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Desalination by Membrane Distillation Using Electrospun Membranes

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ABSTRACT

Electrospinning is a novel technique that can be used to produce highly porous fibers with highly tunable properties. In this research, this technique is adopted to prepare the electrospun nanofiber membrane for membrane distillation application. A custom-built electrospinning setup was made to prepare the nanofibers membrane. Polyvinylidene fluoride (PVDF) polymer was used in the electrospinning process due to its high hydrophobicity. Electrospun (PVDF) nanofibers were tested in direct contact membrane distillation (DCMD) process using 0.6 M sodium chloride as a feed solution. The resulting nanofiber membrane exhibited high performance in DCMD (i.e. relatively high water flux and high salt rejection). It has been found that the prepared membrane has a uniform and fibrous structure as indicated by the scanning electron microscopy (SEM). Relatively thin fibers with a diameter of 250 nm were produced during the Electrospinning process.
Keywords: Electrospinning, Membrane distillation, Desalination, PVDF

تحلية المياه بالتقطير الغشائي بأستخدام أغشية محضرة بتقنية الغزل الكهربائي

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الخلاصة

الغزل الكهربائي: و هي تقنية مبتكرة يمكن استخدامها في انتاج الياف ذات مسامية عالية ممكن التحكم في مواصفاتها بدقة عالية. في هذا البحث تم استخدام هذه التقنية لتحضير أغشية تتكون من الياف نانوية تستخدم في تطبيقات عملية التقطير الغشائي. تم أستخدام منظومة الغزل الكهربائي محلية الصنع لتحضير هذه الأغشية. تم تحضير ألياف نانوية من مادة الـPVDF و تم اختبارها في عملية التقطير الغشائي بأستخدام محلول كلوريد الصوديوم بتركيز 0.6 مولاري كمحلول تغذية. الأغشية النانوية المحضرة أظهرت أداءا جيدا في عملية التقطير الغشائي (معدل تدفق ماء عالي و طرد أملاح عالي). وجد أيضا أن هذه الأغشية ذات تركيب

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ألياف منتظمة بحسب فحص جهاز المجهر الماسح الألكتروني. الألياف المحضرة بطريقة الغزل الكهربائي كانت ذات أقطار نانوية 250 نانومتر تقريبا.

الكلمات الرئيسية: الغزل الكهربائي؛ التقطير الغشائي؛ التحلية؛ PVDF.

1. INTRODUCTION

Progress in materials science has led to the development of the nanomaterials and their potential to be used in the various applications. The advent of these materials has resulted in drastically improving the performance of existing or conventional materials. Electrospinning is a good example of making nanofibers materials with highly tunable properties. The electrospun nanofibers can be the right candidate for membrane materials for water treatment applications.

In the last decade, electrospun nanofiber membranes (ENMs) have been investigated in the different membrane technologies such as microfiltration, ultrafiltration, nanofiltration, and reverse osmosis. Yoon and his co-workers prepared polyacrylonitrile (PAN) based electrospun membranes with a porosity of 70% for nanofiltration (NF) application. The prepared membranes exhibited better performance compared to the commercial NF membranes in treating oily wastewater with > 99.9% rejection, (**Yoon et al., 2006)**.

Recently, electrospun nanofibers have been used for osmotic membrane separation processes, namely forward osmosis and pressure retarded osmosis. Thin-film composite (TFC) membrane (which is used for osmosis processes) consists of two layers: active layer and support later. Most of the recent researches have been focusing on developing the support layer to achieve better forward osmosis performance (i.e. high water flux and salt rejection). The desired properties of the support layer are low internal concentration polarization, high mechanical strength, and high hydrophilicity, (**Ren and McCutcheon, 2014)**. Also, the support layer should have structural parameter as low as possible (i.e. thin, high porosity and low tortuosity). Typically, the support layer is prepared by phase inversion. However, an important step has been taken in the development of the support layer by using of electrospinning process. Electrospun nanofibers can be a good option as a support layer as they have unique features that matching the desired properties of the support layer that was mentioned earlier.

Buie et al. used a mixture polymeric solution from polyethersulfone (PES) and polysulfone (PSF) to make electrospun nanofiber support layer for TFC membrane. The resulting membrane exhibited better performance than the commercial forward osmosis membranes, (**Bui et al., 2011**).

Huang and McCutcheon chose a hydrophilic polymer with good mechanical strength (i.e. nylon 6,6) to prepare TFC membrane for the forward osmosis tests. Although the prepared membrane showed high water flux, it has high reverse salt flux which affects negatively on the process, **(Huang and McCutcheon, 2014).**

Commercial PES electrospun nanofibers from DuPont were used by Chowedhury as a support layer for TFC forward osmosis membrane. The prepared membrane exhibited better selectivity and strength than the TFC membrane, which is supported by laboratory-based electrospun-nanofibers,**(Chowdhury et al., 2017).**

ENMs have been proven as a material that shows a basically high porosity with an organized pore arrangement. These properties lead to consider nanofiber membranes as a potential membrane in membrane distillation (MD) applications, **(Liao et al., 2013)**. Furthermore, ENMs can provide some interesting features for MD like a high hydrophobicity and then ENMs are less prone to wetting by the feed solutions if the inter-fiber space is sufficiently designed (i.e., liquid entry pressure, LEP, in the inter-fiber space should be high to let only vapor to transport through the ENMs), (**Tijing et al., 2014)**.

The first attempt to use the ENMs in MD was conducted by**(Feng et al. in 2008)**. They tested ENMs which were made of PVDF in air gap membrane distillation, (**Feng et al., 2008)**. The prepared nanofibers were in the range of 500 nm. Later, Essalhi and Khayet prepared and tested PVDF nanofibers in direct contact membrane distillation and studied the effect of membrane thickness on the performance of the DCMD process, (**Essalhi and Khayet, 2014, 2013)**. In this research, a polymeric solution of 25 % PVDF dissolved in a solvent of acetone/DMAc mixture was used to prepare the electrospun MD membranes. Their results indicated that thinner membranes show higher water flux while thicker ones provided lower water flux.

In this work, electrospun nanofiber membranes were tested in the membrane distillation process for desalination of saline water. The ENMs prepared in this research were described by scanning electron microscopy (SEM) and atomic force microscope (AFM). Membrane distillation testing was conducted using a DCMD setup and sodium chloride (NaCl) solution was used as the feed solution.

2. MATERIALS AND METHODS

2.1. Membrane Characterization

Scanning electron microscopy imaging was taken to the PVDF samples to evaluate the surface morphology of the PVDF nanofibers using Tescan Vega SEM. Imaging was carried out using an accelerating voltage of 5 kV and current of 12 µA. Average diameters and roughness of the nanofibers were examined using by Atomic Force Microscope (Angstrom advanced Inc., 2008, U.S.A).

2.2. DCMD Performance Tests

The DCMD tests were conducted using the experimental installation shown in **Figure 1**. The setup consists of two tanks: the first one for the feed solution and the second one for permeate. Feed solution and permeate were pumped to the membrane cell using diaphragm pumps from Pure Water©. 0.6 M NaCl solution was used as a feed in all experiment while DI water was used as permeate. The temperature of the feed solution was kept at 50°C using a heater while permeate was kept at room temperature (25°C). The membrane was installed in a custom-made cell with dimensions of 7.5 cm long by 2.5 cm wide by 3 mm deep. Permeate flux was calculated by monitoring the weight change of permeate over the experiment period (5 h). Salt rejection of the membrane was calculated by monitoring permeate conductivity.

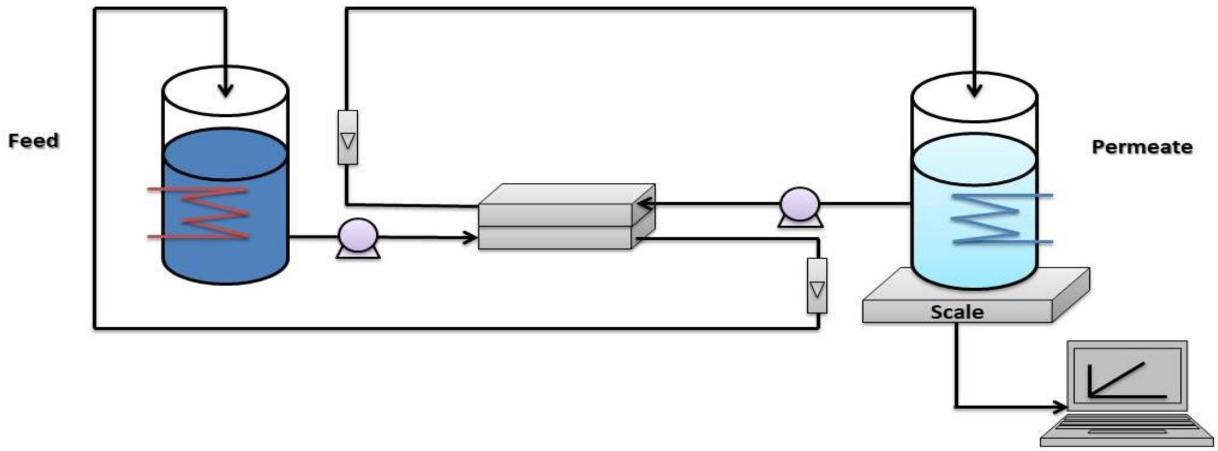


Figure 1. Schematic diagram of the DCMD bench-scale test unit.

2.3. PVDF Nanofiber Membrane Fabrication

PVDF nanofibers were prepared using a custom-built Electrospinning setup. The Electrospinning system consists of a syringe pump, a high voltage power supply, and a rotating drum. A 30 kV high voltage power supply, which is originally used in the zeta potential measurement instrument, was used in the Electrospinning setup. The syringe pump was made from locally available materials.

A grounded aluminum rotating cylinder, which functioned as a collector, was located at 15 cm from the needle tip, and a voltage was applied using a 30 kV power supply.

A solution of PVDF in DMF was prepared by continuously stirring the polymer in the solvent for 24 h at 60^{o} C. Before using in the electrospinning; the polymer solution was degassed overnight at ambient temperature. The as-prepared polymeric solution was electrospun at a flow rate of 2 mL/hr onto an aluminum foil which is peeled of prior to using the membrane in the DCMD test. Electrospinning was conducted at ambient temperature.

3. RESULTS AND DISCUSSIONS

3.1 Membrane Characterization

Figure shows the photograph of the prepared membrane that was formed on the aluminum foil during the Electrospinning process. This membrane was peeled off the aluminum foil for further characterization and testing. The morphology of the electrospun nanofibers is shown in the SEM image of the membrane ,**Figure** . It should be noted that the prepared membrane has smooth and uniform fibers with an approximate diameter of 250 nm, as shown in **Figure** . It can also be seen that there is a very high porosity of the electrospun nanofibers. This guarantees that a major amount of the PVDF nanofibers is in contact with the feed solution through membrane distillation process which means higher mass transfer area and consequently higher water flux. Also, AFM testing was performed for the membrane to investigate the roughness of the membrane as shown in **Figure** . It can be noticed that the membrane surface is clearly rough which is an indicator of the fibrous nature of the membrane surface. Membrane surface with higher roughness provides better mass transfer area, (**Tijing et al., 2014)**.

Figure 2. The prepared membrane that was collected on the aluminum foil.

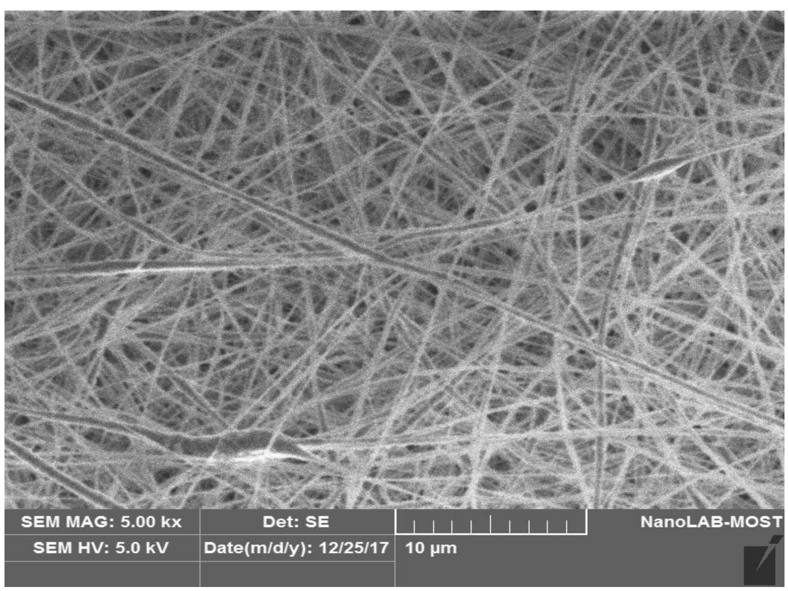
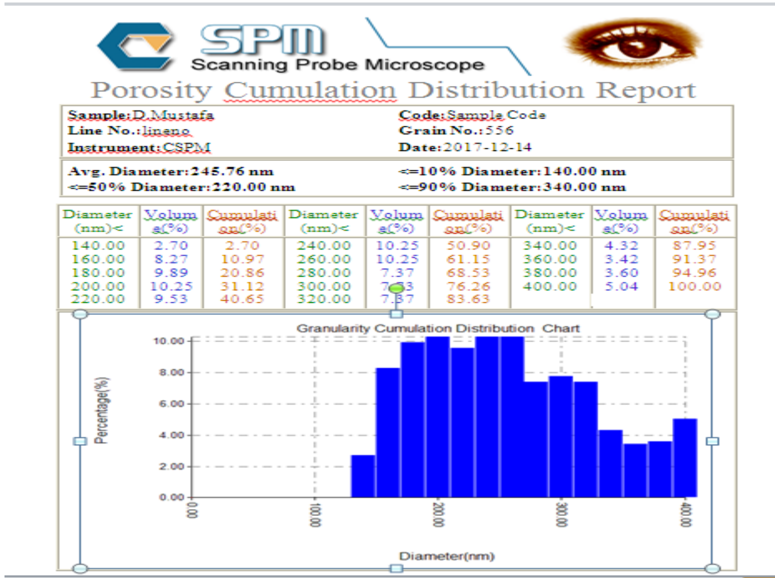


Figure 3. SEM image of the as-spun PVDF nanofiber mat.



Diameter (nm)<	Volume(%)	Cumulation(%)	Diameter (nm)<	Volume(%)	Cumulation(%)	Diameter (nm)<	Volume(%)	Cumulation(%)
140.00	2.70	2.70	240.00	10.25	50.90	340.00	4.32	87.95
160.00	8.27	10.97	260.00	10.25	61.15	360.00	3.42	91.37
180.00	9.89	20.86	280.00	7.37	68.53	380.00	3.60	94.96
200.00	10.25	31.12	300.00	[illegible]	76.26	400.00	5.04	100.00
220.00	9.53	40.65	320.00	7.37	83.63			

Figure 4. Distribution of the nanofiber diameters.

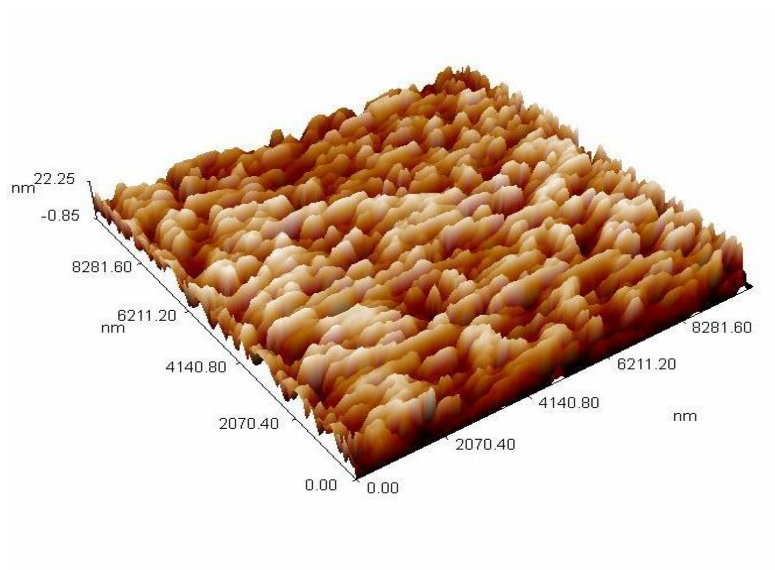


Figure 5. AFM images obtained from the top surface of the PVDF nanofiber membrane.

3.2 Membrane Performance in DCMD

Membrane efficiency in desalination was examined in DCMD experimental system. NaCl solution at a concentration of 0.6 M was used to simulate the salinity of seawater. The permeate flux (as shown in **Figure**) was about 20 kg/m^2.hr for 5 hr. of operation. These results were compatible with the findings of Essalhi and Khayet, (**Essalhi and Khayet, 2014)**. The salt rejection was about 94%. It was anticipated to achieve a complete rejection of salts because of the hydrophobic nature of the prepared membrane. However, the Electrospinning system, which was used in this study, was a home-made set up so it was difficult to control the operating conditions especially the voltage of the power supply. By altering the operating conditions, better performance in terms of water flux and salt rejection can be achieved. This is planned for our future researches.

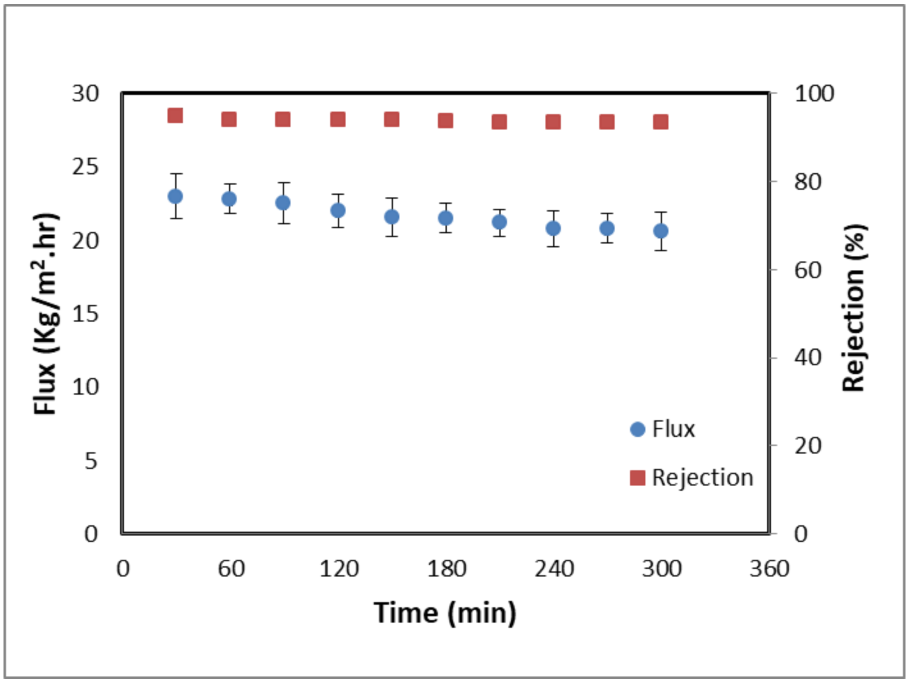


Figure 6. Membrane distillation water flux and salt rejection for the nanofiber PVDF membrane. Experimental conditions: feed solution: 0.6 M NaCl, permeate: DI water, feed temperature: 50 ^oC, permeate temperature: 25 ^oC.

4. CONCLUSIONS AND RECOMMENDATIONS

Electrospun membrane with fibrous structure was prepared in this research and tested for direct contact membrane distillation application. The prepared membrane showed good performance in terms of water flux and salt rejection. Electrospinning setup was made from locally available parts. This system exhibited stable operation in making the electrospun nanofiber membrane. The recommendation is to prepare and test electrospun nanofiber membranes for further applications like forward osmosis and ultrafiltration.

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