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To cite this article: S Rosalam *et al* 2016 *IOP Conf. Ser.: Earth Environ. Sci.* **36** 012032

View the article online for updates and enhancements.

Water desalination by air-gap membrane distillation using meltblown polypropylene nanofiber membrane

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Abstract. This paper presents a study of air gap membrane distillation (AGMD) using meltblown polypropylene (PP) nanofiber membrane to produce fresh water via desalination process. PP nanofiber membranes with the effective area 0.17 m^2 are tested with NaCl solutions (0.5 – 4.0 wt.%) and seawater as the feed solutions (9400 – 64800 μS/cm) in a tubular membrane module. Results show that the flux decreases with increasing the membrane thickness from 547 to 784 μm. The flux increases with the feed flow rate and temperature difference across the membrane. The feed concentration affects the flux insignificantly. The AGMD system can reject the salts at least 96%. Water vapor permeation rate is relatively higher than solute permeation rate resulting in the conductivity value of permeate decreases when the corresponding flux increases. The AGMD system produces the fresh water (200 – 1520 μS/cm) that is suitable for drinking, fisheries or irrigation.

1. Introduction

The shortage in clean water supply worldwide has driven desalination to become a sustainable process of potable water production. Reverse osmosis and thermal evaporation are the current commercial desalination technologies. However, the high energy consumption in these technologies has retarded their sustainability. The use of membrane distillation (MD) is becoming increasingly recommended to produce fresh water as MD has fulfilled the requirement of process intensification i.e., less mechanical parts, non-pressurized system, low energy consumption and low cost [1-3].

In MD, water vapor transfer across the membrane occurs when a driving force is subjected between the feed and permeate sides. On the feed side, saline water is brought direct contact with a porous and hydrophobic membrane surface; water vapor is thermally driven through the membrane pore. Various designs on the permeate side to maintain the driving force categorize the MD into four types of configurations: direct contact MD (DCMD), air gap MD (AGMD), sweeping gas MD (SGMD) and vacuum MD (VMD).

Nanofiber membranes have been attractive in MD applications in the recent years [4, 5] due to the high porosity, interconnected open pore structure and tailorable membrane thickness. These nanofiber membranes are fabricated by using electrospinning technique whereby polymer pellets (<30 wt.%) are

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dissolved in a solvent to form a homogeneous polymer solution. At least 70 wt.% of the solvent is evaporated and released into the air during electrospinning the polymer solution within a high voltage electronic field. As a result, a massive scale of solvent recovery from the dilute air is required which is the major drawback of using electrospinning technique.

In this work, the nanofiber membranes are fabricated by using meltblowing technique where molten polymer instead of polymer solution is used. The polymer pellets are melted at high temperature to form the molten polymer. The molten polymer is then sprayed through a spinneret to form the nanofibers. The applicability of the meltblown nanofiber membranes in AGMD desalination to produce fresh water is investigated in this study.

2. Experimental methods

Meltblown PP nanofiber membranes were fabricated using a melt blowing system (Japan Zetta Co. Ltd.). The polypropylene (PP, Sun-Allomer) was melted at temperature 230°C and sprayed through a spinneret (diameter: 0.8 mm) to a collector at a distance of approximately 240 cm. The nanofibers were formed into tubular membranes with inner diameter 5.5 cm and length 99 cm in that resulted the membrane area as 0.17 m^2. The membrane thickness was varied from 550 to 790 μm.

The nanofibers were sputtering-coated with a thin layer of gold. The morphology of the nanofiber was observed by using scanning electron micrography (SEM) (Carl Zeiss Evo MA10, USA). The diameters of the nanofibers were determined by observing the SEM images.

The membrane thickness was measured with a digital micrometer (MDC-1''M, Mitutoyo, Kawasaki GmbH (Germany). Gravimetric method was employed to determine the membrane porosity. Isopropyl alcohol (IPA) (QRëc) was used as the wetting liquid. The porosity of the membrane was calculated by the equation as follows:

$$\varepsilon = \frac{(w_\text{w}-w_\text{d})/\rho_\text{IPA}}{(w_\text{w}-w_\text{d})/\rho_\text{IPA}+w_\text{d}/\rho_\text{pp}} \tag{1}$$

where w_w is the wet membrane weight, w_d is the dry membrane weight, ρ_IPA is the density of IPA (0.786 g/cm^3), and ρ_pp is the density of PP (0.946 g/cm^3).

A schematic diagram of the air gap membrane distillation (AGMD) is shown in Figure 1. Two types of feed solutions were tested: NaCl solutions (0.5 − 4.0 wt%) and seawater collected from the beach near Universiti Malaysia Sabah. The volume of the seawater feed used was 2 L. The feed solution was circulated through the middle of the membrane module by a calibrated gear pump implemented with a digital flow meter (Micro pump Gear Pump Drives 75211-35, Cole-Parmer Instrument Cp., Illinios, USA) and passed through a heating water bath (Protech HC-10, Tech-lab MFG, Malaysia). The cooling water was circulated through the copper tube and the temperature was maintained at 20°C. After operating time of 2 hours, permeate was collected using a volumetric flask and the readings of mass were recorded. Each experiment was repeated three times under the same operational conditions, and the average values were reported.

3. Results and discussion

3.1. Characteristics of the meltblown PP nanofiber membrane

3.1.1. Morphology and parameters of the nanofiber membrane

The SEM images of the meltblown nanofibers are shown in Figure 2. The diameter of the fibers ranges from 10^2 to 10^3 nm. These fibers piled up to form membranes with the thickness varies from 470 to 800 μm. The average porosity of the nanofiber membrane with dry weight of 5 g is approximately 90%.
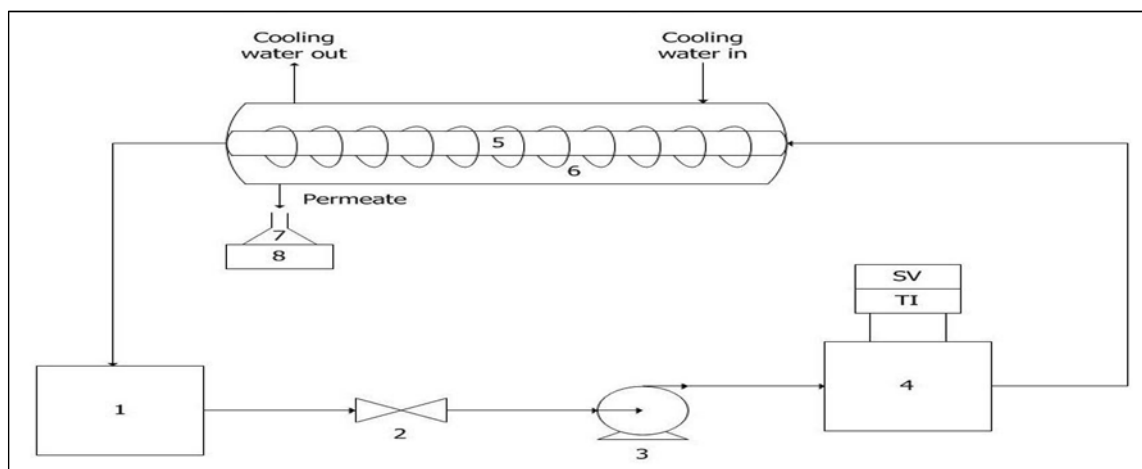
Figure 1. Schematics of AGMD experiment setup: 1, feed reservoir; 2, valve; 3, pump; 4, temperature control bath with heating coil; 5, nanofiber membrane module; 6, cooper tube with cooling water in and out; 7, volumetric flask; 8, electronic weighting balance.
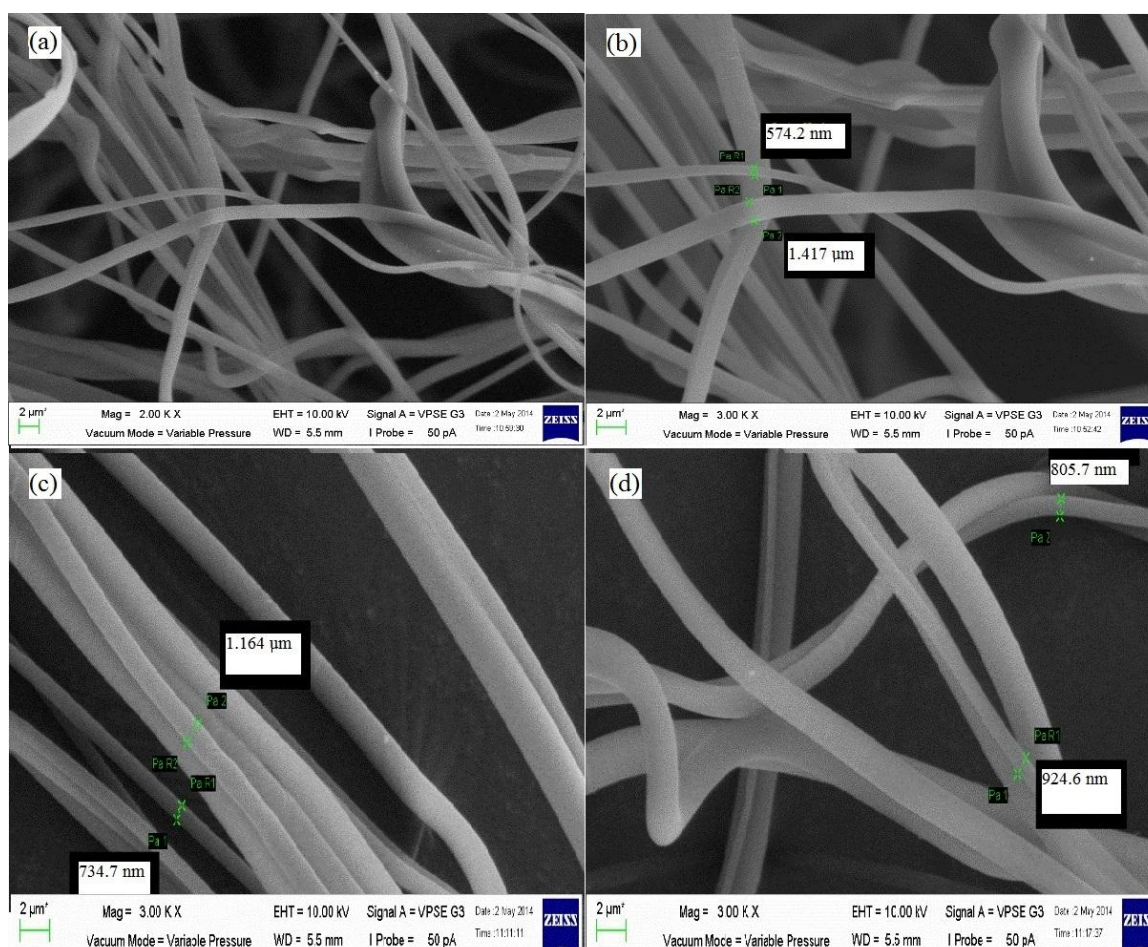

Figure 2. SEM images of the meltblown PP nanofibers at magnification of (a) 2 kX, (b), (c) and (d) 3 kX.

3.1.2. Effect of nanofiber membrane thickness on AGMD flux

Figure 3 shows the variation of flux at the corresponding nanofiber membrane thickness for 2 h AGMD operation when seawater was used as the feed solution. The flux decreases when the membrane thickness increases. The flux reduces significantly i.e., approximately 27% reduction when the membrane thickness increased from 547 to 784 μm. In this AGMD system, the membrane thickness contributes a considerable mass transfer resistance.
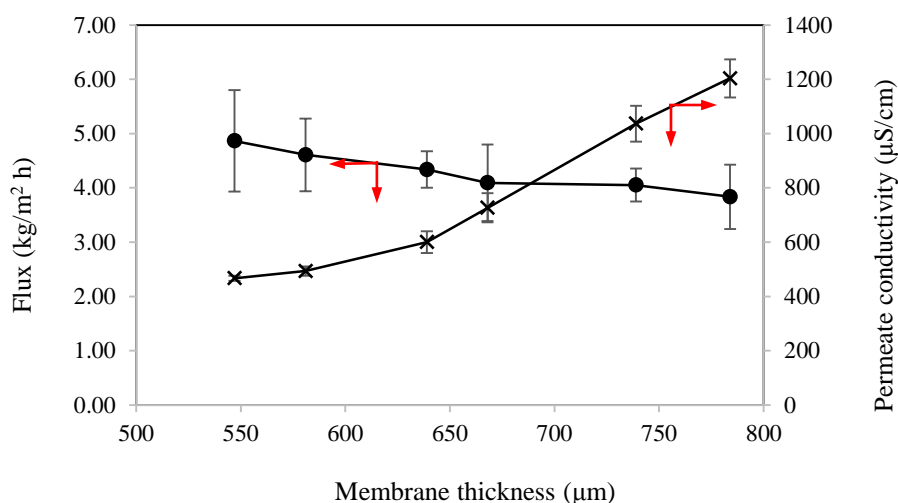

Figure 3. The effect of nanofiber membrane thickness on the flux and permeate conductivity. *(Feed solution: seawater, feed flow rate: 300 mL/min, cooling water temperature: 20ºC)*

3.2. Influence of process conditions on AGMD performance

The influence of process conditions on the AGMD flux was investigated. The membrane thickness for these studies was 520 – 525 μm. The experimental results represented the effect of feed flow rates on the fluxes are shown in Figure 4. The flux increases with the feed flow rate for 3.5 wt.% NaCl was tested as the feed solution and the temperature difference across the membrane was 60°C. The dependence of the flux on the feed flow rate indicates the existence of the boundary layer in the feed side. The boundary layer reduces at higher feed flow rate as resulting in a greater flux.

Figure 5 illustrates the experimental values of AGMD flux as a function of the feed concentration. The flux decreases with the feed concentration insignificantly when the feed flow rate was 300 mL/min and the temperature difference across the membrane was 60°C. This indicates that the concentration polarization effect could be negligible in the feed side.

The experimental results to present the effect of temperature differences across the membrane on the fluxes are shown in Figures 6 and 7 for 3.5 wt.% NaCl and seawater as the feed solutions respectively. The flux increases greatly with the increasing temperature differences. This is due to the exponential increase of the vapor pressure with the temperature which can be described by the Antoine equation.

The error bars corresponding to each point reported in Figures 4 – 7 are below 1% where these percentage values were represented by the standard deviations $s(J)$ calculated as follows:

$$s(J) = \sqrt{\frac{\sum_{i=1}^{n}(J_i - \bar{J})^2}{n-1}}, \ s(J)_{\text{percen.}}\,(\%) = \frac{s(J)}{\bar{J}} \times 100 \qquad (2)$$

where n is the number of experiments and $\bar{J}$ is the mean flux. The percentages of the deviations are small and the experimental fluxes are acceptable.
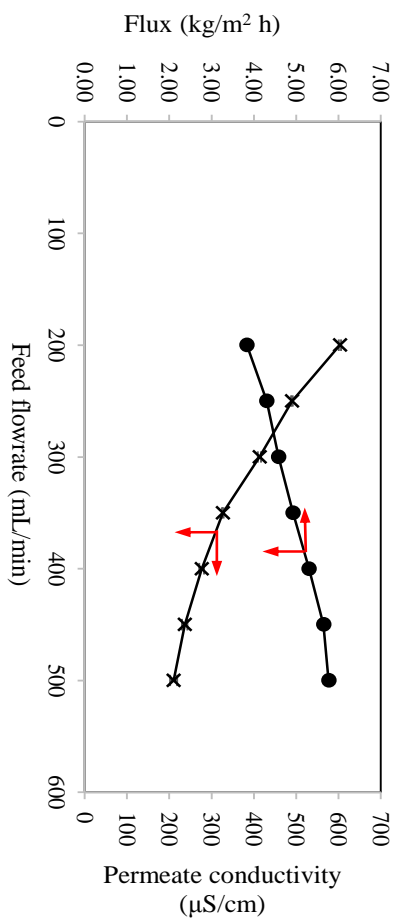
Figure 4. The effect of feed flow rate on the flux and permeate conductivity. *(Feed solution: 3.5 w/w % NaCl, feed temperature: 80°C, cooling water temperature: 20°C)*
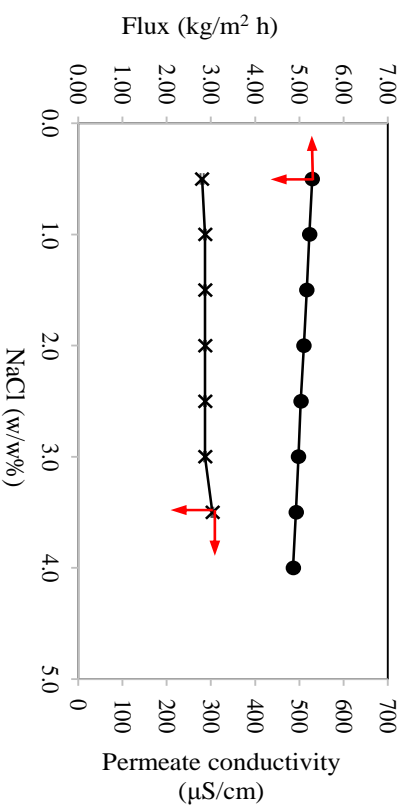

Figure 5. The effect of feed concentration on the flux and permeate conductivity. *(Feed flow rate: 300 mL/min, feed temperature: 80°C, cooling water temperature: 20°C)*
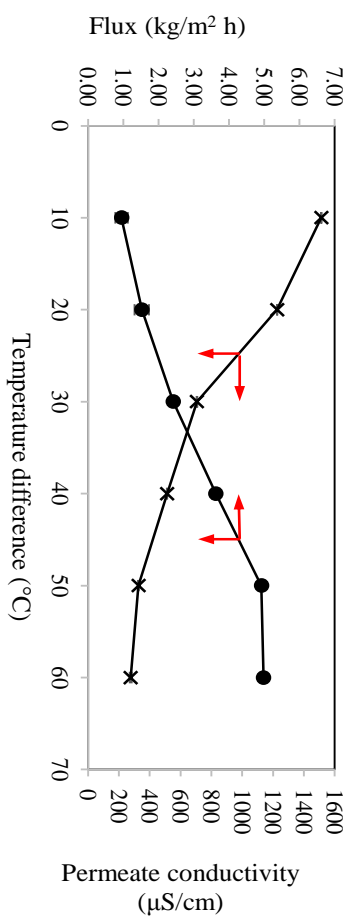

Figure 6. The effect of temperature difference across the nanofiber membrane on the flux and permeate conductivity. *(Feed solution: 3.5 w/w % NaCl, feed flow rate: 350 mL/min, cooling water temperature: 20°C)*
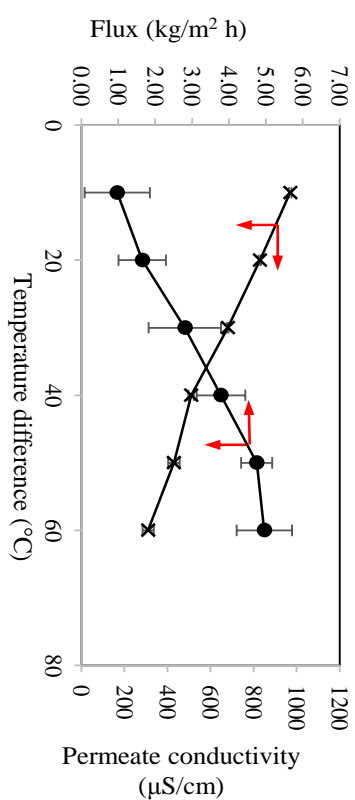

Figure 7. The effect of temperature difference across the nanofiber membrane on the flux and permeate conductivity. *(Feed solution: seawater, feed flow rate: 300 mL/min, cooling water temperature: 20°C)*

3.3. Permeate quality

The effect of the tested conditions on the conductivity values of permeates are reported in Figures 3 – 7. The conductivity values of permeates varied between 200 and 1520 µS/cm, whereas the conductivity values of the feed solutions (the NaCl solutions and the seawater) ranged from 9400 to 64800 µS/cm. As a result, the rejection of salts were above 96% i.e., at least 4% of solute (salts) permeation did take place during the AGMD operation. Interestingly, the conductivity value reduces when the corresponding flux increases as shown in Figures 3 – 7. It is suggested that the water vapor permeation rate is relatively higher than the solute permeation rate. The solute concentration could be diluted by the condensate (liquid water) in permeate. The water produced from the AGMD desalination in this work is fresh water (0 – 1990 µS/cm) which can be used as drinking water (< 500µS/cm), fisheries water (< 500µS/cm), or irrigation (< 2000 µS/cm).

4. Conclusions

This work presented an assessment study of AGMD using meltblown nanofiber membranes in a tubular module for fresh water production via desalination process. The results show that:

(1) The nanofibers made from PP have diameter ranged from 10^2 to 10^3 nm. The average porosity of the nanofibers for 5 g (dry weight) is approximately 90%.
(2) The membrane thickness from 547 to 784 µm contributes a significant mass transfer resistance.
(3) The AGMD flux increases with increasing the feed flow rate. The boundary layer effect on flux reduces when operated at higher flow rate.
(4) The effect of the feed concentration (0.5 – 4.0 wt.% NaCl) on the flux is insignificant.
(5) The AGMD flux increases with temperature across the membrane is attributed to the vapor pressure increase exponentially with temperature based on the Antoine equation.
(6) The rejections of salts are above 96%. The conductivity value of permeate decreases when the corresponding flux increases. The fresh water produced from the AGMD system can be used for drinking, fisheries, or irrigation purposes.

5. References

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