ARABIAN GULF SEAWATER DESALINATION USING FORWARD OSMOSIS MEMBRANE TECHNOLOGY AND POLYELECTROLYTE DRAW SOLUTION: A PILOT SCALE STUDY

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Abstract

The current study assesses and validates the technical feasibility of using Forward Osmosis (FO) technology for desalinating Arabian Gulf seawater (AGS) on a pilot scale level using commercially available hollow fiber (HF) membrane. The main objective of this paper is to explore the feasibility of using thermo-responsive polyelectrolytes as draw solution in FO pilot system. The FO pilot plant test unit with a capacity of 10 m^3/d was constructed by Trevi Systems Inc., USA for desalinating AGS and was successfully installed and operated at Desalination Research Plant of Kuwait Institute for Scientific Research. The FO pilot plant consists of an integrated thermal and membrane separation system utilizing a coalescer and Nanofiltration (NF) membrane processes as draw solution recovery components. The pilot plant consisted of four stages: (1) pre-treatment system (2) osmotically driven transport of water molecules across a hollow fiber membrane resulting in concentration of feed and dilution of the polymer draw solution, (3) regeneration of polymer draw solution using a coalescer, and (4) NF post treatment system. A single element of commercially available HF FO membrane with bore diameter of 230 µm developed by TOYOBO was used in this study. The polymer draw solution used was ethylene oxide-propylene oxide copolymer. The feed used was AGS obtained directly from the beach well. The continuous operation of the FO pilot plant over a longer time at stable operating conditions using a single hollow fiber FO membrane element was able to produce product water with total dissolved solids of 180 ppm at water recovery of 30%. Simulation studies were performed to analyze the distribution of feed and polyelectrolyte draw solution throughout the membrane module and its effect on membrane performance. The osmotic pressure distribution of polyelectrolyte DS at different sections of the HF module was greatly influenced by DS flow rate. The study revealed that the DS had great potential to generate the high osmotic pressure ($\Delta\pi$) difference at the various compartments of the HF module. Consequently, the high $\Delta\pi$, which is considered as driving force of the FO process, resulted in high water flux of the HF membrane over long run experiments. Overall, this study provided encouraging results for the investigated polyelectrolyte DS in terms of flux, rejection, long term stability, and high water recovery.

Keywords: Forward Osmosis, thermo-responsive polyelectrolytes, hollow fiber membrane, bore diameter, water recovery.

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1. Introduction

The increasing demand for freshwater and scarcity of natural sources of freshwater in the State of Kuwait have led the country to turn to 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. 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. Furthermore, these systems are sensitive to the corrosion and scaling problems as well as fouling. Consequently, innovation in nonconventional desalination technologies is substantially needed. The nonconventional membrane separation elements, methods, and systems have been substantially developed through intensive research over a number of years. These research studies have produced a number of promising systems including forward osmosis (FO) technologies, as one of the sustainable solutions for seawater desalination applications in the foreseeable future. Detailed descriptions of the FO processes are available elsewhere [1]. A simplified schematic diagram of the FO approach for desalination is shown in Fig. 1. FO is driven by natural osmotic pressure generated using the draw solution (DS), which has a higher concentration level than that in the feed solution (FS), to withdraw water molecules from undesired solutes, dissolved in the FS, through a semipermeable membrane. As shown in Fig. 1, the FO system is simultaneously diluting the DS and concentrating the FS, and, thus, diluted DS requires a further treatment process, known as DS recovery system, to recover the final product water and concentrated DS from the diluted DS [2].

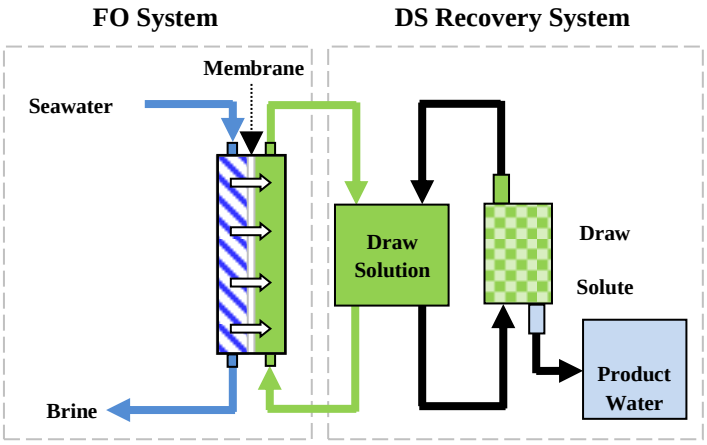

Fig. 1. A simplified schematic diagram of the forward osmosis approach [1].

Previous studies have compared FO with conventional RO and reported that FO system consumes between 20 and 30% less energy [3], generates less brine discharge to the surrounding environment [1], has low fouling potential and high physical cleaning efficiency [4], and higher boron rejection [5]. 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. For example, the

Modern Water Company (MWC) has investigated the first FO-RO pilot plant with a capacity of 18 m^3/d in Gibraltar in September 2008 [5]. Additionally, the MWC investigated two more FO-RO pilot plants in Oman in 2009 and 2011, with the capacities of 100 and 200 m^3/d, respectively. The MWC has reported considerable advantages of FO-RO over conventional RO [5]. However, RO as a DS recovery method has its limitation due to the fact that the osmotic pressure in the DS cannot exceed 70,000 ppm. As a result, the permeate flux is limited in the FO system.

Trevi Systems Inc. (TSI), on the other hand, has invented FO followed by a thermal separation (TS) system for desalination. Carmignani et al. (6) reported that the patented FO system is potentially capable of consuming 87.5% less energy than the conventional RO by utilizing solar energy or waste heat. The TS as a DS recovery method, whether by utilizing the thermolytic polymers or ammonium bicarbonate as the DS, can reach higher DS concentrations than that of the RO process. However, TS has its severe limitation due to the fact that the final product water contains the residue of the draw solute. In order to remove the residue of draw solute from the product water, post-treatment system, such as nanofiltration (NF) or brackish water (BW) RO membrane system, is required, and, thus, the investment and operational costs will be increased. Therefore, the MWC and TSI have both agreed that their technologies are still not well established and many issues still remain to be solved. Therefore, the FO technologies adopted by the MWC and the TSI require further research and development to eliminate their limitations in order to reach a maturity level for large-scale commercial applications.

Therefore, this paper will share some of data and information obtained from the assessment of the performance of a FO-TS system, developed by TSI, using 10 m^3 per day pilot plant test unit. This test unit was investigated at Desalination Research Plant (DRP) of Kuwait Institute for Scientific Research (KISR) in Kuwait. The investigated FO technology was designed specifically for desalinating the Arabian Gulf seawater 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 proposed FO technology.

2. Objectives

The main objective of this paper was to assess the efficiency of the innovative HF FO membrane and thermoresponsive polymer for AGS desalination at pilot scale level, and to check the stability of FO pilot plant for commercial applications under the prevailing conditions of Kuwait.

3. Experimental setup and Materials

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 Fig. 2. The pilot plant test unit is supplied with full-scale HF FO membranes that were recently being developed by TOYOBO Co. This pilot plant utilizes the integration of thermal and membrane separation concepts by utilizing a coalescer system and Nanofiltration (NF) membrane technology as draw solution regeneration process as shown in Fig. 2.

Plate 1. Investigated pilot test unit at Desalination Research Plant (DRP).

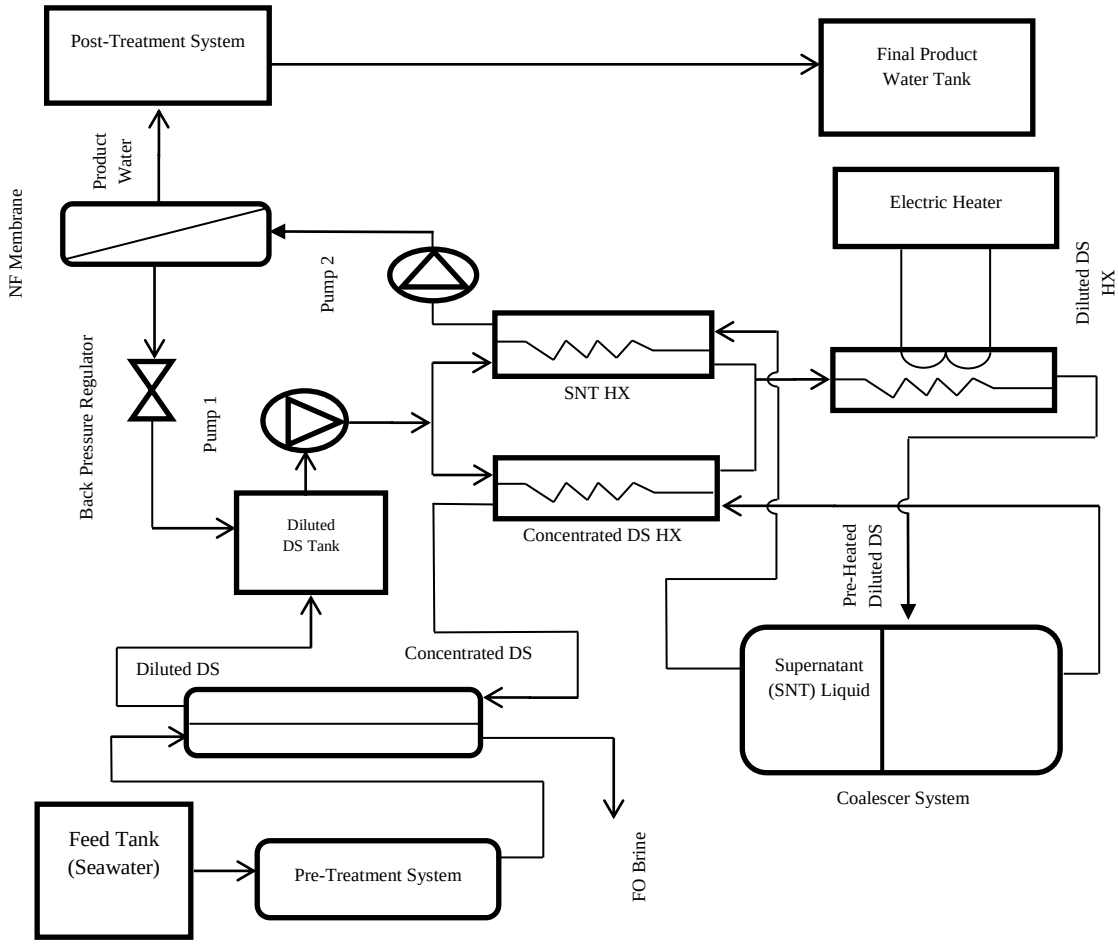

Fig. 2. Schematic diagram of the investigated pilot test unit.

The pilot plant test unit is designed for continuous operation and is composed of the following integrated processes: (1) pre-treatment system and anti-scalant dosing, (2) FO stage, (3) regeneration stage, and (4) the post treatment system. The FO stage consists of DS pump and the FO membrane module. The regeneration stage consists of heat exchangers and coalescer. The FO membrane used was recently developed

commercial 10 inch HF FO membrane from TOYOBO, Japan. The HF membrane is made of cellulose triacetate and has bore diameter of 230 micron. 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 to 90° C. The osmotic pressure and viscosity of polymer DS at various concentrations is shown in Table 1. The feed used was AGS obtained from beach well located at DRP in Doha, Kuwait.

Table 1. The osmotic pressures and viscosity of DS at different concentrations.

DS concentration (%)	Osmotic pressure (atm)	Viscosity (cP)	
	at 25 °C	at 25 °C	at 85 °C
30	40	49.85	12.85
40	45	69. 07	16.94
50	60	86.90	21.74
70	95	194.48	23.714

4. Physicochemical Analysis

Physicochemical analysis was performed by following the standard procedure for all water streams, including feed, product, and brine before and after conducting each run. The physiochemical analysis of water samples included the following parameters: temperature, total dissolved solids (TDS), electrical conductivity, pH, volume, and mass. To ensure and check the reliability of the salinity measurements in this study, two salinity measurements are considered and these are: electrical conductivity and gravimetric method. Furthermore, the accuracy of salinity measurements, using a gravimetric method, was once more ensured by using a simple mass balance equation. In addition, all samples of water streams 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.

5. Experimental Procedure

The AGS obtained from beach well is passed to the bore side of the FO membrane at pressure less than 2 bar. 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 in to 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 though the post treatment system and heat exchangers and final product water is produced.

6. Results and Discussions

The DS flow rate was ranged from 8 to 18 liter per minute while maintaining the FS flowrate at constant level. The DS is distributed to the shell side of the FO membrane through a center tube in the membrane module as shown in Fig. 3. The DS then flows radially through the membrane and the concentration of the DS will be the highest at the area near to the center 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 Fig. 4. 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.

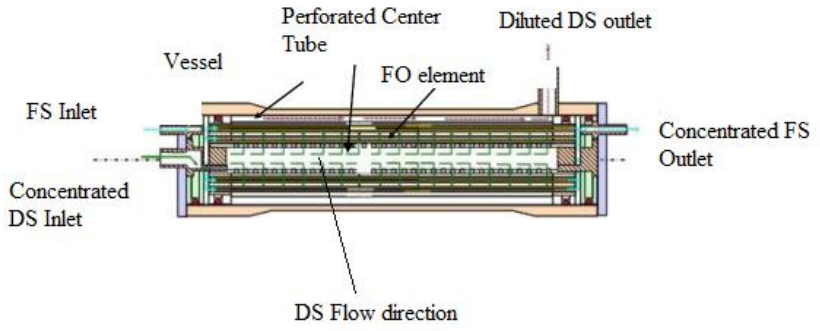

Fig. 3. Schematic diagram of the tested membrane configuration.

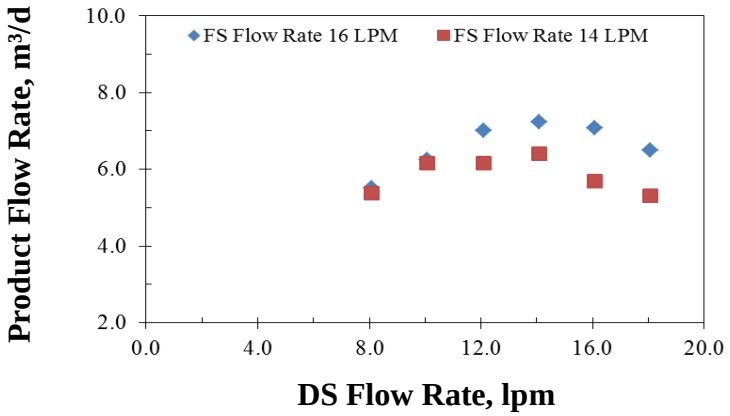

Fig. 4. Effect of DS flow rate upon product water flow rate.

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 2 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 Fig. 3. As the FS flows from the inlet to the outlet side, the concentrated DS near the center 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 2. Effect of FS flow rate upon product capacity and water recovery.

DS Flow Rate, LPM	Product Capacity, m^3/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 3 show the physiochemical analysis of all the three streams of water from the pilot plant, namely, FS, product and brine. 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 Fig. 5, i. e FS flow rate at 14 LPM and DS flow rate at 16 LPM.

Table 3. Chemical analysis of all streams collected from FO pilot plant test unit.

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	35,801	143	49,518
Calcium	mg/L	824	6.16	1,288
Magnesium	mg/L	1,154	5.83	1,720
Sulfate	mg/L	3,600	0	4,600
Chloride	mg/L	26,000	38	37,000
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
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 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 Fig. 5. There was no significant change in TDS and water recovery percentage values during the observation period.

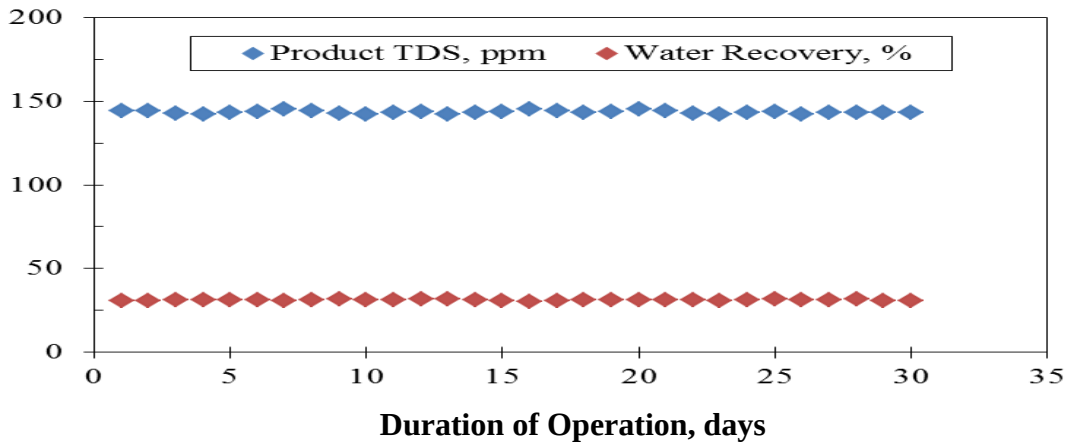

Fig. 5. Product concentration and water recovery ratio versus running time.

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 (70 kWh/m^3 thermal energy) and MED/TVC (65 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.

7. Conclusion and Recommendations

This paper evaluated the feasibility of FO technology for AGS desalination at pilot scale level. 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.

8. References

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