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Effects of operating parameters on permeation flux for desalination of sodium chloride solution using air gap membrane distillation

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ABSTRACT

Desalination of sodium chloride solution has been experimentally investigated by air gap membrane distillation. The effects of process parameters, feed temperature, feed flow rate, feed salts concentration and air gap thickness on the permeation flux have been studied. The flux is increases with increasing feed temperature and flow rate. The flux decreases with increasing salt concentration, air gap thickness. Using commercially available PTFE membranes of 0.01382 m^2 area, the maximum permeate flux was 9.4 L/m^2h at 80 °C with flow rate of 250 ml/min. The salt rejection was observed nearly 99.9% in the all experimental conditions. The AGMD is an ideal process for application of desalination and also alternative process compare to conventional distillation and reverse osmosis.

Keywords: Desalination; Air gap membrane distillation; Permeation flux; Sodium chloride

1. Introduction

Worldwide fresh water is becoming increasingly scarce and it is commonly expected that the demand for drink water will be raised drastically in the near future. Also, rapid industrial growth and the worldwide population increase have resulted in an escalation of the demand for fresh water. The demand for fresh water is also increasing for the household needs, for crops production of the foods. Providing of the fresh water is an important issue for most nations. Water is one of most abundant resources on earth, which covering three quarters of the plant surface. However, about 97% of the earth's water is in the oceans and edible 3% is the glaciers, underground water, lakes and rivers, which are supplied for the most of human and animal needs. An alternative solution for the fresh water is the use of seawater that contains high salinity. In this regard, it would be attractive to explore the desalination of seawater to overcome the water-shortage [1].

Desalination can be achieved by using a number of techniques. The processes require significant quantities of energy to achieve separation of salts from seawater. Current commercially available desalination technologies can be classified as i) phase change or thermal process and ii) membrane or single-phase processes [2]. In the thermal process, distillation of seawater is achieved by using a thermal energy source. The thermal

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processes are multiple-stage flash evaporation (MSF), multiple-effect distillation (MED) and vapor compression (VC). The membrane processes are reverse osmosis (RO) and electrodialysis (ED). The former, which uses cheaper thermal energy as their separation power can produce high purity water in the bulky and expensive facilities, while the latter usually requires more expensive electric power and membrane to segregate water from brine conducted under a compact and less expensive facility.

Membrane distillation (MD) is an emerging alternative technology for separation of liquids. By using MD, pure water can be extracted from the aqueous solutions through a hydrophobic microporous membrane when a vapour pressure difference is established across the membrane. A hydrophobic membrane can inhibit the permeance of water by membrane surface tension, but allow the passage of vapor. Therefore, the water vapor will be able to pass from higher vapor pressure to the lower vapor pressure sides. Since 1980s, along with the rapid development of advanced membrane preparation techniques and low energy consumption for the separation, the membrane distillation process has gained renewed attention worldwide

The main application of MD process is the production of ultrapure water [3], from desalination of brackish sea water and highly salinity water [4–6] and successfully applied to the concentration of several non-volatile solutes in aqueous solutions like salt, sugar, fruit juices, blood, and waste water treatment, etc. [7,8]. In recent years, MD process is also proposed as a separation technique for ethanol from aqueous solution [9,10], breaking of azeotropic mixtures [11], concentrating of the various acids [12–14], and separation of isotopic water [15].

Depending on the collections of the permeate, mass transfer mechanisms through the membrane and the generations of driving force, MD systems may be classified into five different categories; direct-contact MD (DCMD), air gap MD (AGMD), sweeping gas MD (SGMD), vacuum MD (VMD) and osmotic MD (OMD). The present work is focused on the AGMD applications. The schematic diagram of AGMD membrane module is shown in Fig. 1. In the AGMD process, separation of the solutions is determined by the liquid–vapor interfacial conditions at the feed side and by the differences in their diffusion/convection rates across the membrane and the air-gap [16–18]. The main advantages of AGMD are to reduce heat loss caused by conduction trough the membrane and to avoid the membrane wetting on the permeate side, while the main difference from the other MD processes, such as DCMD, arises from the way of condensing the

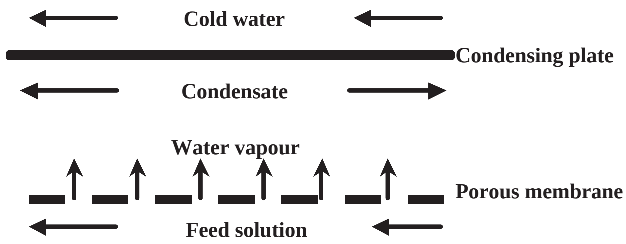

Fig. 1. Schematic diagram of AGMD membrane module.

permeate vapors on a cold surface rather than mixed directly in a cold fluid.

Many researchers were investigated the AGMD for application of desalination of seawater and different application [13,19–21]. Walton et al., using low grade thermal energy supplied by a salt gradient solar pond tested the desalination of brine using AGMD system [22]. In the studies permeation flux was reached a maximum of 6 L/m^2h. Biner and Plantikow investigated solar powered membrane distillation using AGMD module [23]. They observed in pilot plant the mass transfer resistance created by the air gap resulted in a large reduction in the trans-membrane water flux. Meindersma et al., [24] investigated energy requirement and cost estimation of the desalination process using AGMD in the counter current flow mode. Feng et al., [25] studied for the production of drink water from saline water by AGMD using polvinylidene fluoride nanofiber membrane.

Chouikh et al., studied the AGMD and Modified AGMD for desalination of seawater using hydrophobic membrane type [26]. However the permeated flux in the modified AGMD was observed around 9 $kgm^{-2}h^{-1}$. The theoretical and experimental studies are carried out on AGMD of different aqueous solutions by Liu et al [17]. They keep the membrane cell in the vertical direction, in that system directly contacting between membrane and feed solution. Desalination of sodium chloride solution was studied by many researchers, however they is no report available on the influence of various experimental conditions by AGMD using flat sheet PTFE (Polytetrafluorethylene) commercial membrane and also the membrane cell kept horizontal to prevent the contact between the membrane and feed water for reduce the membrane problem like wetting and fouling.

In this paper a systematic study on the influence of the relevant operating parameters on the permeation flux and conductivity, such as effect of hot feed temperature, temperature difference, feed flow rate, feed concentration and air gap thickness using the AGMD process with a hydrophobic PTFE (Teflon) porous membrane.

Table 1
Membrane characteristics

Membrane	FGLP
Material	Hydrophobic PTFE
Average pore size	0.22 μm
Porosity	70%
Thickness	175 μm
Tortuosity factor	2
Air flow rate	3 L/min cm^2
Maximum operating temperature	130 °C

2. Experimental methods

2.1. Materials

A flat sheet porous membrane made of PTFE manufactured by Millipore was used for the experiments. The characteristics of the membrane are given in Table 1. The NaCl solutions were prepared by using de-ionized water and pure NaCl (DAE JUNG chemical Co. Ltd). The solutions with the concentrations in the ranges between 0.5% and 10% were prepared.

2.2. Experimental

The experimental setup of AGMD system is schematically depicted in Fig. 2. The setup consists of three compartments, namely, feed (bottom cell), permeate (middle cell) and the cooling part (top cell). The compartments are made of High Density Polyethylene (HDPE) to resist corrosion by the NaCl solution. The feed NaCl solution is flowed through the bottom cell while the cooling water is passed through one side of the condensing plate in the top cell. The permeate is collected in the middle cell which placed in between the feed and coolant compartment. The AGMD system was horizontally installed. The feed and permeate were separated by a hydrophobic porous membrane. The effective area of the membrane was 0.01382 m^2. A stainless steel perforated plate was used as a membrane support to avoid membrane bending and wrinkling. The cooling plate was made of stainless steel. The permeate vapor was diffused through the membrane and condensed due to contact of cooling plate. The permeate water was collected through two 5 mm circular channel in the one side of the mid cell.

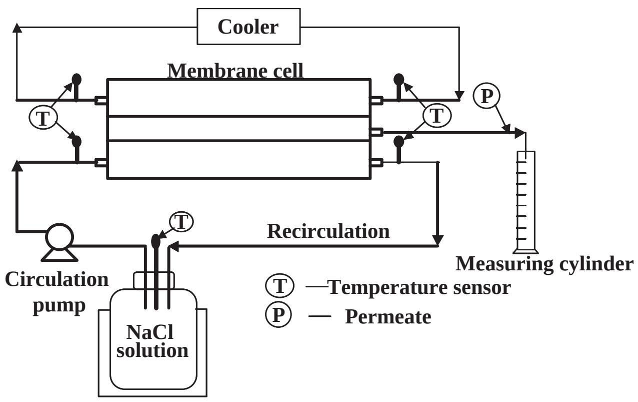

Fig. 2. Schematic diagram of AGMD system.

The feed was contained in a double walled reservoir and was circulated through the membrane module by using variable flow peristaltic pump. The cooling water was maintained at 15 °C and was recirculated. The outlet temperatures of the hot side and coolant side were continually monitored. The permeated liquid was collected in graduated cylinder and volumes were measured at regular time intervals. The purity of the water extracted was determined by the water conductivity using an electric conductivity meter. The effects of various operating parameters such as feed temperatures, feed flow rate, feed concentration and air gap thickness were studied under batch circulation and co-current mode. The air gap thickness was varied by means of varying gaskets from 1 to 5 mm with the gasket thickness of 1 mm.

3. Results and discussion

3.1. Effect of feed temperature and flow rate

Fig. 3 shows the effect of the feed flow rate at different feed temperatures on the permeation flux at

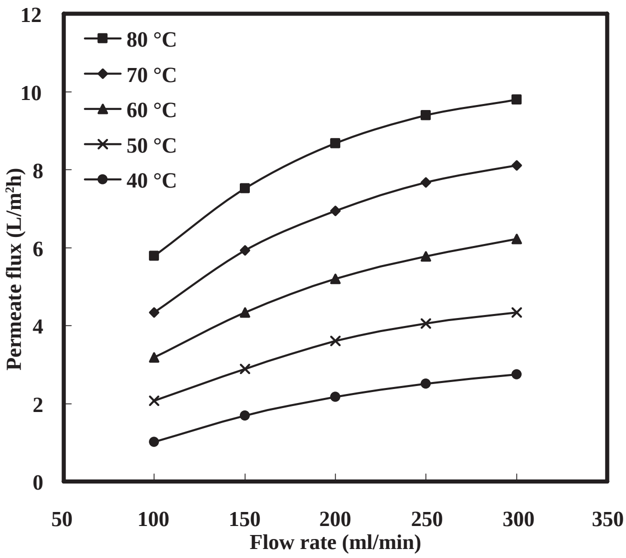

Fig. 3. Effect of feed flow rate on the permeation flux at various feed temperatures (Conditions: Coolant temp.: 15 °C; Coolant flow rate: 250 ml/min; Conc. of NaCl: 0.6 M).

constant coolant temperature of 15 °C and saline feed at 0.6 M NaCl (3.5 wt%). The permeation flux was increased when the feed flow was increased from 100 ml/min to 300 ml/min for each feed temperature. The permeation flux increased rapidly and seems to reach at maximum values asymptotically for higher feed flow rates. This is due to the reduction of the boundary layer thickness when the Reynolds number increases, approaching a limiting value [27]. The permeation flux increases roughly to about 40–50% when one compares the values obtained for a feed flow rate of 100 ml/min, and the values obtained for a feed flow rate are 300 ml/min. At the given feed flow rate, we observed that an increase of the feed temperature was accompanied with increase of the permeation flux. The conductivity of the permeate remains invariable around 6 ~ 8 μS/cm for different feed flow rates and temperatures. This indicates that the distillative effect was producing high quality fresh water. There is no relationship between percentage rejection and temperature as they remain constant at around 99.9%. The production rate for drinkable water of the unit was achieved around 225.5 L/m^2day at feed temperature 80 °C and feed flow rate of 250 ml/min. Fig. 3 also shows the effect of different temperature on permeation fluxes in performing AGMD processes at the various feed flow rates. The feed temperature has a greater influence on the permeation flux. The flux increases with temperature, will require more heat of vaporization. At higher flux, increases the gas-condensate interfacial temperature and temperature drop at the liquid–membrane interface will give the lower driving temperature difference which results in a lower vapour pressure gradient. Also, a temperature change at high temperature levels gives a larger change in partial vapour pressure than the same change at a low temperature.

3.2. *Effect of temperature difference*

The effect of temperature difference was studied at constant feed temperature (80 °C) and feed flow rate (250 ml/min). Fig. 4 shows the relationship between the permeation flux and the temperature difference. The saturated water vapor pressure increases exponentially with temperature. This means that a given temperature difference results in a larger flux with increasing hot water temperature. The temperature difference is calculated based on the flow inside the system. The flow is turbulent with Re value nearly 6,500, so the temperature difference is consider the linear average between hot side and cold side temperature. The solid line represents the best fit lines to Arrhenius type expression

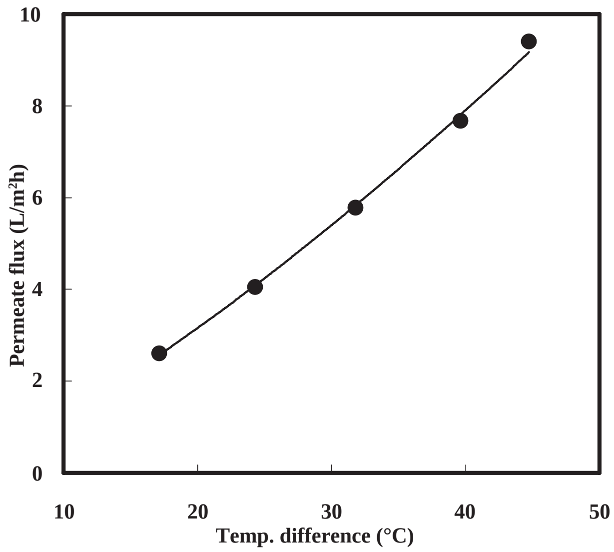

Fig. 4. Effect of temperature difference on the permeation flux (Conditions: Feed and Coolant flow rate: 250 ml/min; Coolant temp.: 15–45 °C; Conc. of NaCl: 0.6 M).

$$N \propto \exp(-B/T_m)$$

which is used in the literature where only one component is transfer through the membrane [28]. Bouguecha and Dhahbi were also observed similar result for desalination of brackish water using AGMD [29].

3.3. *Effect of NaCl concentration*

Fig. 5 shows the relationship between the permeation flux and the concentration of NaCl feed solution. The permeation flux slightly was decreased when the feed NaCl concentration was increased from 0.08 to 1.7 M (0.5 to 10 wt%), and the conductivity was 6 μS/cm. The flux reduction can be attributed to the fact that the higher the concentration of NaCl solution is, the higher the boiling point is resulted. The decrease of vapor pressure is believed to play an important role. This indicates that less vaporization of water occurs at the membrane surface causing decrease of the amount of vapor flows through the membrane [30]. There is also occurring vapour reduction due to the salt concentration effect because of the water activity and the boundary layer mass and heat transfer coefficients decrease. This decrease can be reduced if the membrane module has minimum polarization. Schneider et al. also found similar results of marginal feed concentration effect on the permeation flux and quality. In addition, the conductivity of the permeate shows no dependence with the NaCl concentration as observed. However, the salt rejection was increased with increasing the concentration of

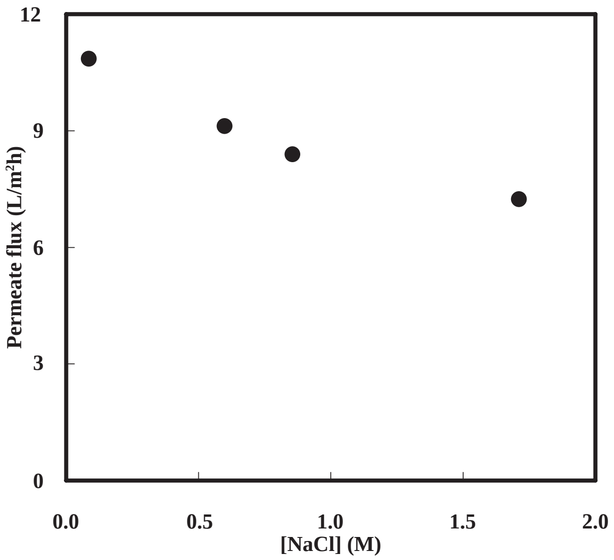

Fig. 5. Effect of NaCl concentrations on the permeation flux (Conditions: Feed temp.: 80 °C; Feed and Coolant flow rate: 250 ml/min; Coolant temp.: 15 °C).

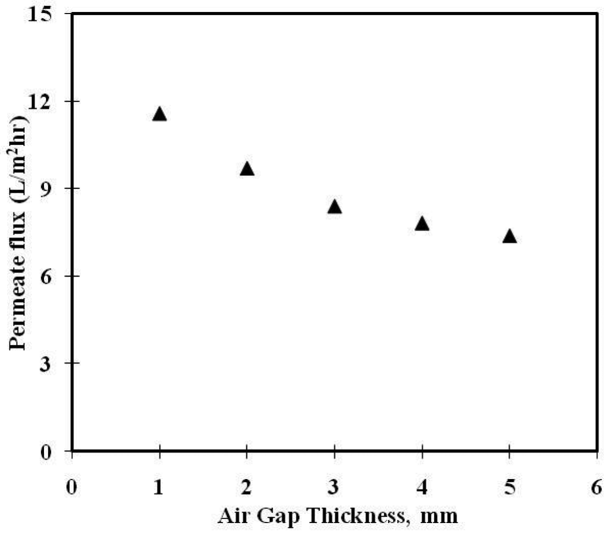

Fig. 6. Effect of air gap thickness on the permeation flux (Conditions: Feed temp.: 80 °C; Feed and Coolant flow rate: 250 ml/min; Coolant temp.: 15 °C; Conc. of NaCl: 0.6 M).

NaCl. The percentage reject was over 99.9% which is similar to the VMD process [31]. These results indicate that the desalting efficiency higher than reverse osmosis process (RO) can able to reach an efficiency of 95–98%.

The MD can be used the high concentration solution for removal of water, even to the supersaturated state of solution. However the RO can hardly be used to high concentration, because RO relates to the solution osmotic pressure. Due to increasing concentration, osmotic pressure increased. But MD is not related to osmotic pressure and can be applied as long as enough temperature difference in the process.

3.4. *Effect of air gap thickness*

The air-gap thickness is an important factor for determining the permeation flux in the AGMD system. The relation between permeation water vapour flux J through the membrane and the air gap is described by molecular diffusion through stagnant air.

$$J = \frac{1}{d_{\mathrm{ag}}} \cdot \frac{D}{Y_{\ln \mathrm{ag}}} \frac{M}{RT_{\mathrm{ag}}} (P_m - P_c)$$

Where

J – Permeation of water vapour flux; d_{ag} – air gap thickness; D – Diffusion coefficient; Y_{lnag} – air mole fraction; M – molar mass of water vapour; R – Universal gas constant; T – Temperature; P – Water vapour pressure at membrane surface and condensate layer. The effect of air thickness was studied at a constant feed temperature of 80 °C, inlet feed concentration of NaCl solution of 0.6 M, feed flow rate of 250 ml/min, and coolant temperature of 15 °C. Fig. 6 shows the permeation flux was decrease with an increasing of air gap thickness. The wider the air gap is, the higher the mass transfer resistance will be, and thus lower the permeation flux as a result. The similar trend of results was observed by Chouikh et al., for desalination of sea water using AGMD [26].

3.5. *Mass transfer*

The driving force for mass transfer across the membrane is the water vapour pressure difference between feed and permeated side. According to the Soret effect, not only pressure difference but also temperature difference induces the mass transfer across the membrane. However the thermal diffusion contribution is negligible in the MD.

Dusty gas model are widely used for mass transfer in the MD [32,33]. The state that the mass transfer is proportional to the vapour pressure difference across the membrane

$$J = C\,\Delta p_{\mathrm{w,surface}}$$

Where J is the water vapour flux in L/m^{2}s
$\triangle p_{\mathrm{w,\ surface}}$ is the water vapour pressure difference between feed and permeate side.
C is the mass transfer coefficient that can be obtained experimentally. (L/m^{2}s.Pa)

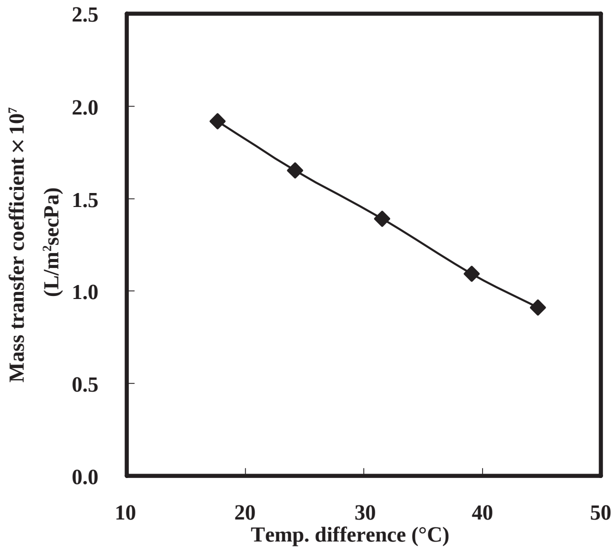

Fig. 7. Effect of temperature difference on the mass transfer coefficient (Conditions: Feed and Coolant flow rate: 250 ml/min; Coolant temp.: 15–45°C; Conc. of NaCl: 0.6 M).

Fig. 7 represents mass transfer coefficient vs. temperature difference between the feed temperature solution and condensate plate. The temperature difference across the membrane induces mass transfer, so the results were expressed in terms of mass transfer coefficient. The mass transfer coefficient was decreased linearly with increasing the temperature. Decreasing the temperature difference, that causes the decrease in the vapours and also the fraction of air. Thus increases the mass transfer coefficient. The temperature difference creates a vapor pressure difference, which leads to water vapor diffusion through the membrane. As the temperature difference increases, so does the vapor pressure difference and thus the membrane permeation flux.

Many researchers reported the mass transfer coefficient for air gap MD with range of 3×10^{-7} to 7×10^{-7} L/m^{2}s.Pa. However, in the investigation was observed values from 0.75×10^{-7} to 2×10^{-7} L/m^{2}s.Pa. The mass coefficient is not only depending on the temperature difference, but also depends on the membrane material, its roughness and its pore size distribution [27]. The specific flux of the memstill process also observed as 1.5×10^{-7} L/m^{2}s.Pa [24].

3.6. Comparison of literature results

The permeate flux of 225.5 L/m^{2}day was obtained using AGMD process having PTFE hydrophobic membrane with a average temperature difference between the feed and coolant side of 45 °C. Table 2 shows the some of the literature values of AGMD having hydrophobic ceramic membrane and RO process with polymeric PTFE membrane. In this investigation, maximum permeate flux of 225.5 L/m^{2}day was obtained. In the AGMD, the rejection was achieved nearly 100% and compare to higher than the RO membrane process.

4. Conclusion

Air gap membrane distillation was successfully applied for distillation of NaCl solution and seems to be the most efficient MD process among others. The separation of fresh water is mainly dependent on the feed temperature, flow of feed solution, concentration of NaCl in the feed solution, and air gap thickness. The permeation flux was increased with increasing the feed temperature and feed flow rate. For high feed flow rate, it seems to reach maximum values asymptotically representing the upper performance limit of the experimental setup. With increasing temperature difference between feed and the coolant, the flux of water was increased linearly. The permeation flux is linearly decreased with increasing the concentration of NaCl in the feed solution. The permeation fluxes measured in this study were in the range of 1–9.4 L/m^{2}h. The experiments carried out so far produced very promising results for desalination of seawater. Taking advantage of integrating several membrane processes such as MD+RO where RO uses softening and warm brine of MD may be another option for enhancing MD efficiency.

Table 2
Comparison of permeate flux for desalination of NaCl solution by RO and AGMD process

	AGMD				RO
Membrane	Grafted ceramic	PVDF	PTFE	PTFE	Polymeric
Temp. difference (°C)	70	45	45	25	Pressure: 6.9 bars
[NaCl], (M)	0.5	0.6	0.6	0.5-0.85	8.5×10^{-3}
Permeate flux, (L/day.m^2)	126	146.5	225.5	120	149.5
Reference	[27]	[23]	This study	[34]	[35]

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