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Submerged membrane distillation for seawater desalination

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ABSTRACT

A submerged membrane distillation (SMD) process for fresh water production from Red Sea water using commercially available hollow fiber membranes has been successfully employed and compared with the conventional direct contact membrane distillation (DCMD) process. The hollow fiber membranes have been characterized for its morphology using field effect scanning electron microscope. In SMD process, a bunch of hollow fiber membranes are glued together at both ends to get a simplified open membrane module assembly submerged into the coolant tank equipped with a mechanical stirrer. Hot feed stream is allowed to pass through the lumen side of the membrane using a feed pump. Continuous stirring at the coolant side will reduce the temperature and concentration polarization. During the conventional DCMD process, using feed-coolant streams with co-current and counter-current flows has been tested and the results are compared in this study. In SMD process, a water vapor flux of 10.2 kg m^{-2} h^{-1} is achieved when using a feed inlet temperature of 80°C and coolant temperature of 20°C. Under the same conditions, during conventional DCMD process, a water vapor flux of 11.6 and 10.1 kg m^{-2} h^{-1} were observed during counter-current and co-current flow streams, respectively. Results show that the water production in the SMD process is comparable with the conventional DCMD process, while the feed-coolant flow streams are in the co-current direction. During conventional DCMD operation, a 15% increase in the water production is observed when feed-coolant streams are in the counter-current direction compared to the co-current direction.

Keywords: Submerged membrane distillation (SMD); Seawater desalination; Wastewater treatment; Partial water vapor pressure

1. Introduction

Increase of fresh water demand due to population growth, pollution, and non-uniform distribution of potable water is forcing mankind to novel, more sustainable, and environmentally friendly technologies for fresh water production. Membrane distillation (MD) is an emerging alternative, more sustainable desalination technology offering high-quality water production from seawater, brackish water, or industrial wastewaters (e.g. produced water) [1–5]. In the MD process, a highly hydrophobic macro-porous membrane separated by two water streams, a hot feed

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water stream (e.g. seawater or wastewater), and a coolant stream is used. The partial water vapor pressure difference created across the membrane contactor due to the transmembrane temperature difference is the driving force of the MD process. The high hydrophobic nature of the membrane prevents membrane wetting and allows only water vapor to pass from hot stream through the pores, which condenses at the other side of the membrane and results in ultra-pure quality water production [4,6–14]. Not only because the hollow fiber membranes are self-supported but also their high surface area to volume ratio has attracted researchers for utilizing them as an efficient MD membrane over conventional flat sheet MD membranes [15–18].

In the present study, a commercially available hydrophobic poly tetrafluoroethylene (PTFE) hollow fiber membrane is subjected to the direct contact membrane distillation (DCMD) process by using Red Sea water as the feed solution. The hollow fiber membrane is characterized for its morphology using field effect scanning electron microscope. A submerged membrane distillation (SMD) process for fresh water production from Red Sea water using hollow fiber membranes has been successfully employed and compared with the conventional DCMD process. Feed stream in the co-current and counter-current directions has also been investigated and water vapor flux is compared in the DCMD process.

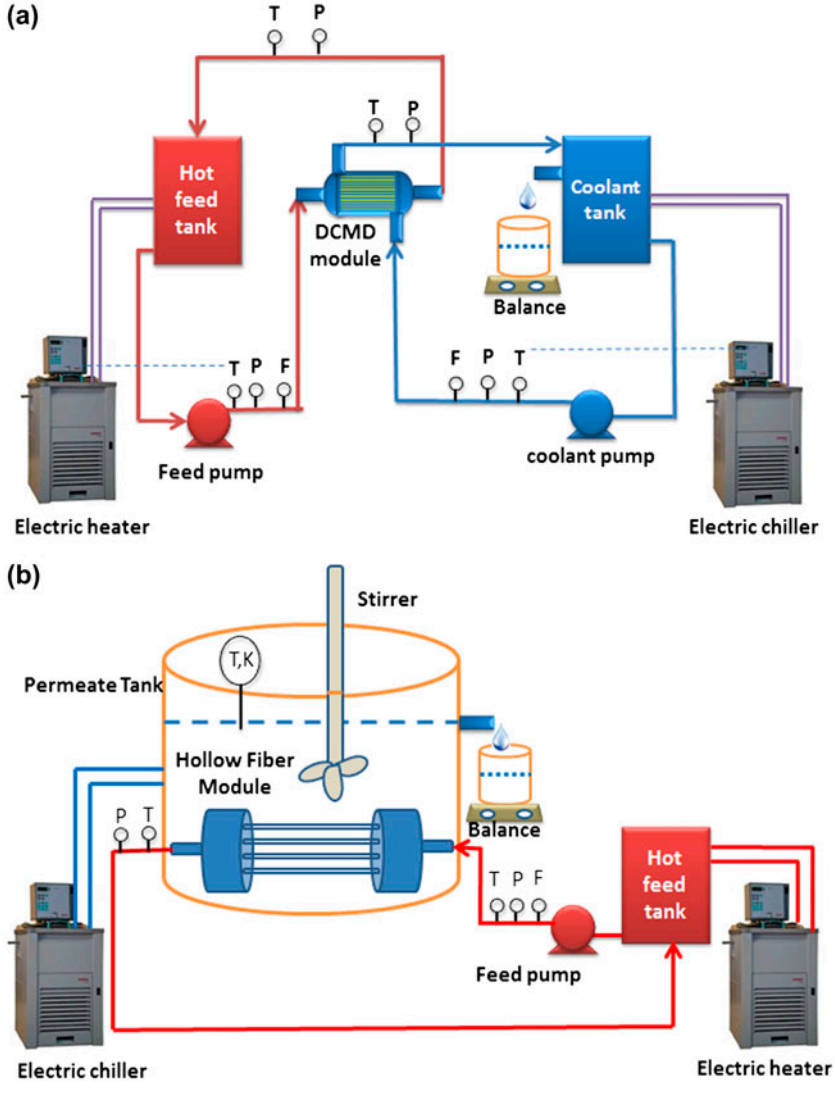

Fig. 1. A schematic diagram of bench-scale experimental setup of (a) DCMD and (b) SMD.

2. Experimental

Commercially available hydrophobic PTFE hollow fiber membranes with a nominal pore size of 0.2 μm, outer diameter of 2 mm, and a wall thickness of 0.5 mm were tested in DCMD and SMD configurations. A schematic diagram of the bench-scale hollow fiber DCMD and SMD setups are shown in Fig. 1(a) and (b), respectively. Red Sea water was used as feed solution in all experiments. Sea water was collected from the King Abdullah University of Science and Technology (KAUST) seawater reverse osmosis plant and filtered through a 10-μm filter to remove suspended solids prior to the MD process. Tap water was used as a coolant in both DCMD and SMD experiments. In the SMD process, a bunch of hollow fiber membranes are glued together at both the ends to get an open membrane module assembly and simply submerged in to the permeate tank equipped with a mechanical stirrer. Hot feed stream is allowed to pass through the lumen side of the membrane using a peristaltic pump. Continuous stirring at the coolant side helps to uniform the temperature and reduce the temperature, and concentration polarization effects at the outer surface of the hollow fiber membrane. Active surface area of the membrane is calculated to be 0.0075 m^2. Seawater was preheated and fed into the lumen side of the membrane in both the DCMD and SMD configurations using an electric heater.

Feed/coolant flow rates were kept at 1.5 L min^{-1} in all experiments. Temperature of the tap water in the permeate tank is controlled using an electric chiller. In both the DCMD and the SMD processes, the flux is calculated by recording the increase in the weight of the permeate overflow from the coolant tank using a weighing balance as a function of time at different feed inlet temperatures (40–80˚C). Conductivity of the permeate was continuously monitored during DCMD and SMD processes using a conductivity meter (Oakton Instruments, Malaysia).

3. Results and discussion

Fig. 2 shows the SEM images of cross-section, outer surface, and inner surface of the PTFE hollow fiber membranes.

Liquid entry pressure and nominal pore size of the membrane is given as 18 psig and 0.2 μm, respectively. The wall thickness of the membrane is higher compared to the conventional membranes used for MD process [19–24]. High membrane thickness causes higher mass transfer resistance and lowers the water flux during the MD process. SEM morphology also reveals that the membrane is less porous and pores are generated as a result of stretching during the fabrication in the form of cracks on the membrane material. Low magnification shows a smoother surface, whereas the high magnification of inner surface shows a fibril structure, and the outer surface shows a porous structure.

Experimental setup of the SMD process is shown in Fig. 3.

Coolant from a chiller is passed through a glass coil in the permeate tank to control the temperature of the tap water. SMD configuration is an easy way of

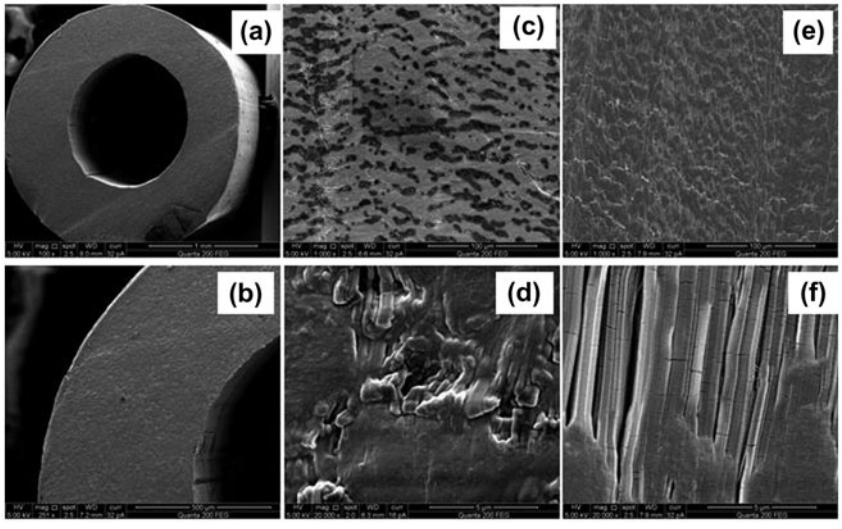

Fig. 2. SEM images of PTFE membrane. Cross-section ((a) and (b)), outer surface ((c) and (d)), and inner surface ((e) and (f)).

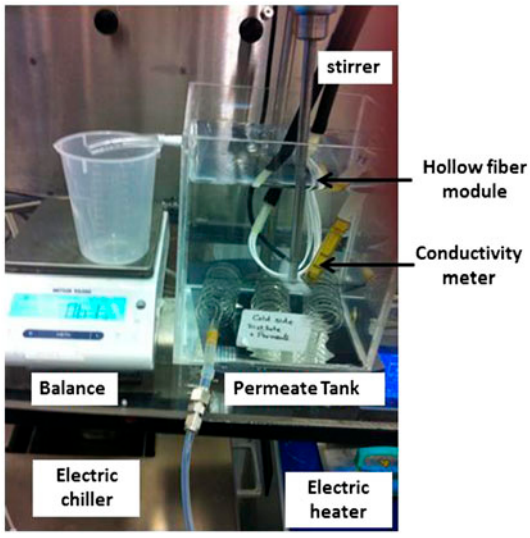

Fig. 3. Experimental setup of SMD process.

the fabrication of membrane modules, which avoids the complex design and fabrication processes. Partial water vapor pressure difference across the membrane is the driving force in the MD processes, which drives the water vapors from the hot feed side to the coolant side across the membrane and allows the vapors to condense along with the tap water. As a result, the volume of the permeate tank increases and excess volume generated is collected through an overflow connection into a beaker placed on a weighing balance. Water vapor flux is calculated using the following equation.

$$J = \frac{W}{A_t} \tag{1}$$

where J is the water vapor flux, W is the weight of permeate collected during a time interval (h), and A is the active area of the membrane (m^2).

Water vapor flux comparison during counter-current and co-current feed streams at different feed inlet temperatures during the DCMD process is plotted in Fig. 4(a). Fig. 4(b) shows the comparison between the water vapor flux during the DCMD

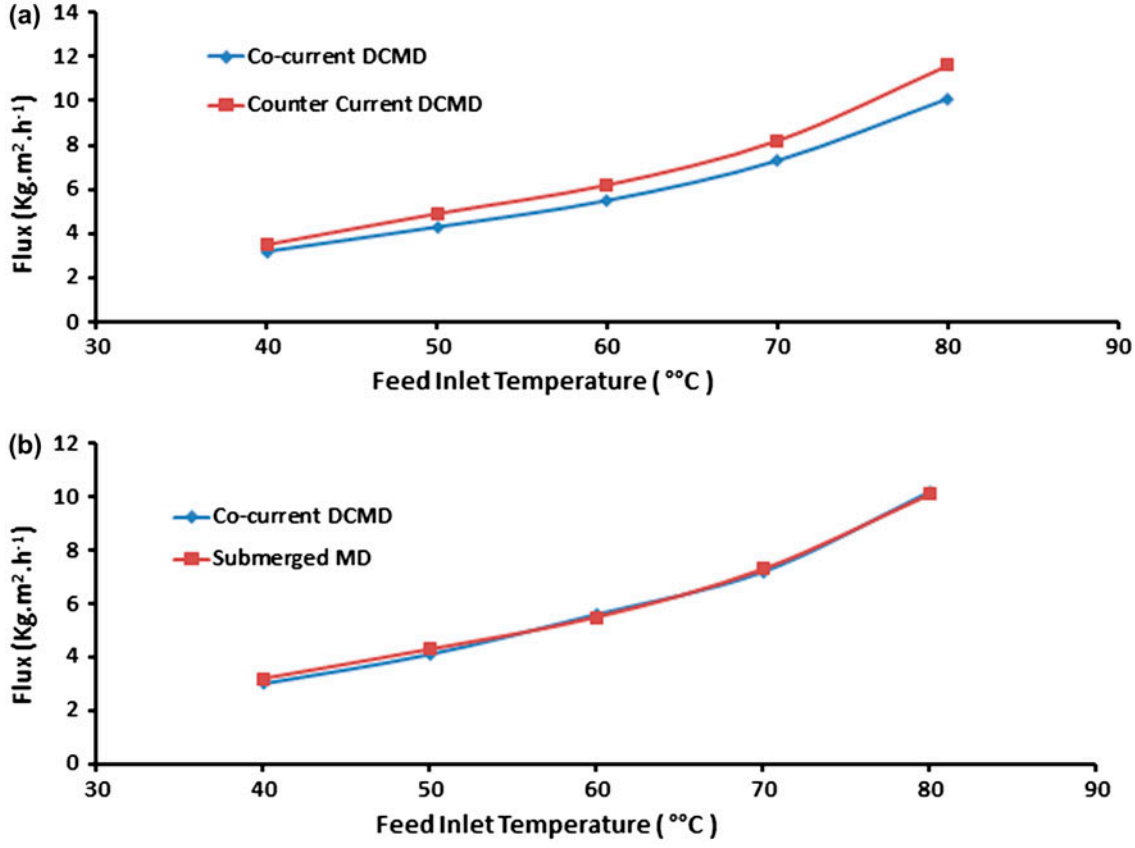

Fig. 4. Water vapor flux profile vs. feed inlet temperature during (a) co-current and counter-current DCMD process and (b) co-current DCMD and submerged MD process.

and SMD processes. The water vapor flux during co-current DCMD and SMD was found to be 10.1 and 10.2 $kg\,m^{-2}\,h^{-1}$, respectively, at a feed inlet temperature of 80˚C and at a coolant inlet temperature of 20˚C. The water vapor flux during counter-current DCMD was determined to be 11.6 $kg\,m^{-2}\,h^{-1}$ at a feed inlet temperature of 80˚C and at a coolant inlet temperature of 20˚C. In the SMD process, a water vapor flux of 10.2 $kg\,m^{-2}\,h^{-1}$ is observed when using a feed inlet temperature of 80˚C and coolant temperature of 20˚C. Under similar conditions, during the conventional DCMD process, a water vapor flux of 11.6 and 10.1 $kg\,m^{-2}\,h^{-1}$ was observed during counter-current and co-current flow streams, respectively. There is a possibility of less turbulence in the SMD process at the coolant side than that in the conventional DCMD process, which may result in a more temperature polarization at the outer surface of the membrane. During the MD process, the temperature polarization at the coolant side or at lower temperatures has negligible influence on the effective transmembrane vapor pressure and water vapor flux compared to the feed side [25]. Results showed that the water production in the SMD process is comparable to that of conventional DCMD process, while the feed-coolant flow streams are in co-current direction. During conventional DCMD operation, a 15% increase in the water production is observed when feed-coolant streams are in the counter-current direction compared to the co-current direction. It was observed that the water flux during the DCMD and SMD processes using PTFE hollow fiber membrane is much less than that of the flux observed during the DCMD process using PTFE and other types of flat sheet membranes under the same operating conditions, as reported in previous studies [25–27]. This is due to the different membrane characteristics, especially the thickness and pore size distribution of the membranes. Conductivity of the tap water in the permeate tank was observed to be decreasing with time during all experiments. This is due to the high quality of water vapors passing from the feed side to the permeate tank by rejecting all non-volatiles at the feed side. The heat and mass transfer during the present study is low due to the increased wall thickness and less porous structure of the membrane. Membrane modules in the SMD design is similar to the membrane bioreactors (MBRs), and it is possible to adapt MD membranes in MBR process to extract fresh water from wastewater and concentrate the nutrients, simultaneously. Engineered membrane design is necessary to make the membrane more appropriate for optimum MD process.

4. Conclusions

A facile design of the MD process is possible, namely SMD is successfully employed, tested, and compared with the conventional DCMD process using commercially available PTFE hollow fiber membranes. A 15% increase in the water vapor flux is observed when feed-coolant streams are in the counter-current direction compared to the co-current direction, whereas the water production in the SMD process is comparable with the conventional DCMD process while the feed-coolant flow streams are in the co-current direction. SMD module design is much simpler than the conventional DCMD modules and it is possible to use this design in MBRs to reduce the volume of wastewater by extracting fresh water using the MD process. Membrane characteristics play an important role in the increased water production during the MD process and it is very important to have engineered MD membranes and optimized process conditions for a low energy and efficient water recovery.

References

[1] G.C. Sarti, C. Gostoli, S. Matulli, Low energy cost desalination processes using hydrophobic membranes, Desalination 56 (1985) 277–286.
[2] L. Camacho, L. Dumée, J. Zhang, J.-D. Li, M. Duke, J. Gomez, S. Gray, Advances in membrane distillation for water desalination and purification applications, Water 5 (2013) 94–196.
[3] A.G. Fane, R.W. Schofield, C.J.D. Fell, The efficient use of energy in membrane distillation, Desalination 64 (1987) 231–243.
[4] L. Francis, N. Ghaffour, A.A. Alsaadi, G.L. Amy, Material gap membrane distillation: A new design for water vapor flux enhancement, J. Membr. Sci. 448 (2013) 240–247.
[5] A. Alkhudhiri, N. Darwish, N. Hilal, Membrane distillation: A comprehensive review, Desalination 287 (2012) 2–18.
[6] K.W. Lawson, D.R. Lloyd, Membrane distillation, J. Membr. Sci. 124(1) (1997) 1–25.
[7] S.T. Hsu, K.T. Cheng, J.S. Chiou, Seawater desalination by direct contact membrane distillation, Desalination 143(3) (2002) 279–287.
[8] A.M. Alklaibi, N. Lior, Membrane-distillation desalination: Status and potential, Desalination 171 (2005) 111–131.
[9] M. Khayet, N.N. Li, A.G. Fane, W.S. Winston Ho, Membrane Distillation, Advance Membrane Technology and Applications, John Wiley, Hoboken, NJ, 2008.
[10] M.S. El-Bourawi, Z. Ding, R. Ma, M. Khayet, A framework for better understanding membrane distillation separation process, J. Membr. Sci. 285(1–2) (2006) 4–29.
[11] S. Bonyadi, T.S. Chung, Highly porous and macrovoid-free PVDF hollow fiber membranes for membrane distillation by a solvent-dope solution co-extrusion approach, J. Membr. Sci. 331(1–2) (2009) 66–74.

[12] A.S. Alsaadi, N. Ghaffour, J.D. Li, S. Gray, L. Francis, H. Maab, G.L. Amy, Modeling of air-gap membrane distillation process: A theoretical and experimental study, J. Membr. Sci. 445 (2013) 53–65.
[13] L. Francis, N. Ghaffour A.S. Alsaadi, G.L. Amy, Performance of different hollow fiber membranes for seawater desalination using membrane distillation, Desalin. Water. Treat. Accepted (2014), doi: 10.1080/19443994.2014.946723.
[14] L. Francis, N. Ghaffour, G. Amy, Fabrication and characterization of functionally graded poly(vinylidine fluoride)-silver nanocomposite hollow fibers for sustainable water recovery, Sci. Adv. Mater. Accepted (2014), doi: 10.1166/sam.2014.1980.
[15] K.Y. Wang, T.S. Chung, M. Gryta, Hydrophobic PVDF hollow fiber membranes with narrow pore size distribution and ultra-thin skin for the fresh water production through membrane distillation, Chem. Eng. Sci. 63(9) (2008) 2587–2594.
[16] K.Y. Wang, S.W. Foo, T.S. Chung, Mixed matrix PVDF hollow fiber membranes with nanoscale pores for desalination through direct contact membrane distillation, Ind. Eng. Chem. Res. 48 (2009) 4474–4483.
[17] C.Y. Feng, K.C. Khulbe, T. Matsuura, A.F. Ismail, Recent progresses in polymeric hollow fiber membrane preparation, characterization and applications, Separ. Purific. Technol. 111 (2013) 43–71.
[18] X. Yang, R. Wang, L. Shi, A.G. Fane, M. Debowski, Performance improvement of PVDF hollow fiber-based membrane distillation process, J. Membr. Sci. 369(1–2) (2011) 437–447.
[19] H. Maab, A. Al Saadi, L. Francis, S. Livazovic, N. Ghafour, G.L. Amy, S.P. Nunes, Polyazole hollow fiber membranes for direct contact membrane distillation, Ind. Eng. Chem. Res. 52 (2013) 10425–10429.
[20] F.F. Shao, L. Ni, Y.F. Zhang, Y.B. Chen, Z. Liu, Z. Cao, Study on vacuum membrane distillation of PP hollow fiber membranes used in concentrated seawater from low-pressure reverse osmosis, Desalin. Water Treat. 51 (2013) 3925–3929.
[21] B. Wu, X.Y. Tan, K. Li, W.K. Teo, Removal of 1,1,1-trichloroethane from water using a polyvinylidene fluoride hollow fiber membrane module: Vacuum membrane distillation operation, Sep. Purif. Technol. 52 (2006) 301–309.
[22] L. Francis, N. Ghaffour, A. AlSaadi, S. Nunes, G. Amy, PVDF hollow fiber and nanofibers membranes for fresh water reclamation using membrane distillation, J. Mater. Sci. 49 (2014) 2045–2053.
[23] N. Peng, N. Widjojo, P. Sukitpaneenit, M.M. Teoh, G.G. Lipscomb, T.S. Chung, J.Y. Lai, Evolution of polymeric hollow fibers as sustainable technologies: Past, present and future, Prog. Polym. Sci. 37 (2012) 1401–1424.
[24] L. Shi, R. Wang, Y. Cao, C. Feng, D.T. Liang, J.H. Tay, Fabrication of poly(vinylidine fluoride-co-hexafluropylene) (PVDF-HFP) asymmetric microporous hollow fiber membranes, J. Membr. Sci. 305(1–2) (2007) 215–225.
[25] L. Francis, H. Maab, A. AlSaadi, S. Nunes, N. Ghaffour, G.L. Amy, Fabrication of electrospun nanofibrous membranes for membrane distillation application, Desalin. Water. Treat. 51(7–9) (2013) 1337–1343.
[26] H. Maab, L. Francis, A.S. Al-saadi, C. Aubry, N. Ghaffour, G.L. Amy, S.P. Nunes, Synthesis and fabrication of nanostructured hydrophobic polyazole membranes for low-energy water recovery, J. Membr. Sci. 423–424 (2012) 11–19.
[27] L. Francis, N. Ghaffour, A.S. Alsaadi, S.P. Nunes, Performance evaluation of the DCMD desalination process under bench scale and large scale module operating conditions, J. Membr. Sci. 455 (2014) 103–112.