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Performance feasibility study of direct contact membrane distillation systems in the treatment of seawater and oilfield-produced brine: the effect of hot- and cold-channel depth

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ABSTRACT

Membrane distillation (MD) is a technology that is emerging as a viable alternative to traditional desalination techniques. This study assessed the feasibility of using the direct contact membrane distillation (DCMD) configuration of MD to desalinate saline water of different concentrations. We considered the feed supply of Arabian Gulf seawater (AGS) sand oil field-produced water and used polypropylene (PP) and polyvinylidene fluoride (PVDF) membranes to consider their performance under different operating conditions, such as channel depth, flow rate, temperature, feed concentration, etc. Their performance was evaluated by determining the water flux relative to the volume of salt rejection. The results showed that the permeate flux increased to 32.4 from 10.1 L/m^2·h when the temperature was raised from 45°C to 75°C. Additionally, the permeate flux decreased to13.6 from 27.3 L/m^2·h and the reduction in flux was around fifty percent when the concentration of sodium chloride (NaCl) in the feed solution was increased to 26% from 0%. The experimental results obtained using oil field-produced water were highly encouraging. The permeate flux was 11.5 and 12.5 L/m^2·h at 80°C and 85°C, respectively. The results indicated the enormous potential of DCMD to treat hypersaline oil field-produced water, with an overall rejection of salts reaching above 99%. In comparison, PP membranes had a higher salt rejection rate but lower water flux, while PVDF membranes had a lower salt rejection rate but higher water flux. This paper presents, for the first time, the results of a laboratory-scale study conducted in the State of Kuwait to treat AGS and oil-produced water using DCMD technology under Kuwait's prevailing conditions. This study's findings will lay the groundwork for conducting pilot-scale studies on AGS and oil-produced water not only in the Middle East region but globally.

Keywords: Direct contact membrane distillation; Arabian Gulf seawater; Oil field-produced water; Channel depth; Permeate flux

1. Introduction

Seawater desalination technologies have significantly increased the possibility of using seawater as an alternative source of water to supply fresh water and to relieve many nations' demands for fresh water [1–3]. The demand for potable water has increased steadily over the past two decades due to rising demand from activities such as the development of villages, towns, municipalities, urban development, commercial operations, agriculture, and industry. Consequently, there is a considerable need for the construction and development of seawater desalination plants to meet all nations' freshwater needs, particularly along equatorial lines. The commercial desalination of seawater is usually

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achieved by using membranes to filter out salt or by using temperature gradients as the driving mechanism via convective heat and mass transfer. Typically, a thermal procedure involves boiling or evaporating seawater, following which the distillate is collected. Desalination is mainly achieved by using conventional energy sources (e.g., oil and gas). In dry regions, such as those of the Arabian Gulf Cooperation Council (GCC), the situation is the worst because practically all freshwater demand is fulfilled by thermal distillation operations that use fossil fuels as their primary energy source [4]. Multi-effect desalination (MED) and multistage flash (MSF) distillation are widely used thermal desalination processes. Membrane technologies, such as reverse osmosis (RO), produce fresh water from saline water using pressure gradients as the driving force.

Membrane distillation (MD) is one of the technologies emerging as a viable alternative desalination technique. MD is a thermal membrane process that results from simultaneous mass and heat transfer phenomena through a hydrophobic microporous membrane [5]. MD is a thermally driven system that utilizes a hydrophobic microporous membrane for separation by liquid–vapor equilibrium. The feed solution is heated, and it comes into contact with the hydrophobic membrane. At each pore entrance, a liquid–vapor barrier is formed due to the hydrophobic nature of the membrane, which prevents liquid from entering the pore and enables only vapor to pass through [6]. The permeate side of the membrane condenses the vapors.

MD setups are commonly classified into four variants based on the mechanism utilized to remove vapor from the hot-feed side of the membrane: direct contact membrane distillation (DCMD), vacuum membrane distillation (VMD), air gap membrane distillation (AGMD), and sweeping gas membrane distillation (SGMD). The cold deionized water on the permeate side condenses vapor from the feed side during the DCMD process. A pump is utilized in VMD to create a vacuum, which serves as the driving power for the vapor. Water vapor condenses either in the membrane unit or in a separate condenser. AGMD employs a stagnant air layer between the condensation surface and the membrane layer on the permeate side. In AGMD, dry air flows on the permeate side of the membrane, sweeping vapor off it. This is then condensed into an outside-of-the-membrane-module condenser [7–10].

The intended application of MD (saline water desalination) has been mainly focused on seawater and brine. As a result, several research studies are still ongoing to improve or establish the performance viability of MD for desalination applications. If reliable and cost-effective desalination technologies are utilized, enormous quantities of seawater can provide a major source of pure water. Conventional desalination methods, including MSF distillation and RO, are mature and widely commercialized, although desalination cost-reduction research is ongoing. Desalination plants use a lot of energy, which results in high operational expenses and these plants' overall cost. Consequently, research into technology with minimal energy requirements and the use of cheaper alternative energy sources is ongoing [10–20]. Other areas of research and applications of MD include wastewater and industrial applications (e.g., boron removal) [21,22], electronic industry wastewater treatment [23], textile industry wastewater treatment [24–27], treatment of wastewater from the metal and pharmaceutical industries [28], and oil field-produced water [29–31]. The food processing industry [32–35], ethanol–water separation [36], ammonia removal application [37–39], acid concentration [40], etc., are some other applications of MD.

Several research investigations are still being conducted to advance MD technology to full-scale industrial and more widespread applications. MD systems currently in use are highly effective. For example, Memstill air gap flat sheet MD technology under direct contact mode was tested by the Netherlands Organisation for Applied Scientific Research (TNO). The evaluated MD systems delivered high-quality water with salt rejection greater than 99.9% [41,42]. An MD system integrated with solar energy developed by Fraunhofer for the MEMDIS project was field-tested in Spain. The MD unit was operated at a feed-water recovery rate of up to 44%, and the membranes achieved a salt rejection of greater than 99% [11]. Similar results have been discussed in other published articles [43,44].

In the current study, a parametric analysis was done to evaluate the viability of MD for Arabian Gulf seawater (AGS) and oil field-produced water feed sources. This study was conducted at the Kuwait Institute for Scientific Research (KISR) to specifically assess the DCMD process for desalinating different saline waters under various operating conditions using polypropylene and polyvinylidene fluoride (PVDF) membranes. Table 1 provides an overview of the experiments performed in this study. This paper presents, for the very first time, the findings of a laboratory-scale study that was carried out in Kuwait to treat AGS, oil field-produced water, and different saline solutions utilizing DCMD technology. Also, this research aimed to investigate the effects of increasing the hot- and cold-channel depths in a DCMD module developed by the research team. To the best of our knowledge, a study on different channel depths using a DCMD has not been previously reported in the literature. This study summarizes results in AGS as a precursor to desalination results in oil-produced brine substrate, which in our opinion is novel.

2. Materials and methods

2.1. Bench-scale experimental setup and procedure

The schematic diagram and photo of the bench-scale MD unit are shown in Figs. 1 and 2, respectively. Flat sheet membranes with effective areas of 0.0155 and 0.003847 m^2 were used in this study. The membrane modules were designed and constructed at KISR using Teflon and acrylic materials, as shown in Figs. 3 and 4. The channel depth effect studies were performed using a 0.0155 m^2 membrane module. Membrane modules with the option of varying channel depths are not commercially available. Accordingly, a new membrane module was designed and developed at KISR to accommodate different plates of 1 mm thickness on the hot channel side and the cold channel side.

Flat-sheet polypropylene (PP) and polyvinylidene fluoride membranes were used in this study. A PVDF membrane (Code: YMJXSP3001, Merck Millipore Ltd., Germany) with an average pore size of 0.3 μm, a thickness of 150 μm, and porosity

Table 1
Overview of the logic of the experiment

Parameter		Reasoning
Feed temperature, °C	45–75	The main reason for studying the effect of temperature on permeate flux is to establish data on how MD performance is affected by the temperature of feed solutions. The temperature range of 45°C–75°C is commonly used in MD research studies because it is within the typical operating temperature range for most MD systems. The maximum temperature was set at 75°C, considering the thermal degradation of the membranes at temperatures above 75°C.
Flow rate, L/min	0.6–1.3	To test the effect of feed flow rate on permeate flux and to establish data on how process performance is affected by different feed-flow rates.
Feed solution concentration, wt.%	Deionized water, 3.5%–26% NaCl solutions, oil-produced water	To test the effect of feed concentration on permeate flux and to establish data to show the feasibility of using MD for feeds with different salt concentrations.
Membranes	Polypropylene and polyvinylidene fluoride	To test the performance of different polymeric membranes for AGS desalination.

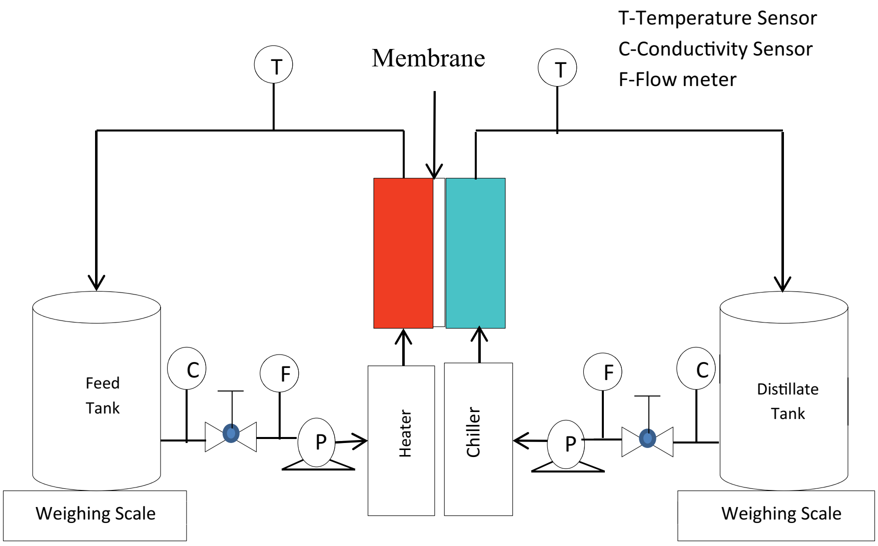

Fig. 1. Schematic diagram of the bench-scale MD unit.

Fig. 2. Bench-scale direct contact membrane distillation (DCMD) test unit.

of 60% was used, and the PP membrane (from Celgard 2500, USA) used had an average pore size of 0.064 µm, a thickness of 25 µm, and porosity of 55%. The NaCl used was analytical reagent (AR) grade, with 99.9% purity (Techno Pharmchem India, sodium chloride AR-33127). NaCl solutions at 3.5%, 7.0%, 15%, and 26% concentrations were used as feed solutions. The NaCl solutions were made by dissolving a known amount of NaCl salt in a known amount of deionized water (DI) produced by Millipore ZRQSVP3WW Direct-Q® 3 UV Water Purification System (Germany). Also, AGS collected from a beach well located at the desalination research plant (DRP) of the KISR in Kuwait was used as feed.

The effectiveness of DCMD was also studied for oil field-produced water collected from Kuwait. Table 2 summarizes the physiochemical analysis of the AGS used in this study in mg/L. A physiochemical analysis was performed using a DR 5000 Spectrophotometer (Hach, DR 5000, USA) and ion chromatography (Dionex 5000, USA) systems.

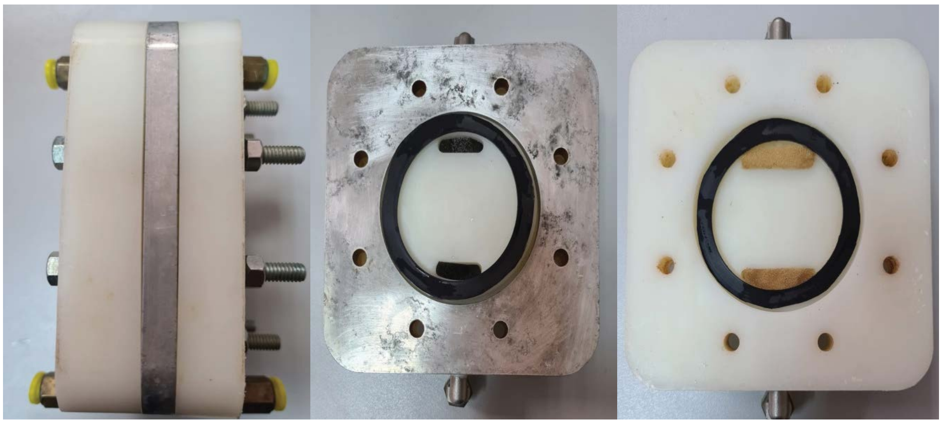

Fig. 3. DCMD module fabricated at the KISR.

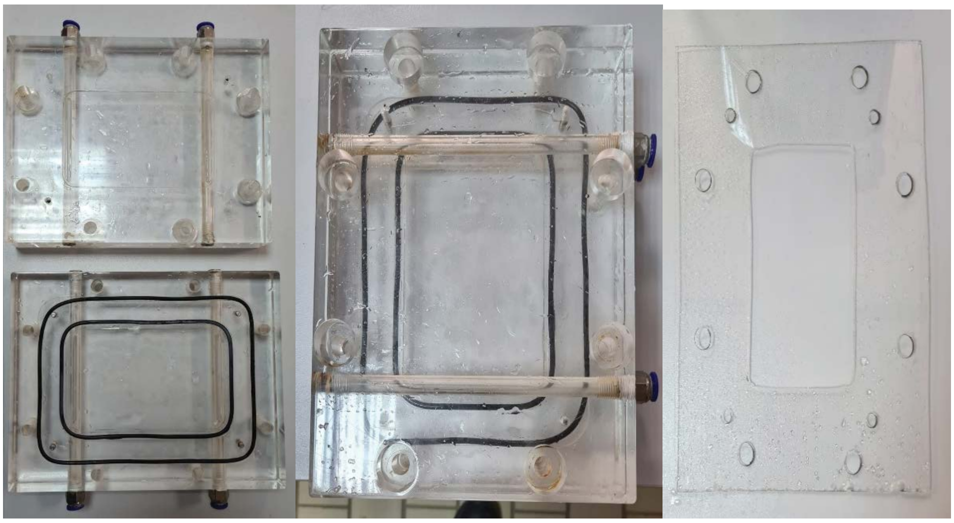

Fig. 4. DCMD module used for studying channel-depth variation.

Table 2
Physiochemical analysis of AGS

Analysis item	Average value in mg/L
Total dissolved solids (TDS)	43,117
Ca^{2+}	817.3
Mg^{2+}	1,521.2
Na^{+}	13,482
$(SO_4)^{2-}$	3,440
$(HCO_3)^{-}$	142.1
Cl^{-}	23,165
K^{+}	331
NO^{3-}	3.78

A membrane was placed between the hot plate and the cold plate of the DCMD module. The DCMD setup consisted of a hot water loop and a cold-water loop. The feed solution was pumped to a heated circulating bath, which was then fed to the hot inlet of the DCMD module and circulated back to the feed tank (Fig. 1). On the cold side of the membrane, deionized water was pumped to a cooling circulating bath, fed to the cold inlet of the DCMD module, and then back to the cold solution tank. A circulating bath (Cole-Parmer Polystat – Item #EW-12122-02) was used for controlling and maintaining the hot- and cold-side temperatures. The flux was determined by measuring the increase in the weight of the cold solution tank over time. A weighing balance (MS32000L/A03, Mettler Toledo, Switzerland) was used to measure changes in the weight of the solutions.

After ensuring that both the flow rate and the temperature of the streams remained stable at the required levels, each experiment was conducted for 90 min. Each experiment was repeated in triplicate, and the average value was taken for analysis. The membrane's active surface was facing the hot feed solution. The temperature and conductivity of all streams were measured and recorded manually. Electrical conductivity meters (Thermo Scientific™ Orion™ Star A322 Conductivity Portable Meter, Indonesia) were used for manual measurements of electrical conductivity, total dissolved solids (TDS), salinity, and temperature. The membranes' water vapor flux and salt rejection efficiency were determined using Eqs. (1) and (2), respectively.

For each membrane, three trials were conducted using similar experimental conditions, and the average flux and rejection values were reported.

$$\text{Water Flux} = \frac{\Delta\text{Weight}}{\text{Water density} \times \text{membrane surface area} \times \Delta\text{time}} \quad (1)$$

$$R = \frac{C_f - C_p}{C_f} \quad (2)$$

where R is the salt rejection, and C_f and C_p are the concentrations of the feed and permeate, respectively. These concentrations were determined via conductivity measurements using a conductivity meter.

3. Validation of DCMD system in Arabian gulf seawater

3.1. Effect of feed temperature

Fig. 5 shows the influence of feed temperature on permeate flux. The temperature varied from 45°C to 75°C. The cold side temperature was fixed at 20°C (Fig. 1). The feed used was a 26% NaCl solution. The feed flow rate and the cold solution flow rate were fixed at 1.2 L/min. Deionized water was circulated on the cold side of the membrane. As expected, it was observed that the permeate flux increased with the temperature. The permeate flux increased to 32.4 from 10.1 L/m²·h when the temperature was raised from 45°C to 75°C. These observations agree with the values reported in the literature [45–50].

Table 3 shows the permeate flux and salt rejection percentages at different feed temperatures. The increase in permeate flux was approximately 66% when the temperature was increased to 65°C from 55°C. A further increase of 10°C resulted in only a 19% increase in permeate flux. Although there was a significant increase in flux with higher temperatures, considering the energy requirement at higher temperatures, the feed temperature for further experiments in this study was set at 65°C. Furthermore, although PP and PVDF membranes can withstand temperatures above 85°C for a short time, a continuous operating temperature of 65°C is recommended for a safe and prolonged duration.

It was observed that feed temperature had less of an effect on the salt rejection property of the membrane. This shows that a high-temperature feed can be used in a DCMD configuration using PP membranes to obtain high water flux with a good salt rejection percentage. A relatively small reduction in feed concentration (from 26% to 24% salinity) over time was observed at all tested temperatures. This could be due to the flow of water toward the feed side resulting from the high osmotic pressure difference between the 26% NaCl feed and deionized water.

3.2. Effect of feed concentration

Fig. 6 shows the effect of feed concentration on the permeate flux. The tests were conducted using deionized water and an NaCl solution at 3.5%, 7.0%, 15%, and 26% concentrations, respectively, as feed. The flow rate at the feed and at the cold-solution channels was 0.9 L/min. Polypropylene was used as the membrane. The feed-side and coolant-side temperatures were 65°C and 5°C, respectively. Deionized water circulated on the coolant side of the module (as shown in the schematic in Fig. 1). From Figs. 6 and 7, it has been validated that an increase in the concentration of feed flow causes a decrease in the permeate produced. According to the results shown in Fig. 6, there was a 50% reduction in the permeate flux produced when the concentration of NaCl in the feed solution was elevated from 0% to 26%. This reduction might be due to the accumulation of salt molecules on the membrane surface, which can cause a

Table 3
Effect of temperature on permeate flux and salt rejection using the DCMD configuration

Membrane	Temperature (°C)	Permeate flux (L/m²·h)	Salt rejection (%)
	45	11.6	99.96
	50	13.6	99.94
	55	18.8	99.97
PP	60	27.4	99.92
	65	31.2	99.97
	70	34.1	99.96
	75	37.1	99.60

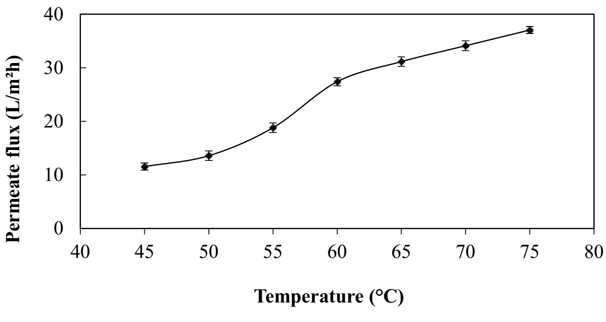

Fig. 5. Effect of feed temperature on the permeate flux of polypropylene membrane using the DCMD configuration shows that higher feed temperature results in increased flux.

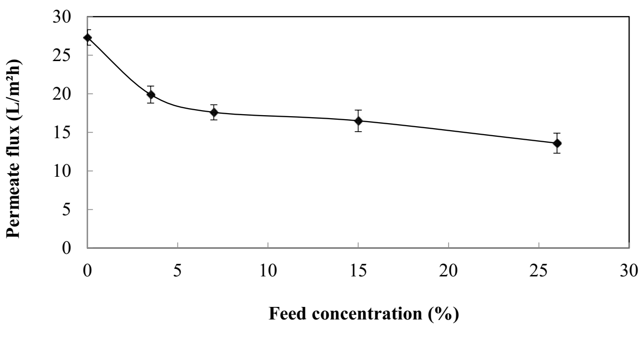

Fig. 6. Effect of feed concentration on permeate flux of polypropylene membrane showing low feed concentration results in high permeate flux.

hindrance to vapor transportation through the membrane. However, this requires further investigation. Furthermore, due to temperature polarization, the feed-side membrane surface might have been colder than the bulk feed as heat was transported from the bulk feed via the boundary layer to the membrane surface. These observations are also consistent with previous studies [45,48,51,52]. Fig. 7 shows that the permeate flux was uniform at each tested feed concentration throughout the test duration. However, long-term performance requires further study.

Further observation revealed that an increase in the concentration of the feed resulted in an increase in the time required to produce the same quantity of product water. For example, after 10 min of operation using deionized water as the feed, a permeate flux of 17.8 $L/m^2 \cdot h$ was obtained (Table 4). When the feed concentration was increased to 3.5% NaCl, it took almost 1 h to obtain the same permeate flux of 17 $L/m^2 \cdot h$. However, it took almost 1.5 h to obtain the same flux when the feed concentration was increased to 7% NaCl. This trend is important and shows the sensitivity of permeate-to-feed concentration. This trend shows that any increase in feed concentration requires more energy and time to create the required vapor pressure for permeate flux to occur.

Fig. 8 shows the effect of the feed concentration on salt rejection. When the feed solution concentration was raised, there was a minor rise in the conductivity of the permeate, but there was also a slight drop in the amount of rejected salt. The high concentration of NaCl in the feed solution might have lowered the liquid entry pressure, which caused a small rise in the permeate TDS.

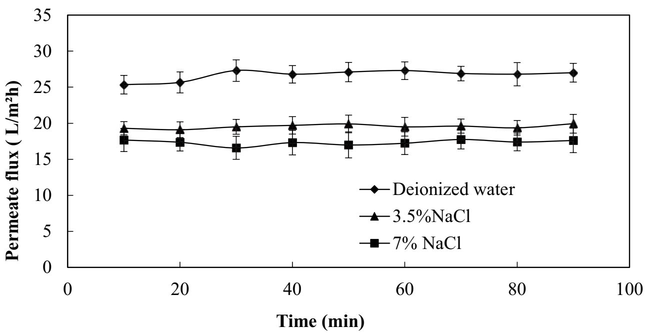

Fig. 7. Permeate flux at different feed concentrations and uniformity of permeate flux with desalination time.

Table 4
Time required to obtain the same permeate flux at different feed concentrations

Time (min)	Water flux, $L/m^2 \cdot h$		
	Deionized water	3.5% NaCl	7% NaCl
0	0.0	0.0	0.0
10	17.8	15.3	13.7
20	22.0	11.3	11.4
30	22.1	12.0	12.6
40	20.0	15.8	13.3
50	23.4	16.8	13.4
60	22.3	18.0	13.4
70	25.3	18.9	15.8
80	25.7	19.4	16.9
90	27.3	19.9	17.6

3.3. Effect of flow rate

Fig. 9 shows the effect of the flow rate on permeate flux. The tests were conducted using a 7.0 wt.% NaCl solution as feed and deionized water as a coolant medium. The temperatures of the feed and coolant sides were 65°C and 5°C, respectively. The flow rate of the feed and cold solution channels varied from 0.6 to 1.3 L/min. The experiment was conducted using a polypropylene membrane. As shown in Figs. 9 and 10, an increase in water flux in conjunction with an increase in flow rate was noticed. The temperature gradient between the membrane surface and the solutions (i.e., feed and coolant) was reduced. This increased vapor pressure and hence enhanced mass transfer in the membrane region [45,53–55]. The positive effects of turbulence on permeate flux have encouraged researchers to develop turbulence promoters for MD and membrane filtration processes [56,57].

Another factor to consider is the residence time of fluid in a channel. The residence time is the duration of the fluid's stay in the channel while moving from the inlet port to the output port. At low flow rates, the fluid residence time

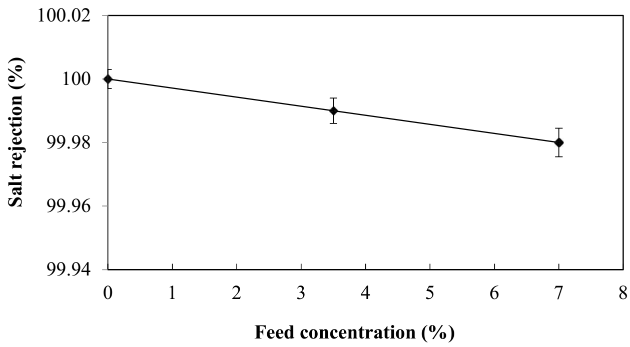

Fig. 8. Effect of feed concentration on the salt rejection of the polypropylene membrane.

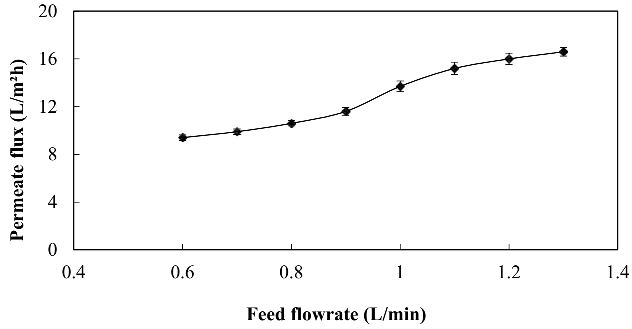

Fig. 9. Effect of flow rate on the permeate flux of the polypropylene membrane, showing an increase in flux with feed flow rate.

in the channel is longer, but at higher flow rates, the fluid residence time is shorter. Therefore, greater heat transfer between the membrane and medium may occur at lower flow rates, reducing the vaporization impact. At increased flow rates, the heat transfer rate decreases, thus accelerating the vaporization process. To the best of our knowledge, this effect of residence time on vapor pressure and permeate flux in MD has yet to be studied. In this current study, the effect of flow rate on salt rejection was negligible (Fig. 11).

3.4. Effect of channel size on permeate flux

We now consider the effect of channel depth on permeate flux. Tests were conducted with a NaCl solution containing 7.0% by weight as the feed and deionized water as the cooling medium. The temperature of the feed side was 65°C, and the temperature of the coolant side was 5°C. The feed and cold solution channels maintained a flow rate of 1.3 L/min. The experiment was carried out using a PP membrane.

As shown in Fig. 4, plates of 1 mm thickness were inserted between the membrane and membrane cell plates (hot and cold sides) to increase the channel's depth on both sides of the membrane. This was done to increase the volume and flow of the solutions on both sides of the membrane. Initially, a single plate was kept on both sides of the membrane. After experimentation with this setup, the number of plates was increased to create different channel depths, and experimentation at each setup was performed. Studies based on increasing the channel depth by using plates and their effect on permeate flux using the MD process have yet to be reported. The channel depth varied from 4 to 10 mm, which was the minimum possible channel depth in the tested DCMD module. The initial round of studies involved altering the depth of the hot channel from 1 mm to 8 mm while maintaining the cold channel depth at 2 mm. The experiments were performed for cold channel depth variation while maintaining the hot channel depth at 2 mm.

As shown in Fig. 12, although the reduction in permeate flux with an increase in channel depth was minimal at a low channel depth, the reduction in flux was much higher at greater channel depths. Fig. 12 reveals that when the cold channel depth was increased to 10 from 4 mm, the flux was reduced from 7.8 to 7.2 L/m²·h. The flux values were most affected by variations in cold channel depth rather than hot channel depth variation. The effect of gap width on flux was less sensitive at lower gap depths due to the thermophysical characteristics of water and the effects of natural convection within the gap [58,59]. Heat and mass flow across the channel depth were affected minimally at a lower channel depth. This impact can vary depending on the medium in the channel, such as air or sand [58,59].

Fig. 13 shows the permeate flux values at different flow rates and temperatures while maintaining the hot channel depth at 8 mm and the cold channel depth at 2 mm. It is evident from Fig. 13 that the permeate flux at higher channel depths can be increased by increasing flow and temperature. At a hot channel depth of 8 mm and a cold channel depth of 2 mm, the flux increased to 8.9 from 7.6 L/m²·h upon increasing the flow to 2 L/min. Furthermore, upon raising

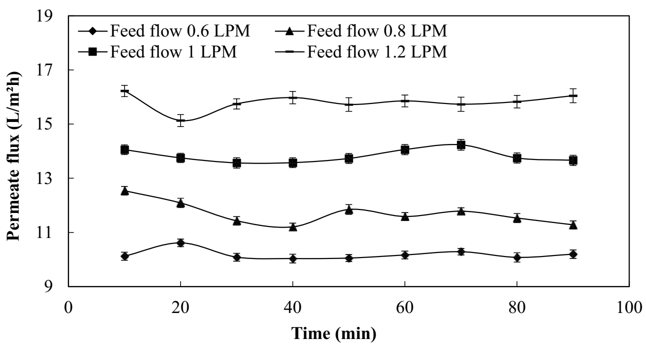

Fig. 10. Permeate flux at different feed flow rates and comparatively consistent permeate flux with desalination time.

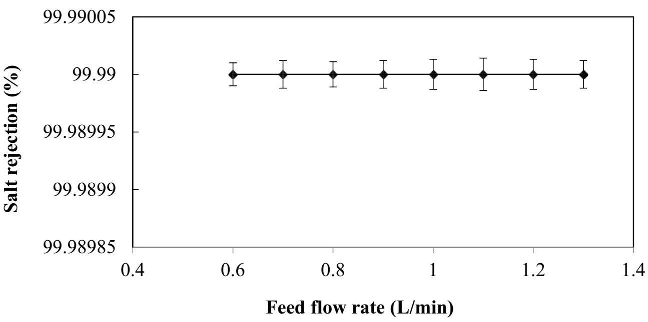

Fig. 11. Effect of the flow rate on salt rejection of the polypropylene membrane.

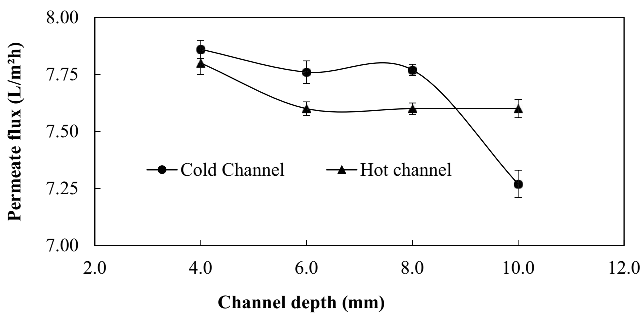

Fig. 12. Permeate flux at different channel depths shows that lower channel depths result in a better permeate flux.

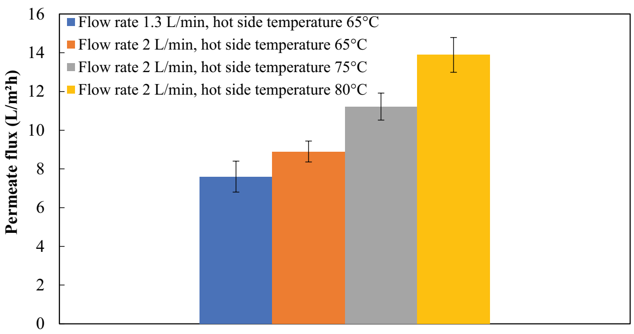

Fig. 13. Permeate flux at different flow rates and temperatures (a hot-side depth of 8 mm and a cold-side depth of 2 mm).

the temperature from 65°C to 85°C, the flux increased by almost 56%, from 8.9 to 13.9 L/m²·h.

The effect of natural convection on flux can also be observed in Fig. 13. The natural convection within the gap increased continually as the feed temperature rose. Higher feed temperatures (for a constant coolant temperature) result in more pronounced natural convection effects within a water gap [58,60]. This leads to an increased flux at higher temperatures. In summary, the above trends indicate that the use of higher flow rates and temperatures will result in a higher permeate flux.

3.5. Oil field-produced water desalination performance study

Oil field-produced water collected from an oil field was utilized as feed without pretreatment. The cooling medium utilized was deionized water. The temperature of the feed side was between 80°C and 85°C. The temperature of the coolant side was 5°C. The feed and cold solution channels maintained a flow rate of 2 L/min. The hot channel depth was 8 mm, and the cold channel depth was 2 mm. The experiment was conducted using a polypropylene membrane. The experimental results in Fig. 14 shows the permeate flux as a function of time. It was observed that DCMD is highly efficient in desalinating oil field-produced water. The permeate flux in this experiment was 11.5 and 12.5 L/m²·h at 80°C and 85°C, respectively. The stable permeate flux indicates that the fouling resistance of the membrane was good. However, long-term performance requires further study.

Studies have reported slight fouling of the membrane in the long run. In such a scenario, washing the membrane with deionized water is effective for cleaning the membrane and restoring the permeate flux [61]. Furthermore, the salt rejection was almost 100% (viz., 99.98% to 99.99%) at both temperatures and maintained the same rejection percentage throughout this current study, as shown in Fig. 15. The results demonstrate the huge potential of DCMD to treat hypersaline oil field-produced water with a salt rejection of more than 99.9% overall.

The observed stable, reliable salt rejection parameters were attributed to the membranes' resistance to wetting over the testing period. The selected membranes were hydrophobic and demonstrated only the transport of water vapors through the membranes' pores. Table 5 shows the analytical results of the feed water sample and permeate collected after the DCMD process.

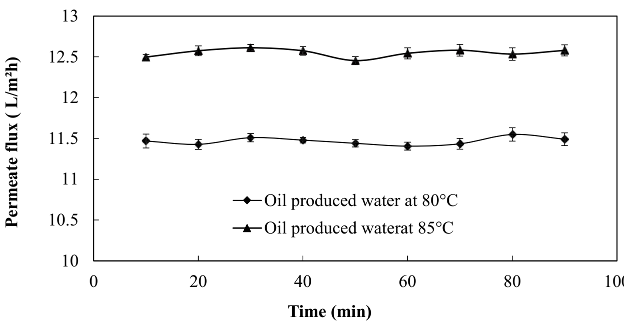

Fig. 14. Permeate flux at different temperatures using oil field-produced water as a feed with a TDS of 168,000 mg/L and oil and grease levels at 71.8 mg/L.

3.6. Seawater desalination performance of PP and PVDF membranes at different flow rates and temperatures using the DCMD configuration

The desalination performance of flat-sheet PP and PVDF membranes was studied using the AGS feed, which was collected from the DRP in Kuwait. The feed temperature was kept at 65°C and the cold side temperature was kept at 5°C. The flow rate of hot and cold side water varied from 0.6 to 0.9 L/m. Experiments were conducted for both membranes at different flow rates, and the results are summarized in Table 6. From Table 6, it is evident that the water flux increased with an increase in the flow rate for the PP and PVDF membranes. The highest water flux for PP and PVDF membranes was 13.2 and 17.8 L/m²·h, respectively, when AGS was used as the feed solution.

PP membranes performed better than PVDF membranes in terms of salt rejection, whereas PVDF membranes showed a higher water flux than the PP membranes (Table 6). PP membranes are suitable for applications where reasonable water flux and high salt rejection are required. In applications where salt rejection is not a major concern, PVDF membranes can be used.

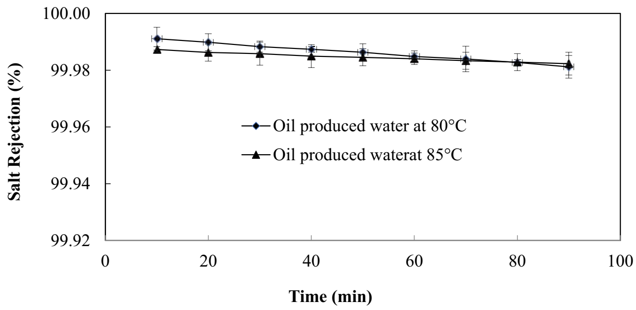

Fig. 15. Salt rejection percentage at different temperatures using oil field-produced water as a feed with a TDS of 168,000 mg/L and oil and grease levels at 71.8 mg/L.

Table 5
Analytical results of oil-produced water and permeate water

Parameter	Unit	Feed water	Permeate water
Total dissolved solid (TDS)	mg/L	168,000	413
Total suspended solid (TSS)	mg/L	95	<2
Chloride	mg/L	99,420	223
Sodium	mg/L	44,417	88
Calcium	mg/L	12,247	21
Magnesium	mg/L	2,029	9
Potassium	mg/L	1,836	8
Strontium	mg/L	345	3
Oil and grease	mg/L	71.8	<0.75
Total organic carbon (TOC)	mg/L	9.5	2.4
Turbidity	NTU	64	0.9

Table 6
Water flux and salt rejection percentages of PP and PVDF membranes were tested under a DCMD configuration at different flow rates using an AGS feed

Membrane	Flow rate, L/h	Water flux, L/m²·h	Salt rejection, %
PP	0.6	11.7	99.98
	0.9	13.2	99.98
PVDF	0.6	12.5	78.83
	0.9	17.8	75.89

4. Conclusion

In this study, the feasibility of the DCMD process for desalinating different saline waters, AGS, and oil field-produced water under various operating conditions using polypropylene and PVDF membranes was investigated at the laboratory scale. Experiments were conducted to determine the effect of feed temperature, flow rate, and feed concentration on permeate flux, as shown in the parametric cases of Table 1. Tests were also conducted by varying the channel depth of the DCMD module. The feed temperature varied from 45°C to 75°C. The permeate flux increased to 32.4 from 10.1 L/m^2·h when the temperature was raised from 45°C to 75°C (Fig. 5).

It has been observed that increments in feed water temperatures increase transmembrane vapor pressure and result in a high permeate flux. Additionally, at higher temperatures, the viscosity of a feed solution decreases, which can lead to an improvement in hydrodynamic conditions and result in a higher flux. Overall, temperatures ranging from 45°C to 75°C are commonly used in MD research studies because they are within the typical operating temperature range for most MD systems and allow for high permeate flux while minimizing the risk of thermal degradation. At temperatures below 45°C, the vapor pressure of a feed solution may not be high enough to provide a sufficient driving force for mass transfer, resulting in low permeate flux. Temperatures above 75°C increase the risk of thermal degradation of polymeric membranes and heat-sensitive feed solutions, resulting in decreased membrane performance and flux.

NaCl solutions at concentrations of 3.5%–26%, deionized water, oil field-produced water, and AGS were used as the feed at different stages of this study. The increment in feed water concentration caused a decrease in permeate flux. Fig. 6, shows that there was a reduction of 50% in permeate flow that was produced when the concentration of NaCl in the feed solution was elevated from 0% to 26%. This shows that more time and energy might be required to produce permeate flux when the feed concentration is increased.

As discussed in Section 3.2 – Effect of feed concentration and shown in Table 4, the amount of time needed to produce the same volume of product water also increased when the feed concentration was increased. The water flux increased with an increase in the flow rate due to turbulence, which reduced the effects of temperature and concentration polarization. Additionally, greater heat transfer between a membrane and a medium may occur at lower flow rates and reduce the vaporization impact. At increased flow rates, the heat transfer rate between a membrane and a medium decreases, thus accelerating the vaporization process, which results in a higher permeate flux.

The effect of a direct contact membrane distillation system on different hot feed and cold-solution channel depths was also studied using a DCMD module developed by the research team. Fig. 12 shows that the flux reduction was much greater at deeper cold-channel depths. Fig. 12 reveals that deeper channel depths (both hot and cold) are good for higher permeate flux. Fig. 13 shows that higher flow rates and temperatures are required to obtain a higher permeate flux upon increasing the hot-channel depth.

The experimental results showed that DCMD was highly efficient in desalinating oil-produced water obtained from the state of Kuwait. This is consistent with the results reported in studies that used effluent water from other parts of the world, as discussed in Section 3.5 – Oil field-produced water desalination performance study. The permeate flux was 11.5 and 12.5 L/m^2·h at 80°C and 85°C, respectively. The results indicate the enormous potential of DCMD to treat hypersaline oil field-produced water, with an overall rejection of salts above 99.9%.

The comparison of PP and PVDF membrane performance for AGS desalination revealed that PP membranes had a higher salt rejection rate but lower water flux, while PVDF membranes had a lower salt rejection rate but higher water flux. This observation is important because it suggests that PP membranes may be a more suitable option than PVDF membranes for seawater desalination and may lead to more energy-efficient and cost-effective desalination. PP membranes are ideal for situations where a balance of water flow and salt removal is necessary, while PVDF membranes are suitable for applications where salt removal is not a primary concern.

This study successfully established and generated reference data on DCMD technology for desalinating different saline waters at the laboratory-scale level under realistic operating conditions. More specifically, it used actual AGS (which has a considerably higher salinity than other seawaters) and oil field-produced water as feed. Overall, the results are promising, and recommend conducting further laboratory- and pilot-scale studies using other MD technologies, such as VMD, AGMD, and SGMD, to desalinate AGS and oil field-produced water.

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