Investigating the potential of meltblown polypropylene nanofiber membrane for desalination by membrane distillation

C K Chiam*, R Sarbatly, S Widyaparamitha
Membrane Technology Research Group, Material and Mineral Research Unit, Faculty of Engineering, Universiti Malaysia Sabah, Jalan UMS 88400 Kota Kinabalu, Sabah, Malaysia

*E-mail: chiamchelken@ums.edu.my

Abstract. A tubular nanofiber membrane module is developed and tested in the seawater desalination by using air-gap membrane desalination (AGMD). Meltblowing device is used to produce the nanofibers which are collected at a distance of 37 cm away from the tip of the spinneret. Results show that the flux varies almost constantly with the feed flow rates. The independence of the flux on the feed flow rates suggested that the meltblown nanofiber membrane is a dense membrane in which the volume of pores has been reduced and compacted significantly. The flux increases exponentially with the feed temperatures which obeys the Arrhenius relation. The quality of permeate is essentially improved by using the compacted nanofiber membrane. The rejection of the dissolved salts is more than 99.3%, in which the conductivity values of permeate ranged between 8 and 50 μS/cm.

1. Introduction
Membrane distillation (MD) has been recognized as a novel desalination technology which is competitive with the commercial reverse osmosis process. MD is attractive recently because it has met the requirement of process intensification such as small footprint, simple flow sheet as less mechanical parts are used, non-pressurized process, feasible to be operated with renewable energies and waste heat, consuming less energy which leads to lower the cost [1-2].

Generally, MD is categorized into four types; they are direct contact MD, air-gap MD, sweeping-gas MD, and vacuum MD. In the desalination process by using MD technique, the seawater is usually heated to the temperatures around 50 – 90°C [3-5]. The heated seawater is contacted directly with the membrane surface on the upstream side. The membrane used in MD is porous and hydrophobic; thus only the water vapor is allowed to transport through the membrane pores. The temperature on the downstream side of the membrane surface is maintained lower than the upstream side; hence the water vapor pressure difference across the membrane drives the water vapor transport through the membrane. The water vapor is then condensed and collected as pure water. Although few MD pilot plants have been developed under projects MEDINA, MEDESOL and MEDIRAS funded by European Commission; membranes especially for MD application are still unavailable commercially.

Nanofiber membrane is newly received attention for MD application in recent years [6-7]. Nanofiber membrane is attractive for MD because of its high porosity due to the interconnected open pore structure, high permeability thus resulting in high flux, and ease for tailoring the membrane thickness. By meltblowing technique, polypropylene (PP) pellets are melted at high temperature to
produce the molten and the molten is sprayed through a spinneret to form nanofibers. Nanofiber membrane is formed when a sheet comprises of the nanofibers overlap with each other randomly.

Meltblown nanofiber membrane has been successfully tested for AGMD by our research team lately [8]. One of the significant findings from our previous study is that the ‘loose’ structure of the nanofiber membrane did not permit the AGMD to operate at high feed flow rates because severe membrane leaking took place easily. However, operating at low feed flow rate and low feed temperature resulted in low fluxes but allow the relatively high permeation of dissolved salts through the nanofiber membrane which eventually reducing the salt rejection. Similarly, increasing the nanofiber membrane thickness (0.55 - 0.75 mm) has definitely reduced the flux but the corresponding permeate conductivity value increased. The conductivity values by using the ‘loose’ structure of nanofiber membrane ranged between 200 and 1520 μS/cm [8].

One of the methods to reduce the ‘loose’ effect in the meltblown nanofibers is to collect the nanofibers immediately once they are sprayed out from the tip of the spinneret. The meltblown nanofibers at the nearer to the tip of the spinneret are hotter and softer. Thus, the membrane formed by these nanofibers can have more ‘compacted’ structure which is possible can reduce the membrane wetting and improve the salt rejection. The current study aims to fabricate the meltblown tubular PP nanofiber membrane at a shorter distance between the spinneret tip and the collector, than the previous study [8].

2. Experimental methods

2.1. Materials
The polypropylene (PP) pellets used to fabricate nanofiber membrane were supplied by Sun-Allomer, Japan. The pellets were used without any further treatment. A polypropylene mesh was used as support of the nanofiber membrane. The isopropyl alcohol (IPA) supplied by QRêc was used for characterizing the nanofiber membrane porosity.

2.2. Fabrication of nanofiber membrane by meltblowing
The meltblowing device (Japan Zetta Co. Ltd.) as illustrated in Figure 1 was used in this study. The PP pellets were poured into the feeder; the pellets were extruded and melted at three different stages of temperatures: 250, 280 and 300ºC. The molten was sprayed through a spinneret with diameter of 0.8 mm. A rotating pipe was located at 37 cm away from the tip of the spinneret. A tubular nanofiber membrane was formed with the inner diameter and length were 2.1 cm and 96 cm, respectively. The tubular nanofiber membrane was wrapped with the PP mesh support, as shown in Figure 2.

![Figure 1. Schematic diagram of the meltblowing device.](image-url)
Figure 2. (a) Cross view of the meltblown PP tubular nanofiber membrane. (b) Side view of the meltblown PP tubular nanofiber membrane.

2.3. Characterization of membranes

The morphology and the size of the nanofibers were investigated by a scanning electron microscope (SEM, Hitachi).

The thickness of the nanofiber membrane was determined by using a digital micrometer (MDC-100M, Mitutoyo, Kawasaki, Japan), with a precision of ±0.001 mm, and the mean value of 20 locations together with its standard deviation were computed.

The membrane porosity is defined as the volume of the pores divided by the total volume of the membrane. The membrane porosity was computed by the gravimetric technique in this work. A small sample of nanofiber membrane in dry condition was cut and its weight was recorded as \( W_d \). The same nanofiber membrane sample was then immersed in the IPA for 1 min to allow all of the voids were fully filled up. The weight of the IPA-wetted nanofiber membrane was recorded as \( W_w \). Next, the membrane porosity was determined by using the equation as follows:

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\varepsilon = 100 \times \frac{(W_w-W_d)/\rho_{IPA}}{(W_w-W_d)/\rho_{IPA}+W_d/\rho_{PP}}
\]

where \( \rho_{IPA} \) and \( \rho_{PP} \) were the densities of the IPA and PP, which were 0.786 g/cm3 and 0.946 g/cm3, respectively.

2.4. AGMD experiment

The meltblown nanofiber membrane with effective area 0.063 m2 was tested in the AGMD system as shown in Figure 3.
Seawater was sampled from a beach near the Universiti Malaysia Sabah. Two liters of the seawater were poured into the feed reservoir. The seawater was circulated through the lumen of the tubular membrane by a gear pump completed with a digital flow meter (Micro pump Gear Pump Drives 75211-35, Cole-Parmer Instrument Cp., Illinios, USA) and passing through a water heating bath (Model 9012A12E, Polyscience, Niles, IL USA). Cooling water was circulated through a copper coil and the coil wound along the tubular membrane module without touching the membrane surface. A chiller circulation system (Thermo Haake, DC 30) was used to maintain the cooling water temperature at 15°C. The tested feed flow rates were 350, 400, 450, 500 and 550 mL/min; while the feed temperatures were 40, 50, 60, 70 and 80 ºC. The experimental flux was computed by using the equation as follows:

$$J = \frac{m_p}{A \cdot t}$$  \hspace{1cm} (2)

where $m_p$ was the weight of permeate, $A$ was the membrane area and $t$ was the time for collecting the permeate.

3. Results and discussion

3.1. Effect of the distance collector on the fiber size

Based on the SEM image shown in Figure 4, the size of the most of the meltblown fibers ranged from 0.3 to 4 μm which falls in the same range of the order of magnitude when the distance collector away from the tip of the spinneret is 240 cm [8]. It is suggested that the distance between the tip of the spinneret and the collector has no essential effect on the size of nanofibers.
3.2. Effect of operating conditions on AGMD flux
The effect of the feed flow rate on the AGMD flux at feed temperature 70°C for 2 h operation is shown in Figure 5. The fluxes are nearly not influenced by the feed flow rates ranging from 350 to 550 mL/min. In a comparison with our previous study [8], the independence of the flux on the feed flow rate designates that the structure of the nanofiber membrane used in this study has become denser in which the similar observations have been reported in various MD systems [2].

The effect of the feed temperature on the AGMD flux at feed flow rate 350 mL/min for 2 h operation is presented in Figure 6. The results show that the flux increases with increasing the temperature of the feed seawater. The flux increases exponentially with the feed temperature which is fitted to the Arrhenius type dependence, with the correlation coefficient approximately 0.97. This pattern of relationship between the flux and feed temperature is commonly found in other MD systems [9-11].

3.3. Permeate quality
In this study, the denser meltblown nanofiber membrane formation shows that the volume of pores of the nanofiber membrane has been significantly reduced and compacted when the distance collector is reduced to 37 cm. The average porosity of the nanofiber membrane is approximately 86%, which is smaller than those collected at about 240 cm away from the spinneret tip [8].

The membrane resistance is the essential parameter to affect the flux because the membrane thickness contributes a considerable resistance to the water vapor transport across the dense membrane. The thickness of the meltblown nanofiber membrane used in this work is 3.2 ± 0.6 mm. Attractively, this nanofiber membrane has successfully improved the quality of permeate. The
conductivity values of condensed permeates varied between 8 and 50 μS/cm while the conductivity value of seawater is 7338 μS/cm which resulting in the rejections of dissolved salts are at least 99.3%.

Figure 5. The effect of the feed flow rate on the AGMD flux. (Feed temperature: 70°C; water cooling temperature: 15°C; Operation duration: 2 hours)

Figure 6. The effect of the feed temperature on the AGMD flux. The solid line is the Arrhenius fit of the data. (Feed flow rate: 350 mL/min; water cooling temperature: 15°C; Operation duration: 2 hours)
4. Conclusions
This work evaluated the improvement of permeate quality in an AGMD seawater desalination by using the meltblown tubular polypropylene (PP) nanofiber membrane which the nanofibers are formed and collected at a distance of 37 cm away from the tip of spinneret. The results show that:

(1) The diameter of the nanofibers ranged from 0.3 to 4 μm.
(2) The volume of pores is reduced to approximately 86% as compared with the nanofiber membrane formed at 240 cm away from the tip of the spinneret (which is approximately 90%).
(3) The effect of the feed flow rate (350 - 550 mL/min) on the AGMD flux is negligible. It is suggested that the membrane is dense which is due to the volume of membrane pores reduced and compacted.
(4) The AGMD flux increases exponentially with increasing the feed temperature which fits the Arrhenius type dependence.
(5) The membrane thickness is 3.2 ± 0.6 mm.
(6) The rejection of the dissolved salts is above 99.3% in which the conductivity values of condensed permeate ranged between 8 and 50 μS/cm.

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