane separation system comprising of coalescer and NF membrane processes for DS regeneration.

### *2.2. Materials used in pilot-scale investigations*

The Trevi System's FO pilot plant is designed for continuous operation. The FO pilot-plant is a hybrid unit of four processes: (1) pre-treatment system and anti-scalant dosing, (2) FO process, (3) polymer draw solution regeneration process, and (4) the post treatment system. The pre-treatment side consists of feed pump, cartridge filters, anti-scalant dosing, pH sensors, temperature sensors and conductivity recorders. The FO part consists of DS pump, various valves and sensors and the FO membrane module. The draw solution regeneration part consists of three heat exchangers, stainless steel coalescer, heater loop, and various sensors and automated valves. The post-treatment system comprises of supernatant pump, nano filters, product water polishing tanks, and assorted automated valves and sensors. The membrane used was recently developed commercial 10-inch HF FO membrane from TOYOBO, Japan. The HF membranes are made of cellulose triacetate and are available at bore diameter of 230 and 135 micron. The HF FO membranes had an outer active layer surface. The HF FO module configuration is similar to HF RO and has four ports; FS inlet, FS outlet, DS inlet and DS outlet. The cross-wound HF FO membranes have high packing density and preferable flow pattern compared with other module configurations (Shibuya et al. 2016). The schematic illustration of the tested HF FO module with cross-wound configuration is shown in Fig. 1 (Shibuya et al. 2016). The FO HF membranes tested are 135 and 230 micron membranes. The thickness of 135 micron HF membrane is 100 µm, whereas, for 230 micron HF membrane is 140 µm. The number of HF in the 135 membrane module is around 500,000 whereas in 230 micron membrane is around 220,000. The large number of HF membranes results in a higher total effective membrane area. The packing density was approximately 50% around a central core tube from which the polymer DS was supplied. The polymer draw solution used was ethylene oxide-propylene oxide copolymer (TL-1150-1) patented by Trevi systems Inc. and the coalescer temperature was set at 85°C. The cloud point temperature of the DS is between 40°C and 90°C. The feed used was AGS obtained from beach well located at DRP in Doha, Kuwait.

### *2.3. Experimental procedure used in pilot-scale investigations*

The AGS obtained from beach well is passed to the bore side of the FO membrane at pressure less than 2 bars. The direction of the feed flow was in axial direction. The DS which is heated to 85°C is passed to the DS heat exchanger and cooled to temperatures lower than 40°C. The DS is then passed to the shell side of the FO membrane through the centre core. The direction of the DS flow was in radial direction between HF tubes. As the FS and concentrated DS flows through the bore side and shell side of the semi-permeable membrane, respectively, due to the osmotic pressure gradient, pure water is drawn through the membrane from the FS into the DS. Thus the DS is infused with and diluted by the pure water that has left the FS. The diluted DS is then fed to the DS recovery systems consisting of coalescer and heat exchangers which are set at temperatures higher than the phase separation temperature of the DS. As a result, the diluted DS is separated into supernatant water and concentrated DS. The concentrated DS is again circulated back to the FO membrane system for further water production and the process continues. The supernatant water is then passed through the post treatment system and heat exchangers and final product water is produced. The flow rates, conductivity, pressure, and temperature of all streams were recorded using a data logging system. In order to assess the efficiency of the innovative HF FO membrane and thermos-responsive polymer for AGS desalination at pilot-scale level, and to check the


Plate. 1. FO Pilot Plant at Desalination Research Plant (DRP).

stability of FO pilot plant for commercial applications under the prevailing conditions of Kuwait, an operating envelope was prepared.

### 2.4. Osmotic pressure measurement

The osmotic pressures of the concentrated and diluted DS were measured using a Wescor 5600 vapor pressure osmometer. The osmolality (m in mol/kg) of DS was measured for DS and then, the osmotic pressure was theoretically calculated using the following equation (Money 1989 and Cheng et al. 2013):

$$\pi = m\ \rho RT$$

where $\pi$ is the osmotic pressure, $\rho$ is the density of water, and $R$ and $T$ are the ideal gas constant and absolute temperature, respectively. The theoretically calculated value is then compared with the osmotic pressure value obtained from the refractive index measurements using Atago PAL-RI meter.

## 3. Results and discussions

This section will give a brief overview on the data obtained so far on the performance of the FO pilot plant.

The DS flow rate was varied from 8 to 18 liter per minute while maintaining the FS flow rate constant. The DS is dispersed to the shell side of the membrane through a central core tube in the membrane module as shown in Fig. 1. The DS then runs radially through the membrane module and the concentration of the DS will be the maximum at the area near to the centre tube. As it flows radially through the membrane between the HF tubes, it gets dilute due to infusion of water molecules from the feed, 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 radially across the membrane. The lower concentration gradient across the membrane at higher DS flow rates resulted in overall high water flux and product flow rate as shown in Tables 1 and 2.

In addition, the higher DS flow rate might lessen the polymer layer thickness on the membrane surface and thus reduces the concentration polarization effect (Kim and Park 2011, Chakrabortty et al. 2015 and Kim et al. 2014). The effect of DS flow rates upon production capacity and water recovery is not linear and this could be due to the restricted capacity of the DS heat exchanger as well as, the limited split-up capacity of coalescer used in the present system. As the DS flow increases, the lasting time of the polymer in the coalescer is reduced and this will

Table 1
Effect of DS flow rate upon production capacity and water recovery ratio using 230 micron membrane

| FS flow rate, LPM | DS flow rate, LPM | Capacity, $m^3/d$ | Recovery ratio % |
|---|---|---|---|
| 16.0 | 8.1 | 5.5 | 23.7 |
| | 10.1 | 6.3 | 28.8 |
| | 12.1 | 7.0 | 31.2 |
| | 14.1 | 7.2 | 31.1 |
| | 16.1 | 7.1 | 29.9 |
| | 18.1 | 6.5 | 28.9 |

Table 2
Effect of DS flow rate upon production capacity and water recovery ratio using 135 micron membrane

| FS flow rate, LPM | DS flow rate, LPM | Capacity, $m^3/d$ | Recovery ratio % |
|---|---|---|---|
| 16.0 | 8.1 | 4.6 | 22.6 |
| | 10.1 | 4.8 | 27.6 |
| | 12.1 | 4.9 | 28.5 |
| | 14.1 | 5.2 | 27.9 |
| | 16.1 | 4.7 | 26.6 |
| | 18.1 | 4.2 | 25.8 |

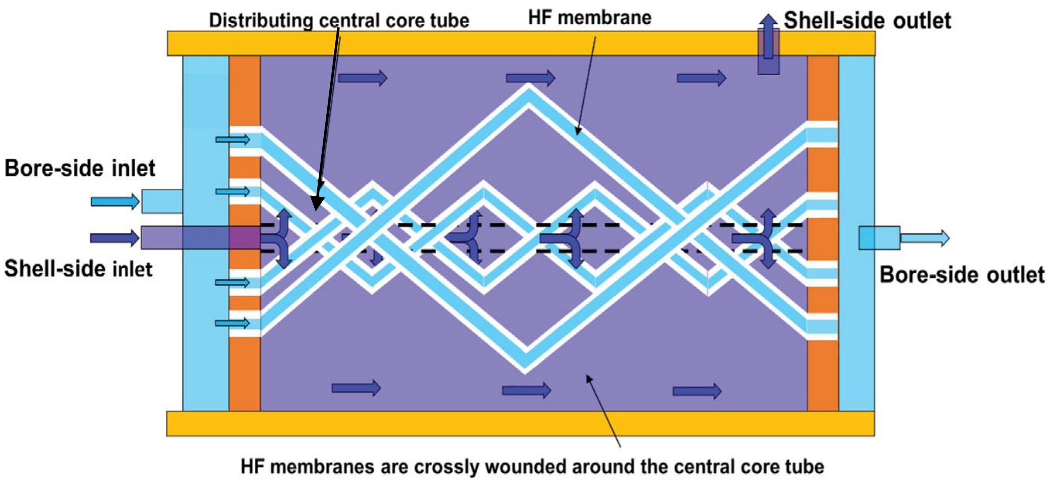


Fig. 1. Schematic of FO HF module with a cross-wound HF configuration.

reduce the rate of separation of polymer into concentrated DS and supernatant water. The non-linear performance in production capacity and water recovery was observed with both 135 and 230 micron membranes. The water recovery was less with 135 micron membranes as compared with 230 micron membrane. The number of HF in the 135 membrane module is higher than in 230 micron membrane. This may slightly reduce the flow of DS into the outermost layers of the module and results in less recovery.

The pilot plant was tested at two FS flow rates, 16 and 14 LPM. Tables 3 and 4 show that higher FS flow rates are suggested to increase the product flow rate. The FS is distributed to the bore side of the membrane and it runs in axial direction as shown in Fig. 1.

As the FS flows through the HF from the inlet to the exit side, the polymer DS pulls water and the FS will get concentrated as it reaches the exit. The DS will be at high concentration nearby the central core tube. Thus, at the FS exit, the FS in the HF tubes near the central core tube will be highly concentrated. There will be a high concentration gradient among the FS inlet and exit in the HF tubes near the central core tube. It is anticipated that as 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. The effect of FS flow rate upon production capacity and water recovery is not as evident with the tested 16 and 14 LPM FS flow rates as seen in Tables 3 and 4. The FS flow rate of 12 and 18 LPM will also be tested in forthcoming tests to have more valid data and the results will be reported in a later stage of the project.

Tables 5 and 6 show the preliminary physiochemical analysis of all the three streams of water from the pilot plant, namely, AGS feed, product and brine. The pH, conductivity and total dissolved solids (TDS) were measured by pH, conductivity and TDS meters, respectively. The other parameters

Table 5
Physiochemical analysis of AGS feed, FO product and FO brine using 230 micron membrane

| Parameter | Unit | AGS feed | FO product | FO brine |
|---|---|---|---|---|
| pH | | 7.5 | 7.2 | 7.3 |
| Conductivity | mS/cm | 54.8 | 0.29 | 75.6 |
| TDS | ppm | 39,841 | 133 | 62,387 |
| Calcium | mg/L | 784 | 2.16 | 1,176 |
| Magnesium | mg/L | 1,314 | 5.83 | 1,846 |
| Sulfate | mg/L | 1,980 | 0 | 2,100 |
| Chloride | mg/L | 25,457 | 69 | 38,780 |
| Sodium | mg/L | 13,853 | 44 | 21,515 |
| Alkalinity | mg/L | 142 | 5.5 | 232 |
| Boron | mg/L | 3.3 | 0.21 | 3.2 |
| Nitrate | mg/L | 4.6 | 0.7 | 4.9 |
| 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 | 103 | 0.49 | 101.5 |
| Phosphate | mg/L | 0.52 | 0.02 | 0.40 |
| Fluoride | mg/L | 5.8 | 0.02 | 5.7 |

Table 3
Effect of FS flow rate upon product water flow rate and water recovery using 230 micron membrane

| 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 4
Effect of FS flow rate upon product water flow rate and water recovery using 135 micron membrane

| 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 | 4.1 | 4.6 | 23.9 | 24.6 |
| 10.1 | 4.2 | 4.8 | 24.8 | 27.6 |
| 12.1 | 4.4 | 4.9 | 26.1 | 28.5 |
| 14.1 | 4.7 | 5.2 | 28.1 | 27.9 |
| 16.1 | 4.3 | 4.7 | 25.9 | 26.6 |
| 18.1 | 3.9 | 4.2 | 24.1 | 25.8 |

Table 6
Physiochemical analysis of AGS feed, FO product and FO brine using 135 micron membrane

| Parameter | Unit | AGS feed | FO product | FO brine |
|---|---|---|---|---|
| pH | | 7.5 | 6.7 | 7.4 |
| Conductivity | mS/cm | 57.2 | 0.19 | 78.6 |
| TDS | ppm | 43,797 | 78 | 61,266 |
| Calcium | mg/L | 776 | 2.64 | 1,144 |
| Magnesium | mg/L | 1,144 | 1.17 | 1,720 |
| Sulfate | mg/L | 4,300 | 0 | 4,600 |
| Chloride | mg/L | 27,200 | 63 | 40,940 |
| Sodium | mg/L | 14,835 | 51 | 20,100 |
| Alkalinity | mg/L | 108 | 4.3 | 155.6 |
| Boron | mg/L | 2.59 | 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 | 20 | 0.574 | 20.1 |
| Phosphate | mg/L | 0.15 | 0.11 | 0.3 |
| Fluoride | mg/L | 4.3 | 0.13 | 4.8 |

such as calcium, magnesium, chloride and sulfate were assessed by ion chromatography system, whereas, boron and sodium are 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 are taken for reporting.

The FO pilot plant in a single-stage process using single HF FO 230 µm membrane reduced the TDS from 39,841 to 133 ppm, whereas, 135 µm membrane reduced the TDS from 43,797 to 78 ppm. The TDS of RO first-stage produce at DRP is about 390 ppm. This shows that the TDS of FO product is lower than RO first-stage product. The 135 micron membrane showed improved TDS than 230 micron membrane and this would be due to the more number of HF and increased membrane area. The rejection of boron by the HF FO membrane is highly noticeable as it was reduced from 3.3 to 0.21 mg/L, which is practically not achievable from a single-stage RO. The reverse salt flux is tested by measuring the refractive index values of the product water and observed no traces of polymer in product water. This indicates that the post treatment system used in the pilot plant is highly efficient to treat the supernatant water and convert it to product water.

The performance stability of the HF FO membranes was tested by operating the pilot plant 24 h per day for 30 d at FS and DS flow rates of 14 and 16 LPM, respectively. The FO membrane as well as the pilot plant showed a steady operation in terms of TDS for the final product water and % water recovery values as shown in Figs. 2 and 3. There was no major change in TDS and water recovery percentage values during the observation period.

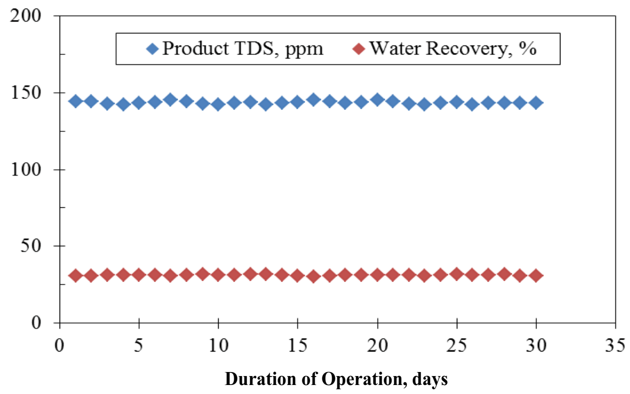


Fig. 2. Product TDs and FO pilot-plant water recovery distribution over a period of 30 d continuous operation using 230 micron membrane.

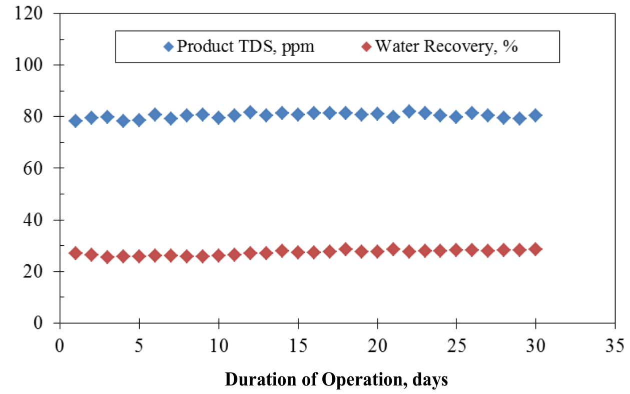


Fig. 3. Product TDs and FO pilot-plant water recovery distribution over a period of 30 d continuous operation using 135 micron membrane.

The primary calculation of energy required by the conventional electrical heater for DS recovery in the FO pilot plant is approximately 35–40 kWh/m$^3$, which is much lower than that the conventional MSF and MED desalination processes. The thermal energy consumption of an MSF plant is around 70–78 kWh/m$^3$ (Karaghouli and Kazmerski 2013 and Banat 2007) and the MED plant is around 62 kWh/m$^3$ (Karaghouli and Kazmerski 2013). It is worthy to note that the total energy consumption by the FO pilot plant without the conventional electrical heater of the DS recovery system was around 2.4 kWh/m$^3$. However, the energy consumed by PLC and control panel used in the pilot-plant test unit was measured and is around 1.4 kWh/m$^3$. This figure is quite high because of the low production capacity of the tested pilot plant. This figure can be drastically reduced by increasing the permeate capacity of the FO pilot plant. The results so far shows that the tested FO pilot plant can produce freshwater with an energy requirement less than the conventional desalination processes, provided the energy needed for DS recovery is supplied in the form of low-grade industrial waste heat or solar 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 1 year will provide a series of data or trends to confirm the performance reliability of FO technology for AGS desalination.

## 4. Conclusion

This study evaluated the feasibility of using innovative FO technology toward the desalination of AGS at a pilot-scale level using two different hollow fiber FO membranes with different bore diameters of 135 and 230 µm, and data produced from this study provided a platform to implement FO technology in Kuwait at a commercial scale. This study is also innovative considering the use of thermo-responsive polyelectrolyte DS in a FO desalination system with single-stage FO desalination process. The product water quality parameters obtained from the FO pilot plant using hollow fiber FO membranes are promising and proved that FO technology can produce water that meets the international standards. The FO pilot plant over a continuous stable operation of 30 d was capable to produce product water of TDS ≈ 70 to 150 ppm at water recovery ratio of ≈30%. The results of the pilot-scale study also established the potential of using thermally separable polyelectrolyte DS in FO system and its economic benefits over NaCl based DS used in FO-RO integrated system. This study also reveals that the FO desalination system is economically beneficial in commercial scale by integration of DS regeneration system with the low energy sources such as waste heat. However, detailed techno-economic analysis is also recommended to estimate the actual energy consumption of the investigated FO process and compare the results with the conventional desalination technologies such as MSF and RO.

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