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Saline Water Desalination by Low Grade Energy: Practical Solution for Water Shortage in Middle East

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Abstract: Large increases in water demand with very little recharge have strained Middle East's ground water resources resulting in serious decline in water level and quality. Both thermal and membrane based desalination technologies have been used in this region of the world. Membrane distillation (MD) is an emerging and versatile non-isothermal membrane separation process. It is based on the phenomenon that pure water in its vapor state can be extracted from aqueous solutions, with vapor passing through a hydrophobic microporous membrane when a temperature difference is established across it. In this work, two commercial hydrophobic microporous membranes, made of PTFE and PVDF polymers, were used for seawater desalination through direct contact membrane distillation (DCMD). The effect of operating parameters as well as membranes' characteristics on the salt rejection and permeate flux has been studied. An experimental set-up was designed, constructed and used for seawater desalination experiments. The results indicated that DCMD process had considerable desalination performance when a hot feed temperature of 80°C with 800ml/min flow rate was used. At optimum conditions, a 99% salt rejection was achieved by use of PTFE membrane. Based on experimental results, DCMD has a great potential for solving the water shortage in Middle East region.

Key words: Saline water · Desalination · Low grade energy · Direct contact membrane distillation (DCMD) · Permeate flux · Middle East

INTRODUCTION

The availability of potable water is a major problem in many regions of the world. Oceans contain about 97% of the world water, by volume, which is too salty for drinking or industrial use. About 3% of the fresh water is available and suitable for mankind use. Therefore, growth of industries, agriculture and population through the world and higher water demand led to increased the shortage for fresh water resources [1-4].

Desalination is a process in which fresh water is extracted from saline solution and is used to alleviate the water shortages [5, 6]. The desalination methods can be classified into various categories based on the driving force, such as thermal, pressure and electrical potential driven processes. The thermally driven processes, e.g. multi-stage flash (MSF) and multi-effect distillation (MED), are the oldest and the most widely used on large scales, especially in the Persian Gulf region because of low cost for fossil fuel based energy resources in this arid region. Reverse osmosis (RO) is a relatively new membrane process with pressure difference driving force that is taking an increasing share of the world desalination capacity [4, 5, 7].

Membrane distillation (MD) is an emerging and versatile non-isothermal membrane separation process. It is based on the phenomenon that pure water can be extracted from aqueous solutions by evaporation, with the

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vapor passing through a hydrophobic microporous membrane when a temperature difference is established across it. The temperature difference leads to a vapor pressure difference across the membrane. Due to hydrophobic nature of the membrane, only the vapor can pass across the membrane and the liquid solution could not pass [8-10].

Based on the permeate side condition and configuration, membrane distillation systems can be classified in four modes i.e. direct contact MD (DCMD), air-gap MD (AGMD), vacuum MD (VMD) and sweeping gas MD (SGMD) [11]:

In this work, two hydrophobic membranes were used for desalination of seawater via DCMD process. The performance evaluations were carried out by consideration the effect of various operating parameters including feed temperature, feed flow rate and cold stream flow rate. Long term runs were conducted to evaluate DCMD as stand-alone desalination process.

MATERIALS AND METHODS

Two flat sheet hydrophobic microporous membranes made of PTFE and PVDF with a nominal pore size of 0.22µm were used for experiments. Figure 1 shows the scanning electron microscopy (SEM) of the membranes. The specifications of the membranes are presented in Table 1. Persian Gulf seawater which was provided from South Pars offshore (located in the south part of Iran) used as feed.

A DCMD set-up with 0.0169m^2 membrane areas located in a plate and frame module mounted horizontally was designed and constructed. Figure 2 shows a general scheme of the applied apparatus flow diagram. In all of the experiments, the active layer of the membranes was faced up to the hot feed stream. Cross-current flow pattern was established in the module for both hot and cold streams using two diaphragm pumps (So~Pure, Korea). In order to establish a steady state condition for long time experiments during 15 days, the permeate stream was recycled to the feed storage tank.

The conductivity of the permeate flow was measured with an EC-meter (model EC470-L, ISTEK, Korea). Scanning electron microscopy (SEM) (VEGA, TESCAN, Czech Republic) and atomic force microscopy (AFM) (DUALSCOP 95-200E, DEM, Denmark) were used for morphological observation (Figure 3). Hydrophobicity of the membranes was tested by a contact angle measuring system (KRUSS G-10, Germany).

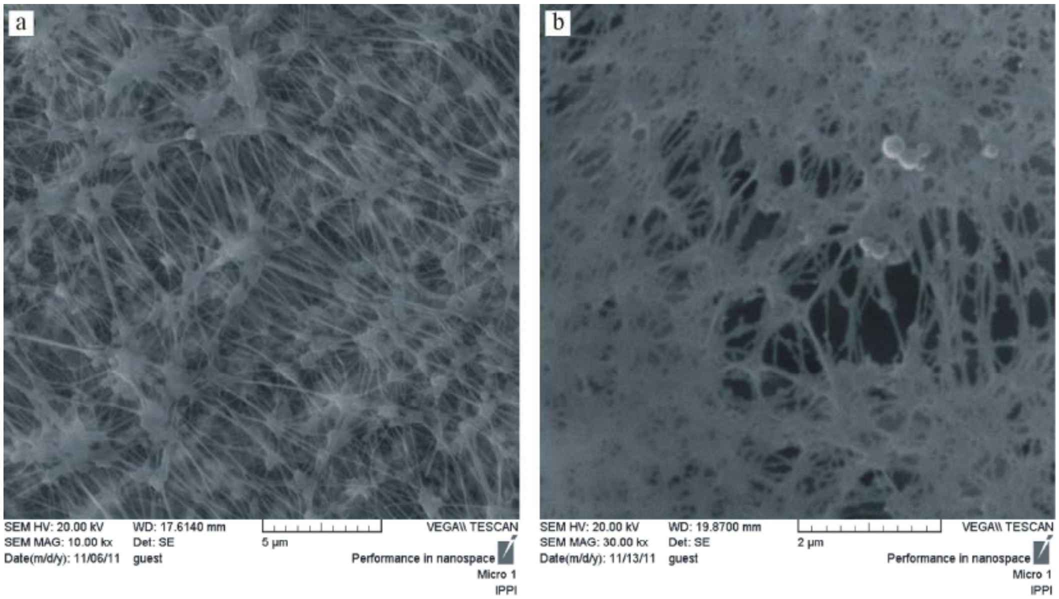

Fig. 1: The SEM images of (a) PTFE and (b) PVDF membranes with 0.22µm nominal pore size

Table 1: The specifications of the membranes used in this study

Material	Pore size (µm)	Thickness (µm)	Porosity (%)	Contact angle (°)	Manufacturer
PTFE	0.22	178	70	132.2±5°	Millipore
PVDF	0.22	180	80	98.7±5°	Sepro

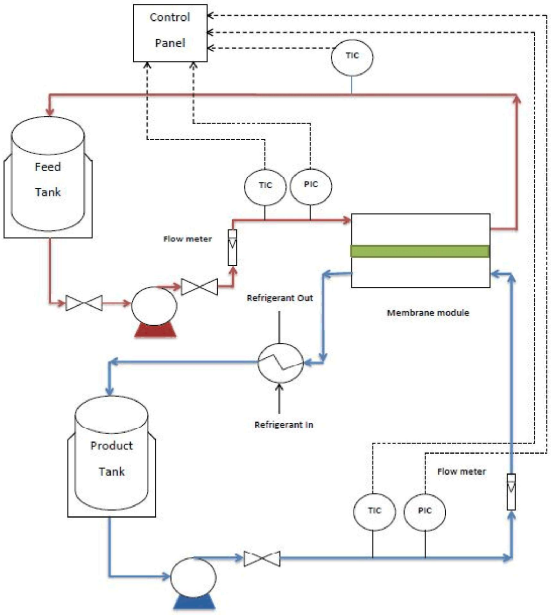

Fig. 2: A schematic diagram of the DCMD experimental apparatus

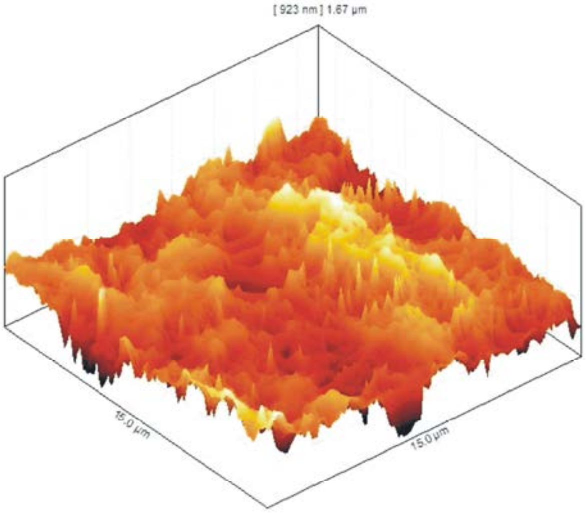

Fig. 3: A 3-D AFM image of the PTFE membrane

RESULTS AND DISCUSSION

In the first step, to evaluate the performance and salt rejection of the membranes, a constant operating conditions (T_h=80°C, T_c=20±5°C, Q_h=800 mL/min and Q_c=400 mL/min) was established. Figure 4 shows the permeate flux and salt rejection for the two membranes after 10 hours continuous operation. It may be observed that PTFE membrane showed the highest flux and rejection in compare with PVDF.

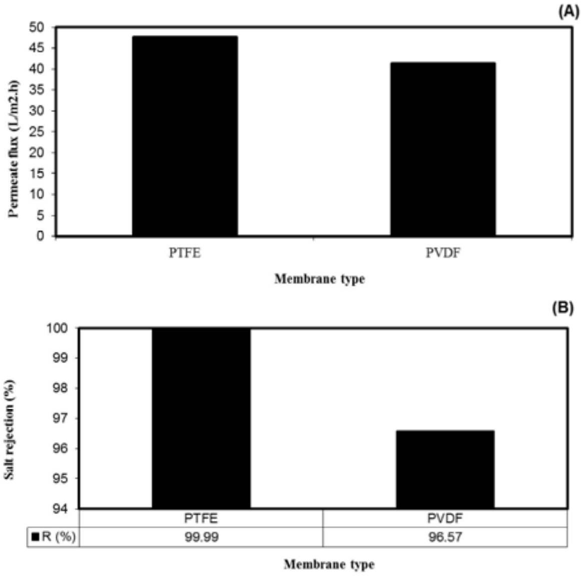

Fig. 4: Permeate flux (A) and salt rejection (B) of the permeate stream for PTFE and PVDF membranes

These can be explained by characteristics (Table 1), morphology and hydrophobicity of the membranes. As it could be observed in Table 1, PTFE membrane had the highest contact angle with water droplet (132.2±5°), which means higher hydrophobicity (one of the major conditions which is required for MD membranes) in compare with the PVDF membrane. Moreover, the SEM images showed that PTFE membrane has more uniform structure than those for PVDF membrane. The non uniform structure and the presence of the large gaps in the PVDF membrane is a powerful potential for brine leakage from feed side into the permeate side. Therefore, PTFE membrane considered for next experiments.

As MD is a non-isothermal separation process, feed temperature (T_h) was considered as the first operating variable in the range of 50 to 80°C. Figure 5 shows the effect of T_h on the permeate flux. The results show that the higher the feed temperature, the higher permeate flux achieved. It can be explained by the well-known Antoine equation ($\log P^* = A - \frac{B}{C + T_h}$) which expresses the relationship between the liquid temperature (T_h) and the corresponding equilibrium vapor pressure (P^*) (the driving force for MD process). In other word, higher feed temperature leads to higher vapor pressure which provides further permeate flux. Therefore, 80°C feed temperature was considered for the next experiments. It worth quoting that high solar radiation (solar heat) in the Persian Gulf region can considered as a practical source for energy demand of MD process.

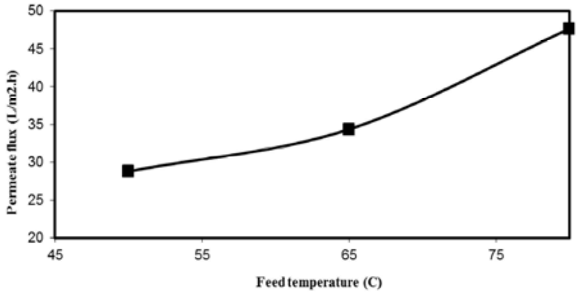

Fig. 5: The effect of feed temperature on the permeate flux.
Q_h=800 mL/min, T_c=20±5 °C, Q_c=400 mL/min

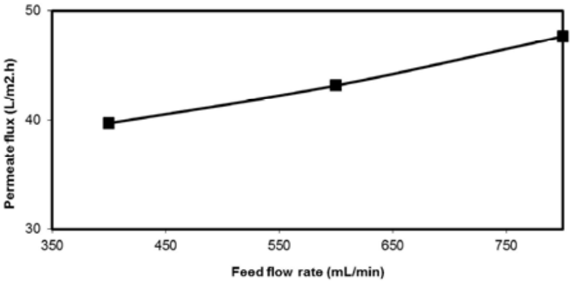

Fig. 6: The effect of feed flow rate on the permeate flux.
T_h=80 °C, T_c=20±5 °C, Q_c=400 mL/min

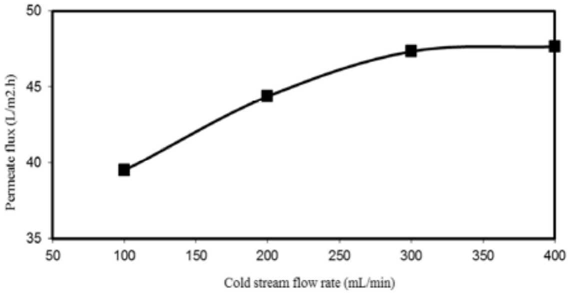

Fig. 7: The effect of cold stream flow rate on the permeate flux.
T_h=80 °C, T_c=20±5 °C, Q_h=800 mL/min

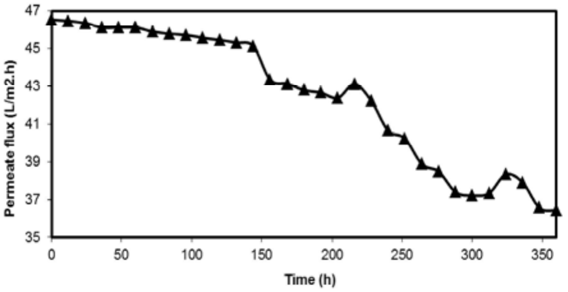

Fig. 8: The performance of DCMD during long time run.
T_h=80°C,T_c=20±5°C,Q_h=800mL/min,Q_c=400mL/min

Like other membrane processes, MD process is sensitive to fouling, in which precipitation of the less soluble constituents in the operating condition on the membrane surface causes a reduction in the permeate flux. Moreover, as vaporization takes place in the membrane-feed interface, both concentration and temperature polarizations exists. One way to overcome these unfavorable effects is to increase the turbulency in the feed channel at the hot side of the membrane module. Therefore, the feed flow rate in the hot side (Q_h) considered as an important operating variable in the range of 400 to 800mL/min. The results have been shown in Figure 6. The results showed that the increase in the feed flow rate led to an increase the permeate flux. Moreover, the effect of feed flow rate on the permeate flux was observed to be less than the effect of feed temperature.

In DCMD, both sides of the membrane are in direct contact with the hot and cold stream process liquids. Therefore, the cold stream flow rate (Q_c) in the permeate side could be considered as another operating variable. The flow rate in the range of 100 to 400mL/min was selected as the cold stream flow rate. The results are presented in Figure 7. As it could be observed, increase in the cold stream flow rate led to increase the permeate flux. However, this effect was less than those of achieved by hot stream flow rate. Increase in the cold stream flow rate has two different effect on the permeate flux. The first, increase in the cold stream flow rate maintains the driving force for condensation at a high level because it reduces the temperature polarization at the permeate side. The second, increase in the cold stream flow rate increases the turbulancy and Reynolds number at the cold stream side which increases the heat transfer between the hot feed stream and the cold stream. By considering that the membranes are very thin polymeric film with a thickness of 100-200 µm, they have a very low thermal resistance. Therefore increase in the cold stream flow rate, reduces the temperature gradient in the membrane which consequently reduces the permeate flux. The results confirms this conclusion because increase in flow from 300 to 400 mL/min had negligible effect on the permeate flux.

To evaluate the DCMD as a stand-alone desalination process, long term performance during 15 days was conducted. Data were logged every 12h. The results which has been shown in Figure 8 showed that the permeate flux reduces slightly within the first 150h of operation which is because of slightly pore blockage by solid particles presented in the feed solution. After almost 204h a sharper decrease in the permeate flux was observed which is the result of scale formation on the membrane surface.

CONCLUSIONS

Following points are concluded in this work:

- DCMD is a powerful, low cost, low temperature and clean method for seawater desalination.
- Flux decline in this process is mainly because of concentration and temperature polarization in the feed side.
- The most important factors in this process are the feed temperature and then the feed flow rate, respectively.
- Cold stream condition has a lesser effect on the permeation flux.
- Scale formation is the major reason for flux decline during long time runs.
- Periodical addition of acid and alkali to the feed solution may be considered as a proper way for online cleaning and flux recovery for this system.

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