Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2017.20744

90 (2017) 1–6
September

Experimental study on the thermal performance characteristics of hollow-fiber vacuum membrane distillation module

Hong-Jin Joo, Hee-Youl Kwak*

Solar Energy Research Division, Korea Institute of Energy Research (KIER), 152 Gajeong-ro, Yuseong-Gu, Daejeon, Korea, Tel. +82-42-860-3516; email: hykwak@kier.re.kr (H.-Y. Kwak), Tel. +82-42-860-3093; email: joo@kier.re.kr (H.-J. Joo)

Received 30 January 2017; Accepted 22 March 2017

ABSTRACT

In this study, a performance experiment was conducted on the feedwater conditions of a polyvinylidene fluoride hollow-fiber vacuum membrane distillation (VMD) module prior to construction of a VMD seawater desalination demonstration plant in South Korea that will have a capacity of 400 m^3/d. The VMD module, manufactured by Econity Co., Ltd., South Korea, has an effective area of 5.3 m^2. For the performance test of the hollow-fiber VMD module, a laboratory-scale VMD system was built and the tests were conducted under various feedwater conditions. The results showed that under feed conditions of 75°C, 8 m^3/h feedwater flow rate, and salinity of 35,000 ppm, permeate flux was up to 18 LMH and salt rejection was up to 99.99%.

Keywords: Membrane distillation; Vacuum membrane distillation; Hollow-fiber membrane distillation

1. Introduction

While humanity's demand for water has constantly increased due to population growth and industrialization, the volume of water available has rapidly decreased due to desertification and changes in precipitation caused by climate change. Due to the continuous increase in water demand, the need for alternative water resources has emerged.

As a technology for securing an alternative water resource to address the problem of water shortage, seawater desalination is becoming increasingly important. Seawater desalination is emerging as a powerful solution to the water shortage problem, as seawater is an unlimited source of water that can be used to produce freshwater [1].

The evaporative, the electrodialysis, and reverse osmosis (RO) desalination methods are widely researched and in use, particularly the RO method. Since the evaporative method requires heating seawater beyond its boiling point, it is primarily used in countries rich in chemical energy resources such as oil and coal [1,2]. As a result, the RO method, which is gradually consuming less energy, is being intensively studied and employed. The RO method is a process that uses a high-pressure pump to obtain freshwater by applying a pressure greater than osmotic pressure after pretreatment. However, it requires high power consumption and the use of hydrophilic membranes, which is disadvantageous in that the membranes are easily contaminated by floating particles and organic substances [3,4].

Accordingly, reduced energy consumption and eco-friendly desalination technologies have been continuously studied in many countries around the world to solve such desalination problems. Among those studies, membrane distillation (MD) is emerging as the next-generation freshwater technology that can make up for the shortcomings of existing distillation methods and the RO method [3].

The MD method is a process that uses a porous separation membrane with a hydrophobic surface to separate water in the pure vapor state from raw water. In MD treatment, when raw water contacts a side of the separation membrane, it won't pass through the membrane's pores due to the surface tension generated by the hydrophobic property of its surface;

---

* Corresponding author.

Presented at the 9th International Desalination Workshop: Sustainable Desalination (IDW2016), 13–15 November 2016, Abu Dhabi, UAE.

only vapor passes through [3,4]. Mass transfer occurs in the MD process because of the temperature difference between the raw water at high temperature and the permeate water at low temperature at the boundary of the separation membrane. The difference in vapor pressure resulting from this temperature difference acts as the driving force that transfers vapor molecules from the raw water to the permeate water as the water changes from the liquid state to the vapor state [5]. MD can be classified into direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), sweep gas membrane distillation, and vacuum membrane distillation (VMD), according to the method applied on the permeate water side to generate the gradient of vapor pressure (the driving force) [3–6].

Among those methods, VMD uses pressure lower than the atmospheric pressure. The fed seawater is capable of producing more vapor at the same temperature than DCMD or AGMD. It is advantageous because it is operable at a lower temperature than other MDs; it is disadvantageous because additional energy is needed to maintain the vacuum state [6].

Currently, no commercial product is available that uses the VMD method, as it is still in the study stage. Therefore, to investigate the performance of VMD under various feedwater conditions before the commercialization of a VMD module and implementation of a demonstration plant using a VMD module at 400 m^3/d, a VMD module with a capacity of 2 m^3/d was designed and built using a polyvinylidene fluoride (PVDF) hollow-fiber membrane, and flux changes and thermal performance, the main operating conditions of the VMD module, were analyzed with respect to changes in the temperature and flow rate of the raw water.

2. Experimental setup and method

2.1. Experimental setup

Fig. 1 shows the schematic diagram of the lab-scale experimental system implemented to derive the freshwater production characteristics of the VMD module. The system was designed and built to use electric heaters as heat sources applied to the VMD module to heat the seawater. The heated seawater was fed to the VMD module through a 0.2 μm micro filter (MF). At that point, the temperature, pressure, and flow rate of the fed seawater were measured by a temperature sensor, a pressure transducer, and a flow meter, respectively [7,8]. The equipment was designed to control flow rate and pressure by a valve and a bypass line. Seawater that had passed through the VMD module was re-heated by the electric heater and re-collected in the seawater tank. The vapor generated in the VMD module was condensed by cold water of 20°C into freshwater as it passed through the condenser and stored in the freshwater tank. The experimental equipment was designed to measure the weight and salinity of the freshwater collected in the freshwater tank to maintain constant salinity of the seawater fed into the VMD module and then returns it to the seawater tank [7,8]. Fig. 2 shows the system used for testing the thermal performance of the VMD module in this study, and Table 1 lists its components.

Fig. 2. Image of the experimental setup.

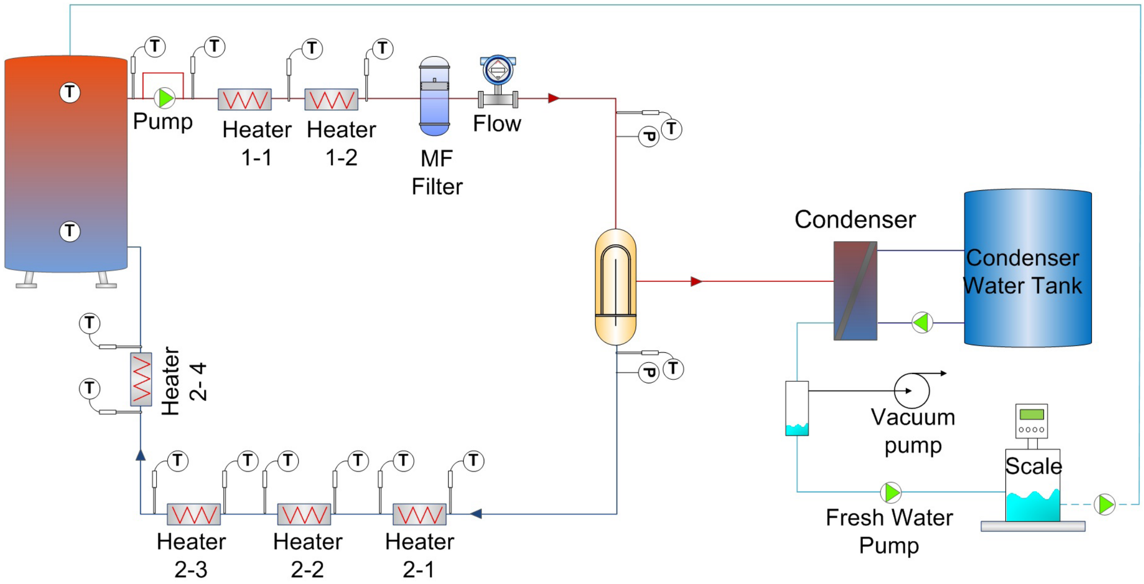

Fig. 1. The schematic diagram of experimental setup.

Table 1
Configuration of the experimental setup

Contents	Specifications
Seawater tank, m^2	0.3
Electric heaters	4 sets of 10 kW and 2 sets of 12 kW
MF pretreatment filter, μm	0.2
Seawater pump, m^3/h	13
Electromagnetic flow meter, m^3/h	1–45
Condenser, kcal/h	47,120
Vacuum pump	120 LPM, 690 mmHg
Pressure transducer, bar	1–20
Vacuum pressure transducer, kPa	0–100
Total membrane area of VMD module, m^2 (inner diameter)	5.3

2.2. VMD module

The VMD module used in this study was produced by Econity Co., Ltd., Korea for commercialization. Hollow-fiber membranes made of hydrophobic porous PVDF were used in the VMD module. Strands of these PVDF hollow-fiber membranes were inserted into a chlorinated polyvinyl chloride cylindrical container which is usable at high temperatures. The vapor generated when seawater passed through the membrane tube passed through the pores of the hollow-fiber membranes and was discharged out of the membranes. The discharged vapor was collected by the pressure difference into a condenser, where it was condensed by heat exchange with the cooling water. The total effective area of hollow-fiber membranes installed in the VMD module used in this study was 5.3 m^2 based on the inner diameter of the hollow-fiber membranes. The total strand number of membranes inserted in the module was 6,030. The average pore size of a hollow-fiber membrane was 0.1 μm and its average porosity was 65%–70%. Fig. 3 shows Econity's VMD module, Fig. 4 shows its schematic diagram, and Table 2 lists its specifications.

2.3. Experimental conditions and method

To analyze the freshwater production characteristics of the VMD module with respect to seawater feed conditions, each experiment was conducted under the same conditions of the external environment. Since the VMD module generated vapor by feeding seawater at a higher temperature than the external temperature, the heat loss effect had to be considered. Consequently, the same external temperature was maintained for each experiment to evaluate the performance. In addition, to minimize experimental errors, the error margins of salinity, temperature, flow rate, and pressure of the seawater fed into the VMD module were maintained within ±1% [7,8].

Bay salt was used to achieve salinity similar to seawater for the feedwater fed to the VMD module and it was maintained at 35,000 ppm based on TDS. The salinity of the feedwater was measured before and after the experiment and kept unchanged so as to provide the same salinity condition for each experiment. The feedwater was fed at temperatures of 55°C, 65°C, and 75°C and at flow rates of 4, 6, and 8 m^3/h, respectively. In addition, due to the characteristic of the VMD module operating in a vacuum state, each experiment was conducted under the same condition of 15 kPa or lower based on the absolute pressure for the vacuum pressure in the module.

Fig. 3. Image of the Econity's VMD module.

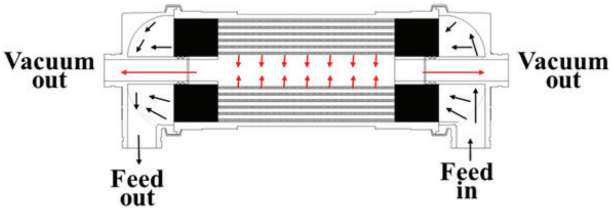

Fig. 4. Schematic diagram of the Econity's VMD module.

Table 2
Specifications of the VMD module in this study

Item	Contents	Material
Membrane	Material	PVDF
	Type	Hollow fiber
	Pore structure	Asymmetric
	Average porosity (%)	65–70
	Average pore size (μm)	0.1
	Diameter (outside/inside) (mm)	1.2/0.7
Module	Material	Acrylonitrile Butadiene Styrene
	Potting material	Polyurethane
	Length/diameter (mm)	914/260
	Membrane surface (m^2)	5.3
	Number of membranes	6,030
	Packing density (%)	15
	Membrane length (mm)	450
	Type	VMD
	Filtration flow	In–out
	Temperature (°C)	10–75

3. Experimental results and considerations

3.1. Processing method of experimental results

In designing the VMD seawater desalination plant, the most important design point was to predict the thermal energy consumption required for the VMD process [6].

As with conventional thermally driven seawater desalination systems, the performance ratio (PR) value in the dimensionless unit was used to evaluate the thermal performance of the VMD module. The PR value could be expressed with the latent heat energy necessary to evaporate the feedwater and the thermal energy consumption used to produce the freshwater, as shown in Eq. (1) [7–12]:

$$\mathrm{PR} = \frac{\dot{m}_{\mathrm{dist}} \Delta h_v}{\dot{Q}_{\mathrm{heat}}} \tag{1}$$

where $\dot{m}_{\mathrm{dist}}$ is the permeate flux, i.e., the produced freshwater quantity, Δh_v is the evaporative latent heat required to evaporate 1 kg of water and $\dot{Q}_{\mathrm{heat}}$ is the thermal energy supplied when producing the freshwater. It was possible to calculate $\dot{Q}_{\mathrm{heat}}$ with the temperature difference and the flow rate of seawater fed into the VMD module as shown in Eq. (2):

$$\mathrm{Q}_{\mathrm{heat}} = \dot{m}_{\mathrm{feed}} C_p (T_{\mathrm{in}} - T_{\mathrm{out}}) \tag{2}$$

where $\dot{m}_{\mathrm{feed}}$ is the flow rate of the seawater fed into the VMD module, C_p is the specific heat of the seawater, T_{in} is the temperature of the seawater at the inlet of the VMD module, and T_{out} is the temperature of the seawater at the outlet of the VMD module.

In addition, the LMH (permeate flux) value which, along with the PR value, is used as one of the indicators of the membrane in the VMD process was calculated in the freshwater quantity produced per membrane area, as shown in Eq. (3) [7–10]:

$$\mathrm{LMH} = \frac{\dot{m}_{\mathrm{dist}}}{A_m} \tag{3}$$

where $\dot{m}_{\mathrm{dist}}$ is the freshwater quantity produced by the VMD module per hour and A_m is the total area of the hollow-fiber membranes installed in the VMD module.

In addition, the recovery ratio (RR) value, which is the ratio of feedwater fed to the VMD module and freshwater produced is as shown in Eq. (4) [8–11]:

$$\mathrm{RR} = \frac{\dot{m}_{\mathrm{dist}}}{\dot{m}_{\mathrm{feed}}} \tag{4}$$

3.2. Freshwater production characteristics

Fig. 5 shows LMH values with respect to the thermal energy of the feedwater fed to the VMD module. The thermal energy increased as the temperature and flow rate of the feedwater increased. Consequently, it appeared that the LMH value of the permeate flux increased as well. The results of the experiments showed that the LMH value of the permeate flux of the VMD module was 18.25 when the heat input to the fed seawater was about 70 kW, and LMH was the lowest at 7.92 LMH at the lowest heat input, 30.6 kW, among the experimental conditions. Thus, it was analyzed that the permeate flux value varies by approximately twice or more depending on the heat input to the feedwater fed to the VMD module [10,13–15].

Fig. 6 shows LMH values with respect to the feedwater temperature difference between the inlet and outlet of the VMD module. For Econity's VMD module used in this study, a maximum temperature difference of 13°C appeared at the inlet and outlet of the VMD module under the experimental conditions of 75°C for the seawater feed temperature and 4 m^3/h for the flow rate. The temperature difference at the inlet and outlet was 3.8°C under the experimental conditions of 55°C and 8 m^3/h. The higher the flow rate of the feedwater was, the smaller the temperature difference was at the inlet and outlet at identical feed temperature. The permeate flux increased as the flow rate of feedwater increased because the difference in the effective vapor pressure increased due to reduced temperature and concentration polarization [16,17].

Fig. 7 shows RR values with respect to the salinity, temperature, and flow rate of the feedwater. The RR value is generally the ratio of the quantity of feedwater to the quantity of freshwater produced by the VMD module. For the VMD module used in this study, the maximum RR value was 2.349% under experimental conditions of feedwater salinity of 35,000 ppm, feedwater temperature of 75°C, and feedwater flow rate of 8 m^3/h, and the minimum RR value was 1.03% under experimental conditions of feedwater salinity of

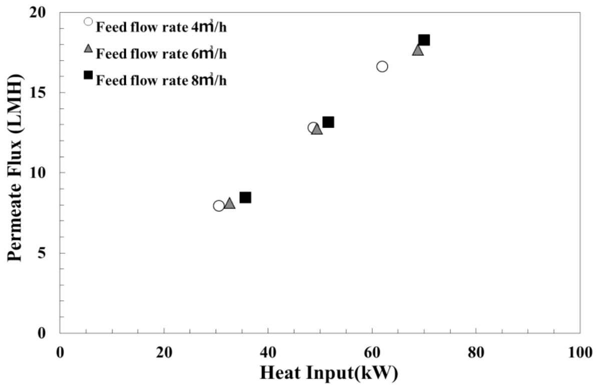

Fig. 5. Permeate flux according to heat input.

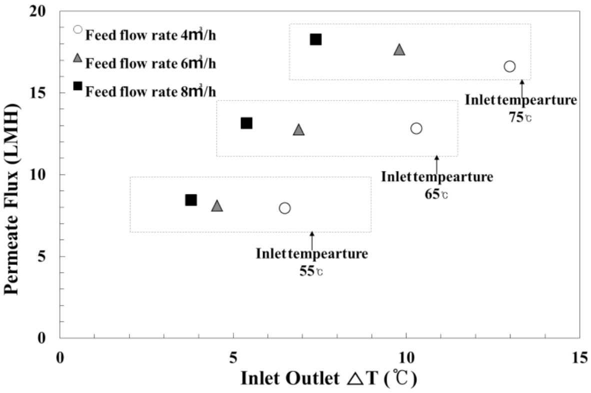

Fig. 6. Permeate flux according to temperature difference between inlet and outlet.

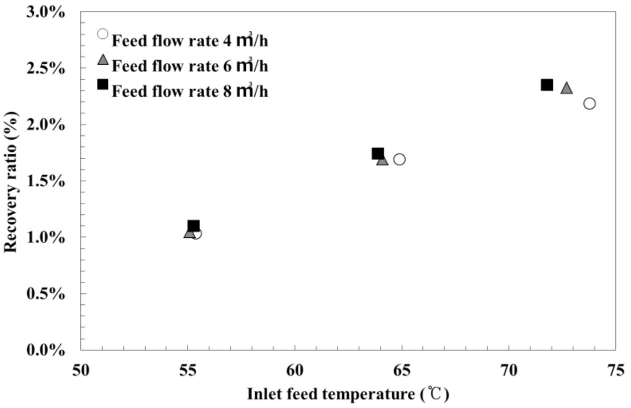

Fig. 7. Recovery ratio according to feedwater conditions.

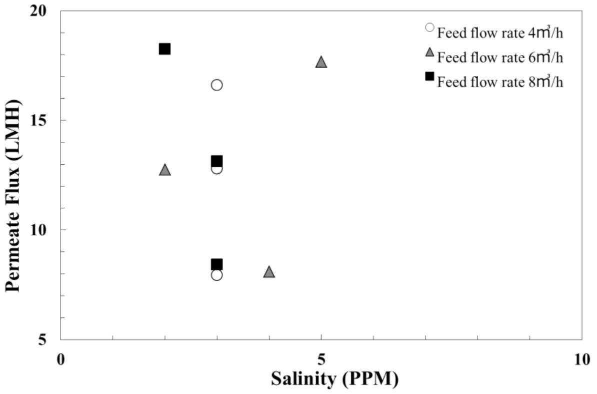

Fig. 8. Salinity of permeate flux.

35,000 ppm, feedwater temperature of 55°C, and feedwater flow rate of 4 m^3/h. Under a constant temperature of the feedwater fed to the VMD module, it appeared that the RR value slightly increased as the flow rate of feedwater increased. As previously described, this was because the permeate flux increased due to reduced temperature and concentration polarization of the membrane, as the flow rate of feedwater increased under the same conditions as well as the high permeate flux increase rate compared with the increase rate of the feedwater flow rate [17].

Fig. 8 shows salinity and LMH values of the permeate flux produced under each set of experimental conditions. For Econity's VMD module used in this study, the salinity of the permeate flux produced under each set of experimental conditions was measured within 5 ppm under all experimental conditions regardless of each feedwater condition.

Fig. 9 illustrates LMH values and PR values (i.e., coefficients of thermal performance of the VMD module with respect to the temperature condition of feedwater fed to the VMD module). For Econity's VMD module used in this study, it appeared that the permeate flux increased in proportion to the increase of feedwater fed to the VMD module. It appeared that the LMH value of the permeate flux increased up to 55% or more if the temperature of the feedwater was increased by 10°C with the flow rate kept the same. In addition, the PR value, which is the coefficient of thermal performance of the VMD module, was up to 0.904 under the conditions of 8 m^3/h for the feedwater flow rate and 75°C for the temperature, and the minimum was 0.82 at a feedwater flow rate of 4 m^3/h and temperature of 55°C. From the results of these experiments, it was considered that setting a high temperature and flow rate of feedwater fed to the VMD module would be relatively advantageous for efficient operation of the desalination system using the VMD in terms of thermal energy consumption [18].

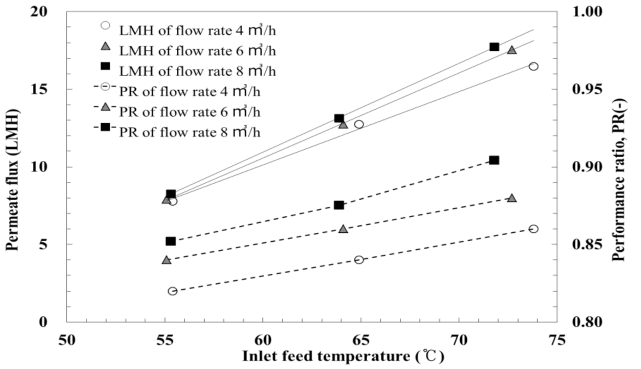

Fig. 9. Permeate flux and performance ratio according to feedwater conditions.

4. Conclusion

To study the characteristics of freshwater production by VMD module with respect to the feed conditions of the fed seawater prior to construction of a VMD desalination demonstration plant with a capacity of 400 m^3/d and commercialization of a VMD module, a laboratory-scale experimental VMD module was constructed. PVDF hollow-fiber membranes were used to design and build the VMD module with a capacity of 2 m^3/d, and the module's thermal performance and permeate flux were analyzed with respect to the feed conditions of the fed seawater.

- In the case of the VMD module designed and built for this study, it appeared that the LMH value of the permeate flux increased up to 55% or more if the temperature of the feedwater was increased by 10°C with the same feedwater flow rate. In addition, it appeared that the desalination rate of the permeate flux produced under each set of experimental conditions was consistently maintained at 99.99% or more.
- In the case of the VMD module used in this study, it appeared that the RR value slightly increased as the flow rate increased with the temperature of the feedwater kept constant, and the RR value increased as the temperature of the feedwater increased.
- For the VMD module used in this study, it appeared that the PR value (coefficient of thermal performance of the VMD module) reached a maximum of 0.904 with feedwater at 75°C and a flow rate of 8 m^3/h, and a minimum of 0.82 with feedwater at 55°C and a flow rate of 4 m^3/h. As the temperature and flow rate of the feedwater increased, the PR value of the VMD module increased. It was therefore considered advantageous for the efficiency of the VMD system to set a high temperature and flow rate of the feedwater.

Acknowledgment

This research was supported by a grant (code 13IFIP-B065893-04) from Industrial Facilities and Infrastructure Research Program funded by Ministry of Land, Infrastructure and Transport of Korean Government.

Symbols

A — Area, m^2
C_p — Specific heat, kJ/kg °C
LMH — Litter per meter square hour, Permeate flux, kg/m^2·h
Δh_v — Latent heat, kJ/kg
$\dot{m}$ — Flow rate, kg/s
PR — Performance ratio
Q — Heating capacity, kW
RR — Recovery ratio
T — Temperature, °C

Subscript

dist — Distillate
feed — Feed seawater
m — Membrane
in — Inlet
out — Outlet

References

[1] I.C. Escobar, A. Shafter, Sustainable Water for the Future: Water Recycling Versus Desalination, Sustainability Science and Engineering, Vol. 2, Elsevier, The Netherlands 2009, p. 444.
[2] E. Curcio, E. Drioli, Membrane distillation and related operations—a review, Sep. Purif. Rev., 34 (2005) 35–86.
[3] A. Alkhudhiri, N. Darwish, N. Hial, Membrane distillation: a comprehensive review, Desalination, 287 (2012) 2–18.
[4] K.W. Lawson, D.R. Lloyd, Membrane distillation, J. Membr. Sci., 124 (1997) 1–25.
[5] M.A.E.R. Abu-Zeid, Y. Zhang, H. Dong, L. Zhang, H.L. Chen, L. Hou, A comprehensive review of vacuum membrane distillation technique, Desalination, 356 (2015) 1–14.
[6] M.S. El-Bourawi, Z. Ding, R. Ma, M. Khayet, A framework for better understanding membrane distillation separation process, J. Membr. Sci., 285 (2006) 4–29.
[7] H.J. Joo, H.Y. Kwak, Experimental evaluation for the freshwater production characteristics according to the salinity conditions of vacuum membrane distillation module, Desal. Wat. Treat., 57 (2016) 10005–10011.
[8] H.J. Joo, H.Y. Kwak, Freshwater production characteristics of vacuum membrane distillation module for seawater desalination using a solar thermal system by seawater feed conditions, Desal. Wat. Treat., 57 (2016) 24645–24653.
[9] R. Sarbatly, C.K. Chiam, Evaluation of geothermal energy in desalination by vacuum membrane distillation, Appl. Energy, 112 (2013) 737–746.
[10] E. Guillén-Burrieza, G. Zaragoza, S. Miralles-Cuevas, J. Blanco, Experimental evaluation of two pilot-scale membrane distillation modules used for solar desalination, J. Membr. Sci., 409 (2012) 264–275.
[11] F. Banat, N. Jwaied, M. Rommel, J. Koschikowski, M. Wieghaus, Performance evaluation of the "large SMADES" autonomous desalination solar-driven membrane distillation plant in Aqaba, Jordan, Desalination, 217 (2007) 17–28.
[12] J. Koschikowski, M. Wieghaus, M. Rommel, Solar thermal-driven desalination plants based on membrane distillation, Desalination, 156 (2003) 295–304.
[13] M.H. Sharqawy, J.H. Lienhard, S.M. Zubair, Thermophysical properties of seawater: a review of existing correlations and data, Desal. Wat. Treat., 16 (2013) 354–380.
[14] S. Minglue, M.M. Teoh, K.Y. Wang, J. Su., T.S. Chung, Effect of inner-layer thermal conductivity on flux enhancement of dual-layer hollow fiber membranes in direct contact membrane distillation, J. Membr. Sci., 364 (2010) 278–289.
[15] E. Guillén-Burrieza, J. Blanco, G. Zaragoza, D.C. Alarcón, P. Palenzuela, M. Ibarra, W. Ibarra, Experimental analysis of an air gap membrane distillation solar desalination pilot system, J. Membr. Sci., 379 (2011) 386–396.
[16] A.S. Alsaadi, L. Francis, G.L. Amy, N. Ghaffour, Experimental and theoretical analyses of temperature polarization effect in vacuum membrane distillation, J. Membr. Sci., 471 (2014) 138–148.
[17] C.K. Chiam, R. Sarbatly, Vacuum membrane distillation processes for aqueous solution treatment—a review, Chem. Eng. Process. Process Intensif., 74 (2013) 27–54.
[18] J.G. Lee, W.S. Kim, J.S. Choi, N. Ghaffour, Y.D. Kim, A novel multi-stage direct contact membrane distillation module: design, experimental and theoretical approaches, Water Res., 107 (2016) 47–56.