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Assessment of pilot scale forward osmosis system for Arabian Gulf seawater desalination using polyelectrolyte draw solution

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ABSTRACT

The main objective of this study is to assess and validate the feasibility of polyelectrolyte driven forward osmosis (FO) process in actual seawater desalination at pilot scale capacity of 10 m^3 d^{-1}. The pilot scale FO system constructed by Trevi Systems Inc., (USA) was tested at Desalination Research Plant in Kuwait for desalinating beach well seawater. The pilot plant consisted of a commercial scale hollow fiber (HF) FO membrane (bore diameter of 230 μm), ethylene oxide-propylene oxide copolymer with molecular weight of ~2,000 Da as a thermo responsive draw solution (DS), a coalesce tank for the regeneration of DS on thermal separation principle, and nanofiltration membrane processes as a post treatment process. The study revealed that the polyelectrolyte DS had great potential to generate the high osmotic pressure difference at various compartments of the HF module leading to an average water recovery of 30%. Simulation studies revealed that the osmotic pressure difference distribution of polyelectrolyte DS at different sections of the HF module was greatly influenced by DS flow rate. In conclusion, the FO system operation using low grade heat allows the FO system to operate with a lower cost of energy than a reverse osmosis plant.

Keywords: Thermo-responsive polyelectrolytes; Hollow fiber membrane; Water recovery; Draw solution distribution

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 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 non-conventional desalination technologies is substantially needed. The non-conventional membrane separation elements, methods and systems have been substantially developed through intensive research over several 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. FO is driven by natural osmotic pressure generated using the draw solution (DS), which has a higher concentration level than in the feed solution (FS), to withdraw water molecules from undesired solutes, dissolved in the FS, through a semipermeable membrane. 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

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recover the final product water and concentrated DS from the diluted DS [1].

Previous studies have compared FO with conventional RO and reported that FO system consumes between 20% and 30% less energy [2], generates less brine discharge to the surrounding environment [3], 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 conventional RO membranes are asymmetric, and the literature proved that these membranes are not suitable for the FO process since FO membrane should be of lower thickness to tackle concentration polarization issue and to attain high flux during the process [6]. However, significant progress have been made in FO membrane fabrication recently which led to advancement in the performance of FO membrane in terms of water flux parameter [7,8]. The separation of the freshwater from the diluted DS and the recovery of DS is the other challenge in FO technology. The effective separation of DS through the efficient DS recovery system with energy efficient system remains a significant challenge for seawater desalination applications [9,10]. 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^{-1} 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^{-1}, respectively. The investigated DS that was used in the MWC test units is a mixture of inorganic salts. The MWC has reported apparent advantages of FO-RO over conventional RO. However, RO as a DS recovery method has its limitation since the osmotic pressure in the DS cannot exceed 70,000 ppm. As a result, the permeate flux is limited in the FO system.

The large-scale FO membranes of cellulose triacetate are currently available in their hollow fiber (HF) form [11]. In general, the FO membranes are designed with ideal characteristics for FO seawater desalination with high water permeability, high rejection of solutes, substantial reduction in internal concentration polarization, and high chemical and mechanical stability (12). Trevi Systems Inc., (USA) has developed a DS that could reach the characteristics of ideal DS including: high osmotic pressure, ease of separation and recyclability, avoiding reverse diffusion, zero toxicity, less expensive chemical, energy-savings regeneration system, simplifying regeneration process, and non-corrosive chemical [12,13]. Additionally, Trevi System attempts to develop a DS recovery system that has the capability to continuously and constantly generate high osmotic pressure required for maintaining the water flux at desired levels in the FO stage, and at the same time it produces high quality water with a total elimination of DS residue in the final product water [14]. McCutcheon et al. [15] conducted intensive investigations on the essential parameters in the FO process using NH_3–CO_2 DS. The proposed thermolytic salts can generate a high osmotic pressure in FO stage. Accordingly, pilot-scale setups with closed-loop operation mode were developed with the aim of demonstrating the viability and efficiency of FO process using NH_3–CO_2 DS for desalination applications [16]. The literature reported that the investigated technology is an energy-saving process with high water recovery rate [17]. However, the DS made from ammonium salts suffers from severe back diffusion. This means that the quality of the product water does not meet the World Health Organization (WHO) standards. Furthermore, there is a strong propensity of membrane scaling with carbonate ions at the FS side [18]. In addition, regenerating NH_3 and CO_2 gases is usually accompanied with undesirable water evaporation, which eventually leads to an increase in the energy consumption as well as difficulties in maintaining a stable DS concentration for FO stage [19].

Carmignani et al. [20] 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 thermal separation (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 limitation since the final product water contains the residue of the draw solute. Therefore, the FO technologies adopted by the MWC and the Trevi System Inc., 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 Trevi Systems Inc., using 10 m^3 d^{-1} pilot plant test unit. The investigated FO technology was tested at Desalination Research Plant (DRP) in Kuwait for desalinating beach well seawater as representative sample of AGS. This study also provides a better understanding and solutions for the existing gaps of know-how in recovering DS from the diluted DS. Thus, this study assesses the efficiency of the commercial scale HF FO membrane and thermo-responsive polymer for seawater desalination at pilot scale level, and to check the stability and energy efficiency of FO pilot plant compared with established desalination technologies.

2. Materials and methods

2.1. Materials

The FO pilot plant test unit with a capacity of 10 m^3 d^{-1} was constructed by Trevi Systems Inc., for desalinating AGS as shown in Fig. 1. The pilot plant test unit is supplied with full-scale HF FO membranes that were recently being developed by TOYOBO Co., (Japan). This pilot plant utilizes the integration of thermal and membrane separation concepts by utilizing a coalescer system and nanofiltration (NF) membrane technology as DS regeneration process.

The FO pilot plant consisted of different stages as presented in Fig. 2. A seawater pretreatment system, polyelectrolyte driven FO membrane process, coalescer system for polyelectrolyte recovery, and NF post treatment system for product

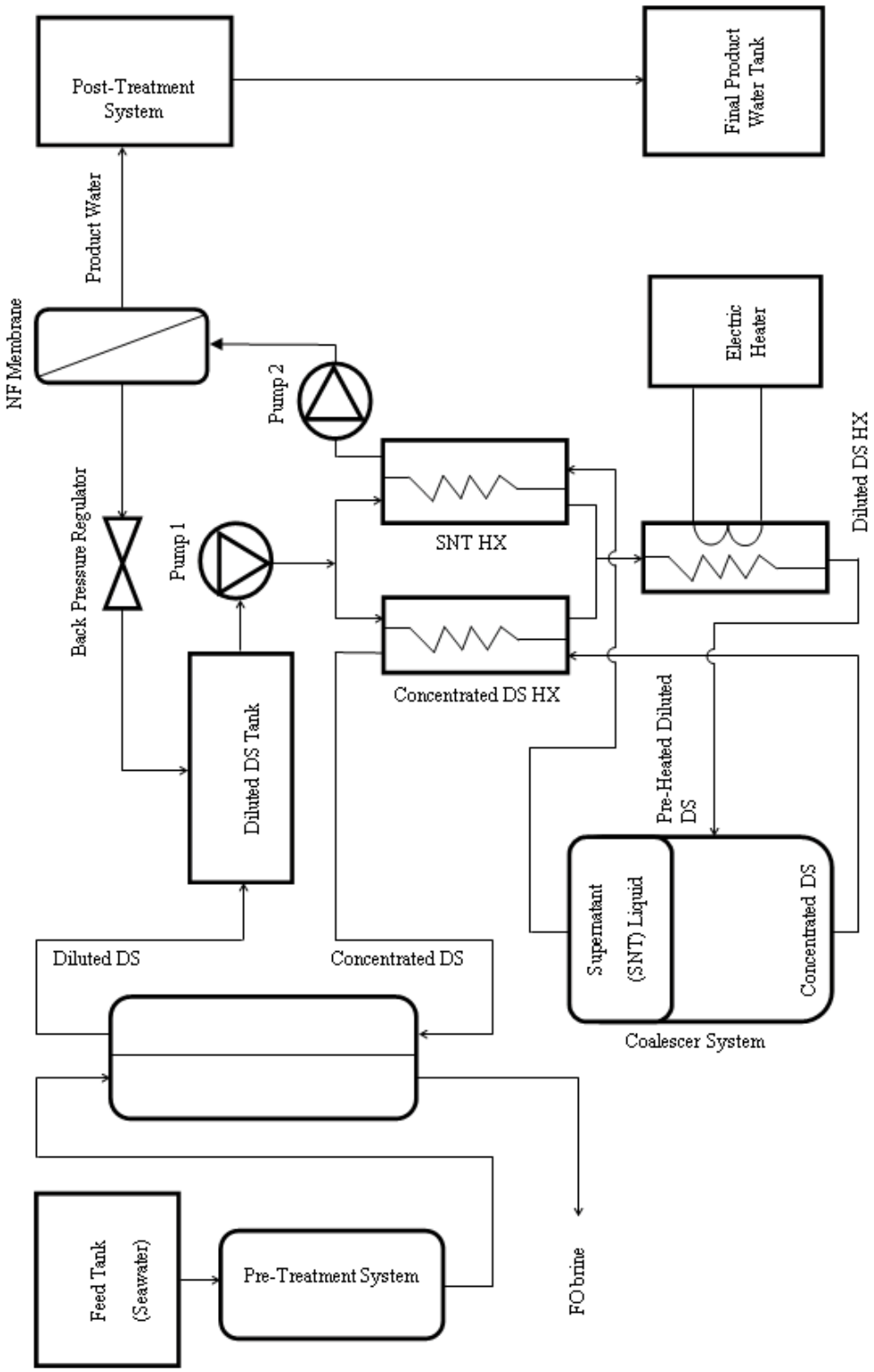

Fig. 1. Schematic diagram of the FO pilot-scale test unit.

water treatment. The FO system was operated by circulating the seawater feed in the bore side while the DS get diluted in the shell side of the membrane. The FO process consisted of various parts such as pumps, cartridge filters, pH, temperature and conductivity sensors.

The pilot plant test unit was designed for continuous operation and is composed of the pre-treatment system and anti-scalant dosing; FO stage; regeneration stage, and the post treatment system as integrated process. The FO stage consisted of DS pump and the FO membrane

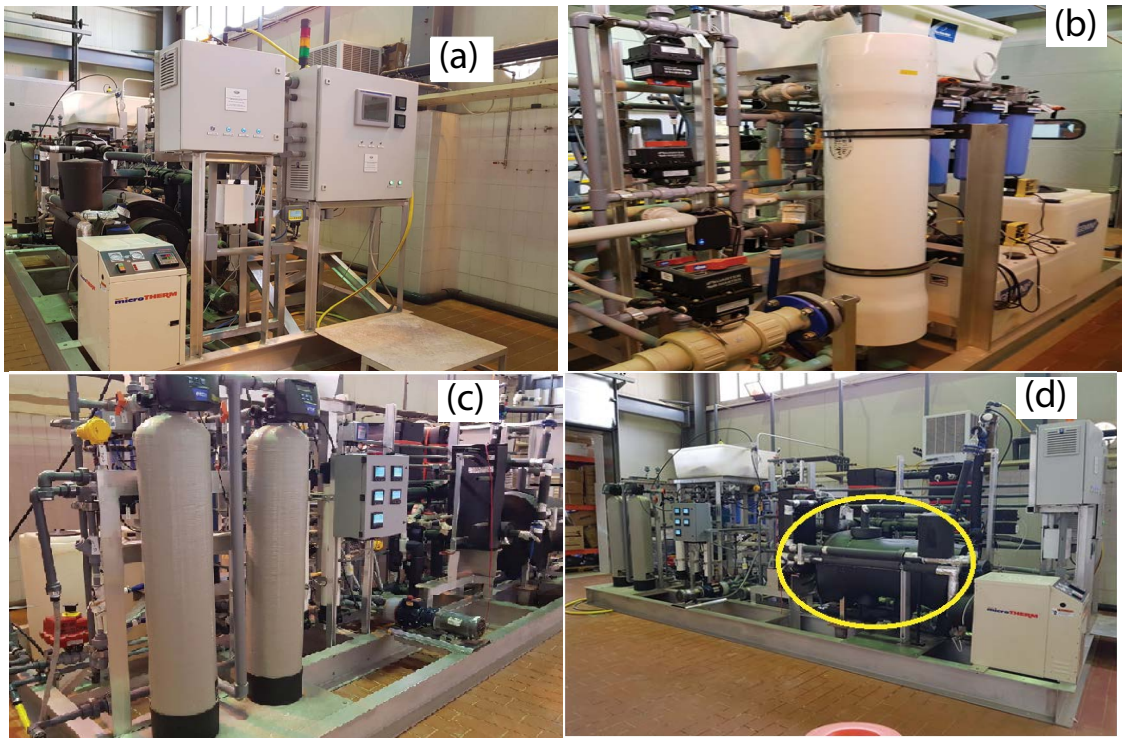

Fig. 2. Pilot scale FO unit (a) online control data acquisition system, (b) Full-scale hollow fiber FO membrane, (c) post-treatment system, and (d) coalesce tank for DS is highlighted.

module. The regeneration stage consisted of heat exchangers and coalesce tank. The FO membrane used was recently developed commercial 10-inch HF FO membrane from TOYOBO Co., (Japan). The HF membrane is made of cellulose triacetate with the bore diameter of 230 μm.

2.2. Characteristics of polyelectrolyte DS

The polymer DS used was ethylene oxide-propylene oxide copolymer (TL-1150-1) supplied by Trevi systems Inc. The copolymer has a random structure to improve phase separation purity with a molecular weight of approximately 2,000 Da. The cloud point temperature of the DS is between 40°C to 90°C. The non-ionic polymer was supplied by the skid manufacturer and its structure specifically designed to reduce reverse diffusion through the FO membrane by two orders of magnitude over salt DSs as well as to lower toxicity to less than a comparable sodium chloride (NaCl) DS of similar performance. Phase separation of the polymer in water to >99.5% using only thermal heat matches the best membrane performance, allowing residual polymer to be easily removed to sub-ppb levels in the final drinking water. 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 and the physicochemical analysis of the AGS feed water is presented in Table 2.

2.3. 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, two salinity measurements were 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 L polyethylene 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 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, whereas, boron and sodium were estimated by inductively coupled

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

DS concentration (%)	Osmotic pressure (atm)		Viscosity (cP)	
	at 25°C	at 40°C	at 25°C	at 85°C
30	40	45	49.85	12.85
40	45	51	69. 07	16.94
50	60	69	86.90	21.74
70	95	108	194.48	23.714

Table 2
The characteristics of the AGS feed water

Parameter	AGS feed
pH	7.4
Conductivity, mS cm^{-1}	55.4
TDS, ppm	35,801
Calcium, mg L^{-1}	824
Magnesium, mg L^{-1}	1,154
Sulfate, mg L^{-1}	3,600
Chloride, mg L^{-1}	26,000
Sodium, mg L^{-1}	14,800
Alkalinity, mg L^{-1}	120
Boron, mg L^{-1}	2.75
Nitrate, mg L^{-1}	3.5
Copper, mg L^{-1}	<0.05
Chromium, mg L^{-1}	<0.05
Iron, mg L^{-1}	<0.05
Silica, mg L^{-1}	16.2
Phosphate, mg L^{-1}	0.15
Fluoride, mg L^{-1}	4.3

plasma optical emission spectrometry. The parameters such as nitrate, copper, chromium, iron, silica, phosphate and fluoride were estimated by spectrophotometer (DR-6000). All analysis was done in triplicate and average values were taken for analysis.

2.4. 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 center 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.

3. Results and discussion

3.1. The system performance

The DS flow rate was ranged from 8 to 18 L min^{-1} 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. As observed in Figs. 3 and 4, the effect of flow rates on product water flow rate and water recovery is not linear and this could be due to the limited capacity of the heat exchanger and coaelesce system used in the current system. As presented in Fig. 5, the combination of FS flow rate, 14 lpm and DS flow rate, 14.1 lpm correspond to an optimum water recovery of 31.3%.

The pilot plant was tested at two flow rates, 16 and 14 lpm and the higher FS flow rates are recommended to increase the product flow rate as showed in Fig. 4. 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, it 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.

The performance of the pilot plant was stable during the 30 d continuous operation and TDS of product water was with TDS 143 ppm from its initial TDS (for AGS) of 35,801 ppm (Fig. 6). The possible leakage of the polyelectrolyte solute into the product water after NF posttreatment was measured by refractive index method. The analysis

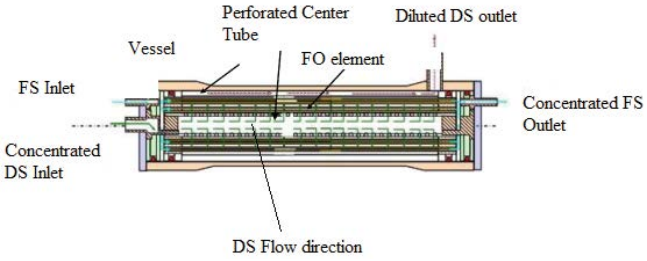

Fig. 3. Schematic diagram of the tested membrane configuration.

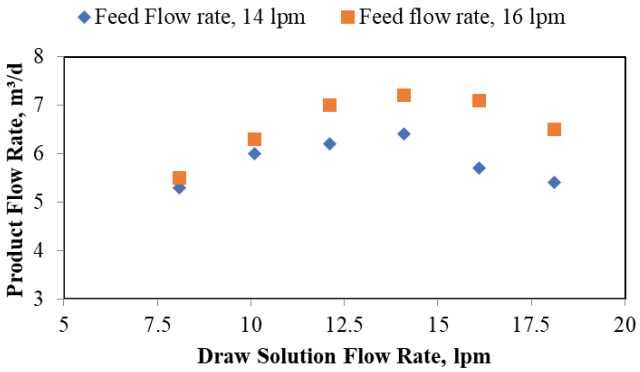

Fig. 4. Effect of DS flow rate on product water flow rate.

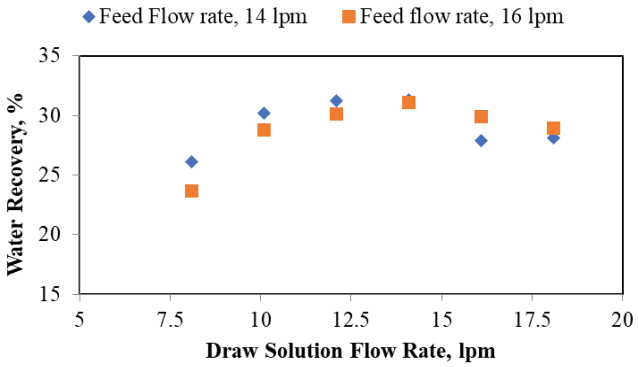

Fig. 5. Effect of DS flow rate on % water recovery.

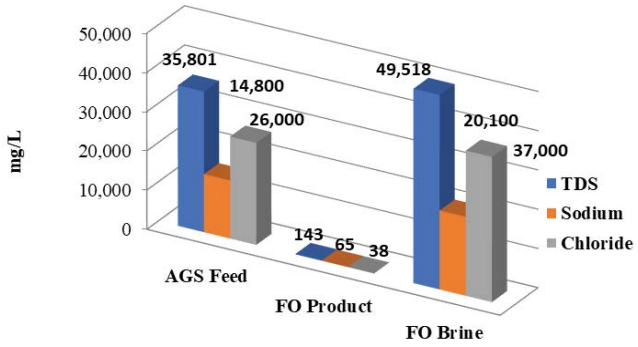

Fig. 6. The TDS and NaCl concentrations of the AGS feed, product water, and brine solution during the FO operation.

report showed no traces of the polyelectrolyte solute and demonstrated the suitability of selected NF membrane as a post-treatment process. The average water recovery of the process was 30% with discharge of brine with the TDS of 49,518 ppm. There was no significant change in TDS and water recovery percentage values during the observation during 30 d of operation. Also, as observed from Fig. 7, the FO membrane witnessed high monovalent and divalent ionic rejection including boron during its operation.

3.2. Energy calculations

A thermo-responsive DS uses two forms of energy to operate in a FO system. The first is the electrical energy to circulate the DS. This can be calculated simply by the mass flow rate and pressure drop the DS experiences traveling through the FO membranes as well as the permeate water flow through the polish NF membrane and its applied pressure. In the actual skid as tested, this electrical energy was approximately 1.5 kWh m^{-3} for specific energy consumption, compared with a calculated 0.4 kWh m^{-3} for a full-scale production system. The small-scale skid did not allow for optimization of pump efficiency at the flow rates under test. This electrical energy at full scale will be almost a full order of magnitude below comparable RO systems. The thermal energy measured on the skid is the energy required to heat water to 85°C, however since no phase change occurs as in membrane distillation (MD), multi effect desalination (MED) or pervaporation, the sensible energy can be largely recovered in the heat recovery

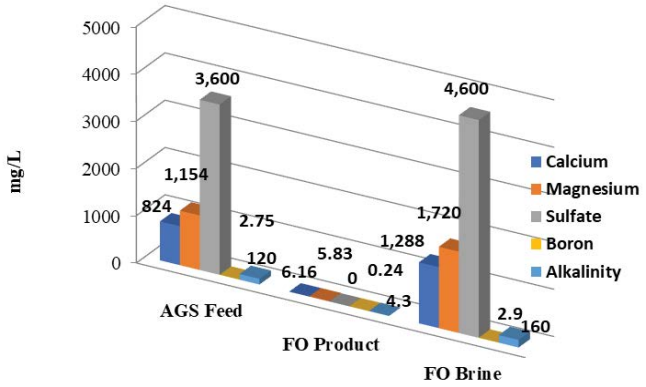

Fig. 7. The ionic compositions of the AGS feed, product water, and brine solution during the FO operation.

heat exchangers, the thermal energy consumption is therefore limited only by the heat exchanger efficiencies, which can easily exceed 95%. The measured thermal energy on a pilot scale system of 37 kWh m^{-3} is less than half that of a comparable MD or MED system. Large scale plants are expected to drop this below 30 kWh m^{-3}. The best performing multi effect desalination-thermal vapor compression systems report numbers in the literature of 65 kWh m^{-3} while MD systems operate around 80 kWh m^{-3} in pilot reports published, making the thermal FO system twice as efficient as any other thermal system available.

For practical applications, desalination using low grade heat sources as an alternative to electricity opens desalination options not available to RO. Since NaCl as a draw agent can only be separated using RO, the energy consumption of such a FO system will be higher than that of a comparable RO system due to the requirement that DS have a higher osmotic potential than the incoming FS. Using low grade heat left over from electricity generation (for example in combined cycle power Gas Turbine exhaust gas, concentrated solar power steam turbine condenser etc.), allows the FO system to operate with a lower cost of energy than a comparable RO plant. If the capital expenditure and maintenance of an FO plant is comparable to a RO plant, then the lower cost of energy will imply that the FO plant will provide a lower cost of water than a RO plant. Large scale trials (at the million gallons per day level) are underway in Hawaii and India using such FO plants runs on waste heat sources. Considering the use of renewable energy, RO system must use battery backup technology for night time operation or be overbuilt to supply the requisite power, which is significantly more expensive than storing thermal energy to power a thermal FO system.

4. Conclusions

Overall, this study evaluated the feasibility of using FO technology for AGS desalination at pilot scale level and viability of using a thermo-responsive polyelectrolyte DS in a FO desalination system. 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 d 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 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 beneficial in commercial scale by integration DS regeneration system with the low energy system 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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