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Effect of operating parameters and membrane characteristics on air gap membrane distillation performance for the treatment of highly saline water

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Abstract

In this study, ten different commercially available PTFE, PP and PVDF membranes were tested in desalination of highly saline water by air gap membrane distillation (AGMD). Process performance was investigated under different operating parameters, such as feed temperatures, feed flow velocities and salt concentrations reaching 120 g/L, and different membrane characteristics, such as membrane material, thickness, pore size and support layer, using a locally designed and fabricated AGMD module and spacer. Results showed that increasing feed temperature increases permeate flux regardless of the feed concentration. However, feed flow velocity does not significantly affect the flux, especially at low feed temperatures. The PP membrane showed a better performance than the PVDF and PTFE membranes. Permeate flux decreases with the increase of salt concentration of feed solution, especially at higher concentrations above 90 g/L. The existence of membrane support layer led to a slight decrease of permeate flux. Membranes with pore sizes of 0.2 and 0.45 μm gave the best performance. Smaller pore size led to lower flux and larger pore size led to pore wetting due to lower LEP values. The effect of concentration polarization and temperature polarization has also been studied and compared.

Keywords: MD membranes performance; Air gap membrane distillation (AGMD); Highly saline water desalination; Concentration polarization coefficient; Temperature polarization.

1. Introduction

Freshwater shortage is an important issue for many countries, especially for arid regions such as the Middle East and Northern Africa. It is attractive to explore the possibility of desalinating seawater to produce drinking water. Currently, seawater desalination can be achieved by

distillation, such as multi-stage flash (MSF), multi-effect distillation (MED), or by reverse osmosis (RO). However, these processes require significant energy input to provide separation of salts from seawater [1]. Many researchers are seeking for alternative technologies, which could be independent of the use of fossil fuel. Membrane distillation (MD) is an attractive new desalination technology with unique advantages, such as higher rejection of inorganic ions compared to other membrane processes, runs at lower feed temperatures than thermal-based processes, lower operating pressures than conventional pressure-driven membrane separation processes, mainly RO, compactness, simplicity, and perceivably more immunity to fouling than other membrane processes [2, 3].

MD is based on a thermally driven transport of water vapor through no-wetted porous hydrophobic membranes, the driving force being the water vapor pressure difference between the two sides of the membrane pores [4, 5]. Since the first MD patent and the first MD publication in the 1960s [6, 7], MD has been known as an effective desalination process for 50 years. But since the 1980s, research on MD has become active and different configurations of MD have been developed. According to the type of the condensing (cold side) design, the MD process can be classified into direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), vacuum membrane distillation (VMD) and sweeping gas membrane distillation (SGMD). Most of the bench-scale work on MD process evaluation has been done with DCMD [8-19]. Interest in AGMD, VMD and SGMD has been increasing in recent years [20-40]. More recently, other new MD configurations aiming to enhance the flux have been developed, such as water gap MD, material gap MD and liquid gap MD [41-43].

In AGMD, a stagnant air layer is placed between the membrane and the condensation surface. The main advantage of the AGMD configuration is that the presence of the air gap layer reduces the heat loss by conduction through the membrane [44]. Besides that, permeate can be collected directly through the air gap rather than to be mixed with the coolant as it is the case for DCMD. In AGMD, it is easy to judge whether membrane leakage or wetting occurs by detecting conductivity of permeate. In the case of AGMD configuration, most of the published papers are relative to theoretical models and transport phenomena. However, few researchers have focused on the membranes themselves [25, 45-50]. Polyvinylidene fluoride (PVDF), polypropylene (PP) and polytetrafluoroethylene (PTFE) are the most common membrane materials for MD application due to their hydrophobic property and high thermal stability. It is known that

membranes are critical in determining the vapor transport. Therefore, it is necessary to study the performance of these commercially available membranes used in MD, mainly under harsh conditions as is stated as one of the MD advantages, such as its performance for highly saline feed water concentrations. Several authors tested MD performance for treating desalination brines, such as RO and MSF [51-55].

In this work, ten different commercially available PVDF, PTFE and PP membranes with various pore sizes and support layers were tested for desalination of highly saline water using a locally designed and fabricated AGMD experimental set-up. The effect of operating parameters, such as feed flow velocity, temperature gradient and a large range of feed concentration varying from 40 g/L to 120 g/L, membrane materials, support layer and membrane pore sizes were investigated.

2. Experimental

2.1 Experimental setup

A schematic diagram of the MD bench scale experimental setup is shown in Figure 1.

Fig. 1 Schematic of the MD bench scale experimental setup

The membrane module, tubing system, and feed and coolant tanks are made of plastic-based materials. The module consists of three compartments, feed solution flows through the top part, coolant flows through the bottom, and the generated permeate is collected in the middle chamber. The

membrane is placed between the feed and air gap compartments. A stainless steel perforated plate, having a thickness of 0.5 mm and circular holes diameter of 6.5 mm, was used to support the membrane and prevent the membrane from possible deformation or damage. It was also acting as a spacer aiming to create more turbulence near the membrane surface. Feed solution is heated by the heater inserted into the feed tank. Feed solution and coolant are pumped in countercurrent flow in a closed loop system within the membrane module. The feed and coolant flow velocities were controlled by gear pumps supplied by Coleparmer Company. The inlet and outlet temperatures of the feed water and coolant were continually measured by four thermocouples with an uncertainty of ± 0.5 °C placed at the inlets and outlets of each side of the membrane module. The inlet feed pressure was also continually measured by a pressure transmitter with an uncertainty of $\pm 0.25\%$ of gauge reading.

MD membrane modules, spacers and the whole fully automated experimental unit were designed and fabricated locally. Photos of the AGMD modules and spacers are presented in Figure 2.

Fig. 2 Photos of the AGMD module

Simulated seawater with different concentrations were prepared using sodium chloride, sodium sulfate, calcium chloride dihydrate, magnesium chloride hexahydrate and sodium bicarbonate provided by Sigma-Aldrich Company and used as feed solution. Each experiment was run for 4 hours. Salt concentrations of feed solution and permeate were measured by a WTW Cond 3310 meter. Permeate mass was measured by using a balance (TOLEDO ML 3002 with an uncertainty of ± 0.01 g connected to a computer via Lab View software. Permeate flux was calculated by the logged mass. The air gap between the membrane and the condensation surface is 10 mm, and the membrane area is

0.005 m². Characteristics of commercially available membranes used in this study provided by different manufactures are presented in Table 1.

Table 1 Characteristics of MD membranes used in this study

Membrane	Nominal pore size ^a (μm)	Thickness (μm) ^b	support ^a	Porosity ^b (%)	LEP ^b (bar)	Supplier
PTFE 11	0.2	166	PP non-woven	68.7	1.5	STERLITECH
PTFE 12	0.45	206	PP non-woven	70.6	0.98	STERLITECH
PTFE 13	1.0	195	PP non-woven	61.0	0.31	STERLITECH
PTFE 2	0.2	87	PP scrim	68.5	1.63	STERLITECH
PTFE 3	0.2	30	Non-supported	72.1	1.98	STERLITECH
PVDF 1	0.2	121	Non-supported	66.3	1.25	SIGMA-ALDRICH
PVDF 2	0.45	138	Non-supported	75.0	0.84	SIGMA-ALDRICH
PP 1	0.1	155	Non-supported	78.9	2.07	STERLITECH
PP 2	0.2	150	Non-supported	69.6	0.95	STERLITECH
PP 3	0.45	112	Non-supported	70.1	0.75	STERLITECH

a. Values provided by suppliers

b. Values measured in the lab

The salt rejection (SR) and water flux (J_V) were calculated using the following equations:

$$SR = \left(1 - \frac{C_p}{C_f}\right) \times 100 \quad (1)$$

$$J_V = \frac{m_p}{At} \quad (2)$$

where C_p and C_f are the salt concentration of permeate and feed solutions, respectively, m_p is the mass of collected permeate, A is the effective membrane area and t is the running time.

A digital micrometer with accuracy of 0.005 mm, DML 3032 from Digital Micrometers Ltd., UK, was used to measure the membranes thicknesses. An auto pore IV 9500 Mercury Porosimeter was used to measure porosity of the membranes.

3. Results and discussion

3.1 Effect of feed flow velocity and feed temperature on permeate flux

A PTFE11 membrane of 0.2 μm pore size laminated onto a PP non-woven layer was first used to investigate the effect of the feed flow velocity on permeate flux for feed temperatures ranging from 40°C to 80°C. The coolant temperature was kept constant at 20°C, and coolant flow velocity was maintained at 0.07 m/s. The concentration of feed solution was 90 g/L, which is far higher than sea water salt concentration and is generally representative of desalination brines and some industrial brines (e.g. produced water from oil and gas recovery). The Reynolds number (Re) was 272, 544,

1089 and 1634, individually, and the residence time was 3.33 s, 1.67 s, 0.83 s and 0.56 s, individually. The results are shown in Figures 3 (a and b).

Fig. 3a Effect of feed temperature and feed flow velocity on permeate flux (PTFE 11), feed concentration = 90 g/L

Fig. 3b Effect of feed temperature and feed flow velocity on permeate flux (PTFE 11), feed concentration = 90 g/L

Feed velocity plays a role in the MD process due to its impact on the temperature difference across the membrane and reduction of the polarization at the membrane surface [23, 56, 57]. As shown in

Figures 3 (a and b), the feed flow velocity over the investigated range has no significant effect on permeate flux regardless of feed temperature. An increase in the feed flow velocity was accompanied by a slight increase and asymptotic trends in flux, which is similar to other reported results [4, 57-61]. There are two possible reasons. One is that an increase in the feed flow velocity over the investigated range slightly changed the boundary layer thickness of temperature and concentration as the AGMD process thermal efficiency and heat transferred by conduction were hardly influenced by the feed velocity [56]. The turbulence is low in the laminar regime and the short residence time is not helpful which is relevant to temperature polarization. At high velocities, the decrease of the residence time slightly changes the effect of temperature polarization, which might be another reason for the low effect on flux. It is worth noting that change in water flux was hardly observed for low feed temperature of 40 °C. The possible reason is that the process is heat transfer limited within a laminar region for low flow velocity, turbulence in heat transfer boundary layer was not increased with the increase of flow velocity and temperature polarization was not decreased, so permeate flux hardly improved. On the other hand, at very low cross-flow velocity (0.03 m/s), we observe a difference in flux at higher feed temperatures, above 70 °C, most probably due to higher temperature polarization and conduction effects. It is important to mention here that one has to expect much higher influence of feed flow velocity on permeate flux for larger scale modules as the liquid contact time with the membrane is longer.

Effect of feed temperature on permeate flux for different membranes with a 0.2 μm pore size and different materials was also investigated for different feed temperatures ranging from 50 °C to 80 °C and a coolant temperature of 20 °C. Feed and coolant flow velocities were maintained at 0.12 m/s and 0.07 m/s, respectively. The results are shown in Figure 4 (a, b and c).

As shown in Figure 4a, a significant increase in permeate flux was observed as feed temperature increases regardless of membrane material used. PP 2 behaves the best among these membranes, especially at higher temperatures; its water flux increased from 0.76 kg/ $\text{m}^2\cdot\text{h}$ to 4.86 kg/ $\text{m}^2\cdot\text{h}$ when feed temperature increased from 50 °C to 80 °C. Feed temperature is an important operational parameter that significantly affects the MD permeate flux. MD is a thermal separation process, and the driving force of the process is a vapor partial pressure difference influenced by the temperature difference created between both sides of the membrane [62]. The increase in feed temperature causes the increase of water vapor pressure, consequently enhancing the driving force. Although higher feed temperature is beneficial for high flux, energy consumption and the process thermal efficiency of the

MD process should be considered when the operating temperature and other parameters are optimized [23]. The thermal efficiency is expressed as [44, 63]:

$$\eta = \frac{Q_v}{Q_v + Q_c} \times 100\% \quad (3)$$

where Q_v is the heat of the vaporized liquid and Q_c is the heat lost by conduction via the membrane and the air gap.

$$Q_v = J_v H_v \quad (4)$$

where H_v is the evaporation heat of water (kJ/kg) which could be calculated by [63] below:

$$H_v = 1.75535T + 2024.3 \quad (5)$$

where T is the absolute temperature in (K).

$$Q_c = \frac{(T_{mf} - T_{cd})}{\frac{\delta}{K_m} + \frac{b}{K_g}} \quad (6)$$

where T_{mf} is the temperature of the membrane at the feed side, T_{cd} is the temperature of the condensate, δ is the membrane thickness, b is the air gap width, K_m is the effective thermal conductivity of the membrane material and the gas filling its pores. T_{mf} , T_{cd} and K_m can be estimated from the methods given by [44, 64].

The results showed that the thermal efficiency increased with the increase of feed inlet temperature, as shown in Figure 4b, which is in agreement with the theoretical results [55, 63, 65]. Thermal efficiency is high because the vapor pressure is high and the heat loss by conduction is low at higher feed temperatures.

Fig. 4a Effect of feed temperature for different membranes with the same pore size of 0.2 μm , feed concentration = 90 g/L

Fig. 4b Thermal efficiency at different temperatures for different membranes with the same pore size of 0.2 μm , feed concentration = 90 g/L

Salt rejection is also shown in Figure 4c. For feed solution with high salt solution, three kinds of membranes (PTFE11, PVDF 1, PP 2) showed different salt rejection, most of which is above 99%. The behavior of difference in salt rejection by the three membranes is maybe caused by the various preparation methods applied by the different manufactures, which could affect the membranes' mean pore size, pore size distribution and porosity [66, 67]. Amongst these membranes, PP 2 membrane had the highest and more stable salt rejection which is above 99.9%. PTFE 11 gave the lowest salt rejection of 99.2% possibly due to dense defect distribution or unhomogenous pore size distribution compared to the other two membranes [68].

Fig. 4c Salt rejection for different membranes with the same pore size of 0.2 μm , feed concentration = 90 g/L

3.2 Effect of salt concentration on permeate flux

Effect of feed salt concentration varying from 40 g/L to 120 g/L on permeate flux was investigated for feed and coolant inlet temperatures of 80°C and 20°C, respectively. Coolant and feed flow velocity were maintained at 0.07 m/s and 0.12 m/s, respectively. All the tested membranes have the same pore size of 0.2 μm and different materials (PVDF, PP and PTFE). Effect of membrane pore size is presented in the next section. Figure 5 shows the variations of permeate flux with feed salt concentration for different membrane materials.

Fig.5 Effect of feed salt concentration on permeate flux

Water flux decreased modestly with increasing feed salt concentration for all membranes. Nevertheless, MD can operate at very high salinities, a big advantage over other membrane desalination processes, such as RO (disc tube RO system type can be applied for such high concentrations) whose performance (low flux and very high pressure required) is significantly affected at similar feed salinities. The trend of the decrease was noticeable when salt concentration was higher than 80 g/L. This decrease can be explained in several ways: vapor pressure reduction at these concentrations [69], concentration polarization at the membrane surface and temperature polarization [4]. It is important to mention here that one has to expect a more significant decrease in flux at higher feed concentrations and can reach zero flux or even a negative flux (MD process will turn into an osmotic distillation process). We did not investigate higher feed concentrations to confirm this statement because it is outside the scope of this study.

Also, membrane thickness doesn't seem to be a dominant parameter in the AGMD configuration as membranes with lower thicknesses, e.g. PTFE2, gave lower fluxes than thicker membranes (more details will be discussed in the next Sections).

With the assumption of liquid-vapor equilibrium at the membrane surface, the vapor pressure of salt solution can be described by:

$$P = \gamma(1 - x)P^* \quad (7)$$

where P is the vapor pressure, γ is the water activity coefficient, x is the mole fraction of the solute in the salt solution and P^* is the vapor pressure of pure water which is a function of temperature and can be calculated by Antoine equation:

$$P^* = \exp\left(A - \frac{B}{T-C}\right) \quad (8)$$

where A , B and C are water-specific constants. The value of γ , which is a function of temperature and solute composition, can either be calculated from empirical equations (NRTL and VanLarr) or estimated from available experimental data. Therefore, vapor pressure not only depends on temperature but also on the salt concentration. At constant temperature, water activity of salt solution decreases with the increase of salt concentration [5, 69-71]; it is known according to Eq. (3) that vapor pressure will decrease. As a result, the pressure difference across the membrane decreases, which leads to less water vapor permeating through the membrane pores.

The temperature polarization effect causes the temperatures at the membrane surfaces to differ from the bulk temperatures in the feed and in permeate sides. It can be measured by the temperature polarization coefficient (TPC), τ :

$$\tau = \frac{T_{hm} - T_{cd}}{T_h - T_c} \quad (9)$$

where T_{hm} and T_{cd} are the temperatures at the feed and coolant sides of the membrane, respectively, and T_h and T_c are the temperatures in the feed and permeate bulk solutions, respectively. T_{hm} and T_{cd} could be calculated according to the method reported in the literature [61, 71] τ ranges from 0 to 1. The larger the value of τ is, the smaller the effect of the temperature polarization is. As $\tau \rightarrow 1$, the effect of temperature polarization becomes insignificant. The calculated TPC values are presented in Figure 6. TPC values ranged from 0.63 to 0.74, so the effect of temperature polarization should be considered. It is also noticeable that TPC values are higher at higher feed concentrations for all membranes.

Fig. 6 Temperature polarization coefficient versus salt concentration

Typically at higher feed concentrations, concentration polarization formed due to the water vapor permeation through the membrane is higher. The solute concentration c_m at the membrane interface becomes higher than that in the bulk solution, c_b [72]:

$$c_m = c_b \exp\left(\frac{J}{\rho K}\right) \quad (10)$$

where K is the solute mass transfer coefficient, which is evaluated using analogy of the Graetz-Lvque equation [63]:

$$Sh = 1.86(Re Sc \frac{d_h}{L})^{0.33} \text{ for laminar flow} \quad (11)$$

where Re , Sh and Sc are the Reynolds ($Re = \frac{d_h \mu \rho}{D}$), Sherwood ($Sh = \frac{K d_h}{D}$) and the Schmidt ($Sc = \frac{\mu}{D \rho}$) numbers, where D is the diffusion coefficient of the solute. According to these equations, concentration polarization coefficient ζ ($\zeta = \frac{c_m}{c_b}$) for salt solution with high salinity can be calculated. Results are presented in Figure 7.

Fig. 7 Concentration polarization coefficient versus feed salt concentration

However, for all membranes used in this study, $\zeta \rightarrow 1$, which means that the interface concentration becomes close to the bulk concentration ($C_m \approx C_b$) and the effect of the concentration polarization becomes negligible compared to temperature polarization. It is known that concentration polarization is a major cause of flux reduction in pressure driven membrane processes. It can be concluded here that the decrease of the permeate flux caused by higher feed concentrations (over the range investigated in this study) contributes to temperature polarization and the change of water vapor pressure with concentration rather than concentration polarization effect. This phenomenon could be more significant if scaling occurs, which was not observed in this study. This confirms that MD is a potential process to be used to treat highly saline solutions

such as desalination brines (RO or thermal brines [51, 55] or some hypersaline industrial brines [55, 69, 70]. However, a longer term operation is required to investigate the stability of the flux and membrane fouling/scaling.

3.3 Effect of membrane thickness on permeate flux

Effect of membrane thickness on permeate flux was investigated using PTFE membranes with the same pore size and similar porosity for feed and coolant inlet temperatures of 80°C and 20°C, respectively. Coolant and feed flow velocities were maintained at 0.07 m/s and 0.12 m/s, respectively, and the concentration of feed solution was kept constant at 90 g/L. As shown in Figure 8, the thicker membrane didn't show the lowest flux. At the same time, the thinner membrane didn't show the highest flux. It didn't follow the general trend of that the permeate flux is inversely proportional to the membrane thickness. In AGMD, the mass transfer can be described as [73]:

$$J_v = 4.1 \times 10^{-3} \frac{1}{\left(\frac{\delta}{\varepsilon\sqrt{T_h}} + \frac{b}{\sqrt{T_c}}\right)} \ln\left(\frac{1-x_c}{1-x_h}\right) \quad (12)$$

where x_c is the mole fraction of water vapor at the condensate and x_h is the mole fraction of water at the evaporation surface. The term, $\frac{\delta}{\varepsilon\sqrt{T_h}}$, is relative to the membrane and $\frac{b}{\sqrt{T_c}}$ is relative to the air gap.

This means that a change in the smallest term of Eq. (12) doesn't affect the mass flux when the other term is much larger. In AGMD, the unit of the air gap width is in mm and the unit of the membrane thickness is in μm ; which means that the term $\frac{\delta}{\varepsilon\sqrt{T_h}}$ is much smaller than $\frac{b}{\sqrt{T_c}}$ when b is larger than 5 mm. Therefore, the term $\frac{\delta}{\varepsilon\sqrt{T_h}}$ could be negligible in the calculation. Jonsson et al., [73] have theoretically tested it. According to their theoretical results, the permeate flux slightly decreased from 12 kg/m²·h to 11 kg/m²·h when the thickness of the membrane increased from 100 μm to 200 μm for an air gap width of 1 mm, while the permeate flux was almost the same with the increase of the membrane thickness for an air gap width of 5 mm. Cipollina et al. [64] also tested it for an air gap width of 3 mm and concluded that the main resistance was in the gap. This means that the thickness of the membrane will not affect the rate of evaporation as long as the air gap term is larger. Our results gave experimental evidence.

Fig. 8 Effect of the membrane thickness on permeate flux

3.4 Effect of membrane pore size on permeate flux and salt rejection

Effect of membrane pore size on permeate flux was investigated for feed and coolant inlet temperatures of 80°C and 20°C, respectively. Coolant and feed flow velocities were maintained at 0.07 m/s and 0.12 m/s, respectively, and the concentration of feed solution at 90g/L. Eight membranes with different pore sizes and materials, namely laminated onto a PP non-woven layer PTFE (11, 12 and 13) membranes with pore sizes of 0.2 μm, 0.45 μm and 1 μm, PP membranes (1, 2 and 3) with pore sizes of 0.1 μm, 0.2 μm and 0.45 μm, and PVDF membranes with pore sizes of 0.2 μm and 0.45 μm, have been tested. The results are presented in Figure 9 (a and b). Liquid entry pressure (LEP) for different membranes are given in Figure 10.

As shown in Figures 9 (a and b), water flux increased with the increase of pore size for all membranes. This is mainly due to the enhanced mass transfer within the pores with increasing pore size, which is controlled by the Knudsen diffusion mechanism that results in increased vapor permeability and therefore a higher flux is obtained. PP 1, PP 2, PP 3, PTFE 11 and PTFE 12 showed excellent salt rejection (higher than 99%), but PTFE 13 membrane with pore size of 1 μm showed poor salt rejection, only 68%. Membrane with the smallest pore size (0.1 μm) has the highest salt rejection, but its flux is the lowest (3.53 kg/m²·h). Membrane pore size below 0.45 μm does not have a significant effect on salt rejection. However, a significant decrease of salt rejection is observed when pore size increases from 0.45 μm to 1 μm while conductivity of the permeate increased from 43.3

$\mu\text{S}/\text{cm}$ to $35.7 \text{ mS}/\text{cm}$. This means that the membrane was wetted and feed solution went through the membrane pores under the experimental conditions. This explanation is supported by the LEP value shown in Figure 8. Water vapor pressure of 90 g/L salt water at 80°C is 0.44 bar , which is higher than LEP (0.31 bar) for PTFE 13 [74]. For a given pore size, if the ratio of LEP to water vapor pressure is lower than 1, the liquid will go through the membrane pores, hence higher permeate conductivity.

Fig. 9a Effect of membrane pore size on permeate flux

Fig. 9b Effect of membrane pore size on salt rejection

Fig. 10 LEP of different membranes

Based on the experimental results obtained and LEP values shown in Figure 10, it can be concluded that suitable membranes for the AGMD process for the application under study are those having pore sizes ranging between 0.2 μm and 0.45 μm .

3.5 Effect of membrane material on permeate flux

Effect of membrane material on permeate flux was investigated for feed and coolant temperatures of 80°C and 20°C, respectively. Coolant flow velocity was maintained at 0.07 m/s. Currently, available polymeric materials for manufacturing hydrophobic membranes suitable for MD are typically PP, PVDF and PTFE. In this part, membranes with pore sizes of 0.2 μm were tested in the AGMD process. Here the effect of porosity was negligible. As we know from Eq. (12), the effect of porosity was slightly compared to the air gap width like in the case of the membrane thickness. It was found that the permeate flux varies with different membrane materials (Fig. 11). The PP membranes gave the highest permeate flux of 4.86 $\text{kg}/\text{m}^2\cdot\text{h}$ among these membranes, while the PTFE membrane had the lowest performance. This attributes to the lower thermal conductivity of PP and higher thermal conductivity of PTFE. Membrane material with a high thermal conductivity offers a lower thermal resistance, which causes an increase in the conduction heat transferred through the membrane, and results in the reduction of the heat for vapor production [75, 76]. As a consequence, the membrane with low thermal conductivity has higher permeate flux. Salt rejection of all membranes was above 99.9%.

Fig. 11 Effect of membrane material on permeate flux, membrane pore size = 0.2 μm

3.6 Effect of membrane support on permeate flux

Effect of membrane support on permeate flux was investigated for feed and coolant temperatures of 80°C and 20°C, respectively. Coolant and feed flow velocities were maintained at 0.07 m/s and 0.12 m/s, respectively. PTFE 11, PTFE 2 and PTFE 3 membranes were used. SEM images of PTFE 11 and PTFE 2 membranes are shown in Figure 12. PTFE 11, PTFE 2, and PTFE 3 membranes have a non-woven fabric support, a scrim support and a non-support, respectively. Thicknesses of these membranes, presented in Table 1, are 166 μm , 87 μm and 30 μm , respectively.

It can be seen from Figure 13 that fluxes of these membranes are 4.16 $\text{kg/m}^2\cdot\text{h}$, 4.09 $\text{kg/m}^2\cdot\text{h}$ and 4.26 $\text{kg/m}^2\cdot\text{h}$, respectively. Although PTFE 3 without a support layer gave the highest water flux compared to membranes with support, the difference of flux is not significant. The presence of support only leads to a flux reduction of 2.35 %, which is not significant compared to DCMD having a reduction of the flux by up to 56% [66]. It means that the presence of membrane support in AGMD has only a slight influence on permeate flux.

Fig. 12 SEM images of support layer of (a) PTFE 11 and (b) PTFE 2

The existence of the membrane support does not affect the process mass transfer coefficient very much. Because the air gap width is much larger than the membrane thickness; the effect of membrane thickness in AGMD can be neglected due to the stagnant air gap representing the predominant resistance to mass transfer [3, 77, 78].

The SEM images (Figure 12) indicate that structure of the non-woven fabric support layer is different from that of the scrim support layer. Although non-woven fabric support layer can provide more open area for vapor transport than that of the scrim support layer, the difference of water flux between them is small. In AGMD, the effect of the structure of the membrane support layer is negligible compared to the resistance created by the air gap between the membrane and the condensation surface.

Fig. 13 Effect of membrane support on permeate flux

4. Conclusions

In this study, the AGMD performance of ten different commercially available membranes with various properties (pore size, thickness, porosity) and different support layers were investigated in desalination under different feed inlet temperatures, feed flow velocities and salt feed concentrations, reaching 120 g/L.

Higher feed temperature is beneficial in improving the thermal efficiency of the AGMD process. In laminar regime, the increase of feed flow rate enhances slightly permeate flux. However, at low feed temperatures, the change in permeate flux was lower with the increase of feed flow rate. On the other hand, the permeate flux decreased with the increase of salt concentration, especially at high concentrations (above 80 g/L), due to the decrease of the vapor pressure and the higher effect of temperature polarization. The effect of the concentration polarization on permeate flux decline could be neglected compared to the temperature polarization effect regardless of the feed concentration (over the range of the investigated values). Permeate flux also depends on membrane material, the PP membrane showed a better performance than the PVDF and PTFE membranes. AGMD performance (water flux) of 0.2 μm membranes tested in this work decreases as the feed concentration increases, especially with concentrations above 80 g/L. The existence of a membrane support has slightly effect on permeate flux. The existence of a support leads to a slight reduction of about 2.35 % only. The thickness of the membrane doesn't affect much the AGMD permeate flux because the air gap

width is much larger than the thickness of the membrane. Membranes with pore size of 0.2 and 0.45 μm are suitable for AGMD process, as these showed higher salt rejections. Smaller pore size led to lower flux and larger pore size led to pore wetting due to lower LEP values.

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Highlights

- Ten different membranes were tested in desalination of highly saline water by AGMD
- Effect of operating parameters and membrane characteristics on flux are studied
- The effect of concentration polarization (CP) and temperature polarization (TP) is discussed
- CP has a lower effect than TP on flux regardless of the feed concentration

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