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Utilization of solar energy for direct contact membrane distillation process: An experimental study for desalination of real seawater

Nallasamy Palanisami, Ke He, and Il Shik Moon†

Department of Chemical Engineering, Sunchon National University, 315, Maegok Dong, Suncheon, Chonnam 540-742, Korea
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Abstract−Membrane distillation (MD), a non-isothermal membrane separation process, is based on the phenomenon that pure water in its vapor state can be extracted from aqueous solutions by passing vapor through a hydrophobic microporous membrane when a temperature difference is established across it. We used three commercially available hydrophobic microporous membranes (C02, C07 and C12; based on the pore size 0.2, 0.7 and 1.2 μm respectively) for desalination via direct contact MD (DCMD). The effects of operating parameters on permeation flux were studied. In addition, the desalination of seawater by solar assisted DCMD process was experimentally investigated. First, using solar power only short-term (one day), successful desalination of real seawater was achieved without temperature control under the following conditions: feed inlet temperature 65.0 °C, permeate inlet temperature 25.0 °C, and a flow rate of 2.5 L/min. The developed system also worked well in the long-term (150 days) for seawater desalination using both solar and electric power. Long-term test flux was reduced from 28.48 to only 26.50 L/m^{2}hr, indicating system feasibility.

Keywords: Direct Contact Membrane Distillation, Solar Energy, Permeation Flux, Salt Rejection

INTRODUCTION

Potable water supply is expected to be a major worldwide challenge in the near future. However, fresh water constitutes only about 0.8% of all water sources on the earth's surface. Fortunately, seawater is an abundant and nearly inexhaustible resource that covers three quarters of the earth's surface. The main drawback, however, is the high salinity. Thus, desalination has become an important means of potable water supply and emerging research area.

Desalination systems can be divided by energy sources into those that use a conventional source of energy and those powered by renewable energy sources (wind, solar, etc.). The most important desalination technologies are: phase-change and membrane processes, such as, multi-effect distillation (MED), multistage flash (MSF), vapor compression (VC), freezing, humidification/dehumidification, solar stills, membrane distillation (MD), reverse osmosis (RO), and electro-dialysis (ED). The factors that primarily affect produced water costs are salinity of the feed stream, plant capacity, site conditions, labor, energy costs, and amortization [1]. In particular, unit product costs are highly dependent on plant capacity, for example, higher capacity leads to higher space demands and increases fixed costs, which makes this approach unsuitable for domestic use. Some important devices depend on fossil fuels, nuclear energy, or electricity to generate the heat required to produce vapor or to power high-pressure pumps. However, these non-renewable energy sources will possibly be consumed within the next few decades [2]. Whether or not fossil fuel sources run out or not, alternative energy sources are likely to be used to reduce environmental pollution, and solar energy is the most promising substitute for fossil fuels. Presently, solar energy is converted into electricity and heat using photovoltaics (PV) and solar thermal collectors, respectively. Furthermore, these two power sources are suitable for driving small-scale desalination processes, such as, RO [3], ED [4], MD [5,6] and solar stills [7]. For phase-change desalination, solar thermal technologies are more significant than solar electricity technologies. In general, phase-change desalination provides high quality condensate and solar thermal desalination is feasible for producing high purity water for domestic use.

Membrane technology is an emerging technology. The benefits of membrane technology in desalination processes can be summarized [8] as follows: (1) separation can be carried out continuously, (2) membrane processes can easily be combined with other separation processes (hybrid strategies), (3) separation can be carried out under mild conditions, (4) up-scaling is straightforward, and (5) membrane properties are variable and can be adjusted. Membrane distillation (MD) is a phase-change process that permits vapor transport to pass through a non-wettable porous hydrophobic membrane. Direct contact membrane distillation (DCMD) is a type of membrane distillation process in which liquid feed and liquid permeate solution are always in direct contact with the membrane surface. It uses hydrophobic microporous membranes, and therefore, only water vapor and volatile components transport through the membrane pores, while non-volatile components remain in the feed solution. The non-wettability property of hydrophobic membrane prevents liquid penetration of feed solution into membrane pores. DCMD is a thermally driven separation process that operates on the principle of vapor-liquid equilibrium (VLE) conditions, and it is characterized by simultaneous heat and mass transfer [9]. Reverse osmosis is the most attractive process for producing fresh water from brackish water or seawater, but it requires more power and membrane pretreatment [10] and suffers from serious flux decay on increasing solute concentration than conventional MD [11,12]. DCMD has a number of potential advantages over conventional desalination process, includ-

†To whom correspondence should be addressed.
E-mail: ismoon@sunchon.ac.kr

ing (1) nearly 100% salt rejection, (2) lower operation pressure and temperature, and (3) reduced vapor space compared to conventional processes resulting in low mass-transfer resistance between the liquid and condensate phases [13]. In addition, MD desalination is suitable for high capacity water production and has been used to achieve outputs of 41-79 (kg/(m^{2}h)) when optimum designs are used [14]. Several excellent researchers have been conducted on MD processes involving the applications, advantages, transport mechanism and product cost estimation [15-23]. Thus, MD is potentially useful for seawater desalination, especially in combination with a renewable energy source. Nevertheless, pretreatment devices, hybrid strategies, process design, and new membrane manufacturing technologies are needed for long-term and efficient operation.

In our previous study, we described some basic work on air gap membrane distillation (AGMD) and direct contact membrane distillation (DCMD) processes, such as on the effect of operating parameters and membrane types on an AGMD system [24,26], long-term fouling of a DCMD system [24], and the effect of module dimensions on membrane flux [27]. Nonetheless, reducing energy consumption is a major challenge for MD desalination, as this has been estimated to be >40 kWh/m^3, which prohibitively increases product costs [28-34]. On the other hand, MD only requires a moderate temperature to generate the thermal driving force across the membrane, which makes amenable the use of solar energy [35-40].

In the present study, a solar assisted DCMD system was constructed to desalinate seawater. The solar energy was collected using a solar water heater to provide the heat required for the process. There is no reported example in the literature for membrane desalination for the long term (150 days) in real sea water by using solar energy as a heating source. In this study, three different types of PTFE membranes were compared with respect to membrane liquid entry pressure (LEP), contact angle (CA), pore diameter, effective porosity, and pore size distribution. For short-term operation (1 day), only solar energy was used as the heating source. The system inlet temperature for different weather conditions and MD performance were tested. The solar energy assisted DCMD system was operated continuously for more than 150 days using real seawater to examine fouling.

Table 1. Membrane details

Membrane	C02	C07	C12
Material	PTFE	PTFE	PTFE
Price ($/m^2)	16	16	16
Pore size (μm)	0.2	0.7	1.2
Thickness (μm)	120	120	110
Porosity (%)	88	88	88

EXPERIMENTAL METHODS

1. Membranes and Analysis Method

Three different pore sized polytetrafluoroethylene (PTFE) membranes were obtained from the Ningbo Changqi Porous Membrane Co. (Ningbo, China); material pore size and thickness were provided by the manufacturer and are listed in Table 1. Using a 20% NaCl solution, we measured the LEP values of the three membranes [41]. Membrane surface contact angles were measured with an SV Sigma 701 tension-meter (KSV Instruments Ltd., Helsinki) [42]. A gas permeability test was used to confirm average pore size of all three membranes [43].

2. Solar Assisted DCMD Setup

The solar-assisted DCMD experimental setup is schematically depicted in Fig. 1. The inlet and outlet temperatures and pressures of the hot and cold sides were monitored continually and recorded electronically. The volume of the permeated side was measured continually with an electric balance. Purities of extracted water were determined by an electrical conductivity meter (EC470-L, ISTEK, South Korea). Heat energy of the system was obtained from a solar and an electrical heater. For operation 1, only solar energy was used and tap water was used for cooling. System inlet temperature changed

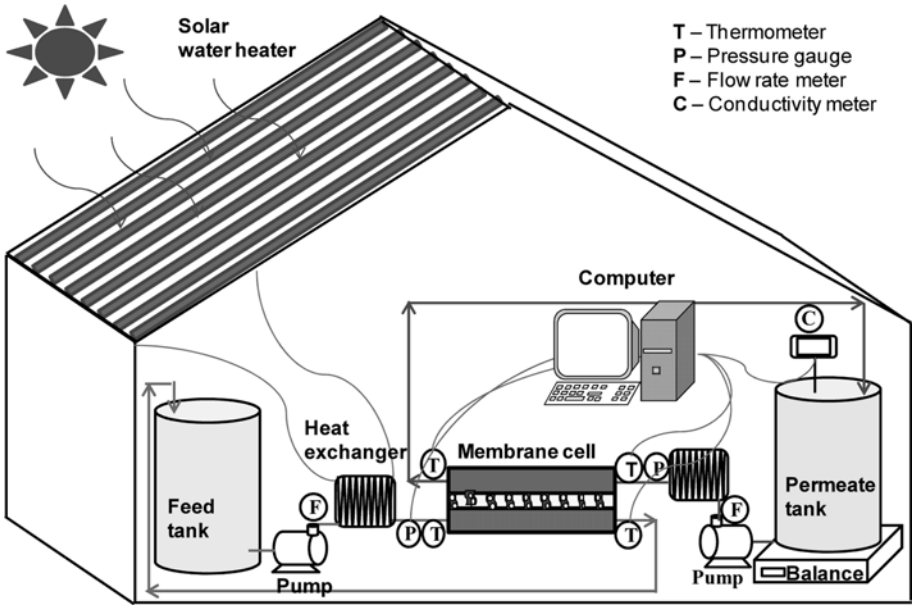

Fig. 1. Diagram of the DCMD with a solar heating system.

Table 2. Membrane characteristics

Membrane	C02	C07	C12
LEP (kPa)	125.5±5	100.3±5	70.4±5
[a]Pore size (μm)	0.40±0.1	0.73±0.1	1.05±0.1
[b]Pore size (μm)	0.41±0.1	0.68±0.1	1.15±0.1
[b]Effective porosity (m^{-1})	4.21×10^3	4.09×10^3	2.98×10^3

[a]From capillary flow porometer test
[b]From gas permeability test

with variation of weather conditions. This operation was used in short-term testing. For operation 2, solar and electric energy were used for heating, and the system inlet temperature was controlled at set values. This operation was used for operation parameter testing over 150 days of continuous running. The solar heater had an effective heat accepting area of 4.7 m^2. A titanium heat exchanger was used to overcome the problems associated with seawater corrosion.

RESULTS AND DISCUSSION

1. Membrane Characterization

Some characteristics of the three membranes were tested and the results are shown in Table 2. The LEP values decreased with increasing pore size. The C02 membrane was more hydrophobic with an LEP of 125.5±5 kPa than the C07 (100.3±5 kPa) and C12 membranes (70.4±5 kPa). Gas permeability test results provided estimated mean pore diameter ($2\cdot r$) values for the C02, C07, and C12 membranes of 0.41, 0.68 and 1.15 μm, respectively, and effective porosities, $\varepsilon/\tau\cdot\delta$, ranged from 2,980-4,210 m^{-1}. The pore sizes from the capillary flow porometer test were similar to the values from the gas permeability test.

2. Comparison of Three Types of Membrane on Flux and Salt Rejection

Fig. 2 shows the permeate flux (a) and salt rejection (b) for different membranes under the following conditions: hot side inlet temperature, 60 °C; cold side inlet temperature, 20 °C. The C12 membrane showed higher permeation flux than the other two membranes. On the other hand, the salt rejection decreased frequently under high flow rate conditions as shown in Fig. 2(b). The C02 and C07 membranes showed high hydrophobicity, which showed almost 100% salt rejection. The C07 membrane was more competitive for the MD process with a high permeation flux and high hydrophobicity and was used in subsequent studies.

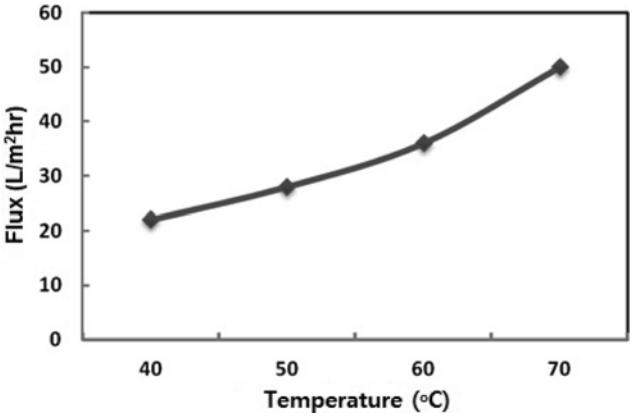

Fig. 3. Effect of the hot side inlet temperature on the flux at 4.5 L/min for C07 membrane.

3. The Effect of Feed Temperature and Flow Rate

Fig. 3 shows the effect of feed temperature (T_h) on permeate flux. The results show that the higher the feed temperature, the greater the permeate flux was achieved. It can be explained by the well-known Antoine equation which expresses the relationship between the liquid temperature (T_h) and the corresponding equilibrium vapor pressure (the driving force for MD process). In other words, higher feed temperature leads to higher vapor pressure, which provides further permeate flux. This finding was also in accordance with previous studies [44]. A feed temperature of 65.0 °C was considered optimal for sea water desalination.

Unlike other membrane processes, the MD process is less sensitive to fouling, in which precipitation of the less soluble constituents

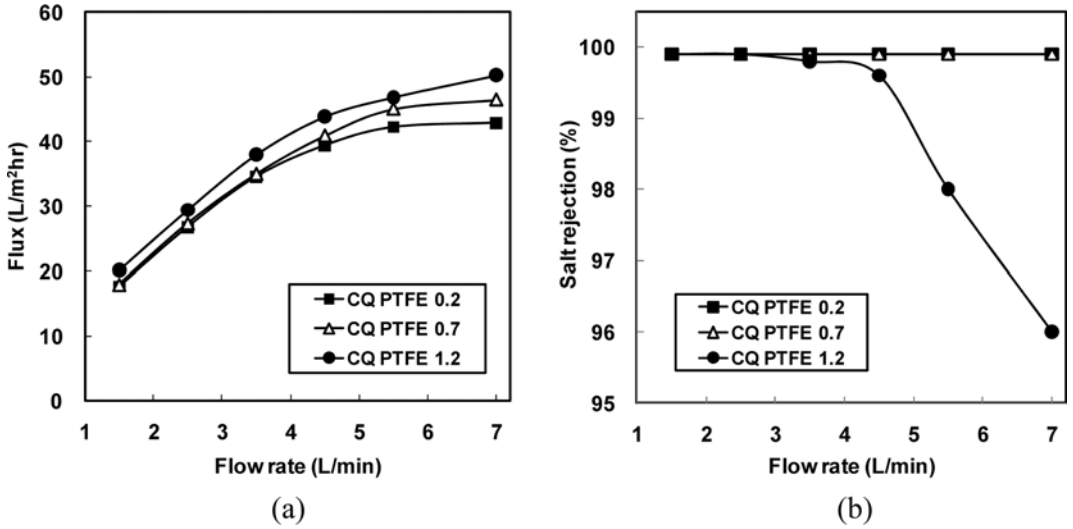

Fig. 2. Comparison of the permeate fluxes (a) and salt rejection rates (b) of different membranes (Hot side inlet temperature is 60 °C; cold side inlet temperature is 20 °C).

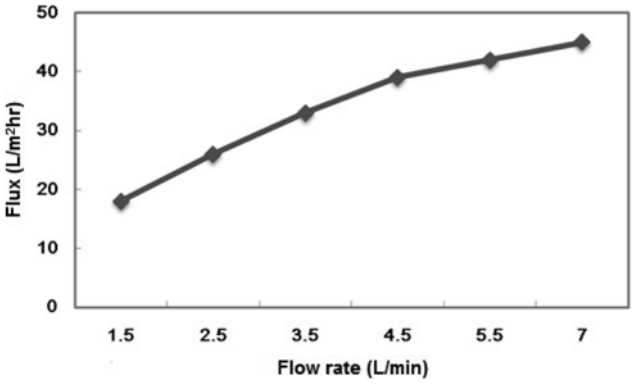

Fig. 4. Effect of flow rate on the flux at 60.0 °C for the C07 membrane.

in the operating condition on the membrane surface causes a reduction in the permeate flux [11]. Moreover, as vaporization takes place in the membrane-feed interface, both concentration and temperature polarizations exist [45]. One way to overcome these unfavorable effects is to increase the turbulence in the feed channel at the hot side of the membrane module. Therefore, the feed flow rate in the hot side is considered as an important operating variable in the range of 1.50-4.5 L/min. The results obtained are presented in Fig. 4. The results show that the increase in the feed flow rate led to an increase in the permeate flux, which is in agreement with previous literature [46]. The optimum feed flow rate of 2.5 L/min was selected for subsequent work on sea water desalination.

4. Economic Analysis and Energy Consumptions

Economic analysis of this solar-DCMD system was performed under the following assumptions: (1) system life of 20 years, (2) membrane life of 5 years, (3) system availability of 90%, and (4) operation and maintenance costs are not considered. Water production costs (WPC) were calculated using membrane module, heat exchanger, solar heater capital, and installation costs and electricity requirements for pumping.

Gained output ratio (GOR), which is used to assess the performance of solar desalination processes, is the latent heat of evaporation per unit mass of product divided by the amount of energy required by the desalination system per unit mass of product. The parameters for energy consumption for the DCMD system under various conditions are listed in Table 3. The evaporation efficiencies were found in the range of 46.8% to 74.4%. The heating energy consumption was in the range of 3224 kJ/L to 5160 kJ/L, and GOR values were from 0.44 to 0.70. The maximum evaporation efficiency and heating energy consumption results agreed with the GOR results under the following conditions: feed and permeate temperature is 60.0 °C, 20.0 °C, respectively, with flow rate 4.5 L/min. When performance increases with GOR ratio, the economic cost will decrease. In the present study, MD water production required 1.9-3.0 kg/MJ, which is lower than the 1.7-6.4 kg/MJ obtained by multi-effect distillation (MED) and the 5.17 kg/MJ achieved by multi-stage flash distillation (MSF) [47,48].

5. Short Term Performance-DCMD System (Operation 1)

To identify suitable conditions for a long-term desalination DCMD process, a short-term experiment was conducted with the solar-assisted DCMD system. Insolation is a measure of the solar radiation energy received on a given surface area over a given time. South Korea has near ideal solar insolation as reported by Dok-Ki [49]. For example, on 07/02/2012, a sunny day in Sunchon (Latitude: 34°57'00"N, Longitude: 127°29'24"E), sunrise was at 05:26 and sunset at 19:45. Fig. 5 shows dynamic behavior (a) and seawater desalination performance (b) for short term using C07 membrane. The system started operation at 8:00 AM. The maximum feed inlet temperature reached around 61.0 °C from 11:00 AM to 3:00 PM. At the same time the maximum of seawater distillation production reached 28.27 L/m²hr.

The weather plays an important role during solar energy harnessing. We also tested the solar-DCMD system on rainy and cloudy days during the summer rainy season (June and July). Fig. 6 shows the system inlet temperature for sunny (a) and rainy/cloudy (b) days. During sunny days, use of the solar heater delivered energy enough to maintain a feed water temperature of 60 to 70.0 °C, that is, the temperature required for the membrane distillation process. On rainy and cloudy days, the feed inlet temperatures decreased and depended on the previous day's weather, that is, the energy remaining in the solar heater. Weather conditions did not greatly attenuate cold side inlet temperatures, which remained at 24 to 26.0 °C. Through the experimental results, the feed and cold side inlet temperature can

Table 3. Energy consumption for the DCMD system under different operating conditions

Flow rate (L/min)	Feed temp. (°C)	Permeate temp. (°C)	Flux (L/m²hr)	Evaporation efficiency (%)	Heating energy (KJ/L)	GOR
Variation of the feed and permeate flow rates						
1.5	60	20	17.5	60.9	3942	0.62
2.5	60	20	27.0	68.8	3486	0.65
3.5	60	20	34.1	69.8	3435	0.66
4.5	60	20	40.9	74.4	3224	0.70
5.5	60	20	45.0	67.0	3579	0.63
7	60	20	45.0	63.4	3784	0.59
Variation of the feed side inlet temperature						
4.5	40	20	14.7	46.8	5160	0.44
4.5	50	20	23.5	49.9	4808	0.51
4.5	60	20	40.9	74.4	3224	0.70
4.5	70	20	51.8	73.2	3306	0.62

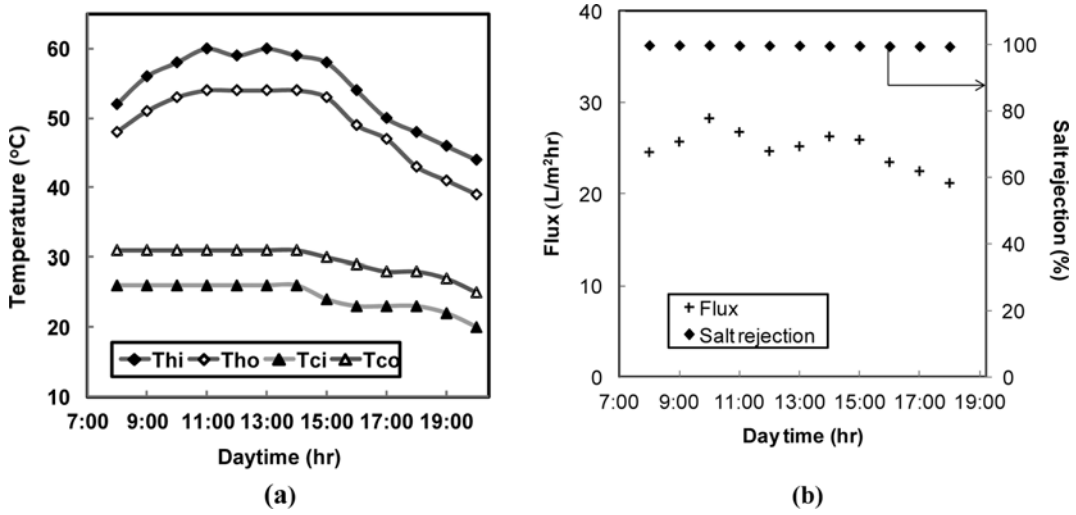

Fig. 5. Investigations on the dynamic behavior (a) and seawater desalination performance (b) during one day at Suncheon, South Korea, 07/02/2012 (Hot and cold side flow rates were 4.5 L/min, C07 membrane, operation 1).

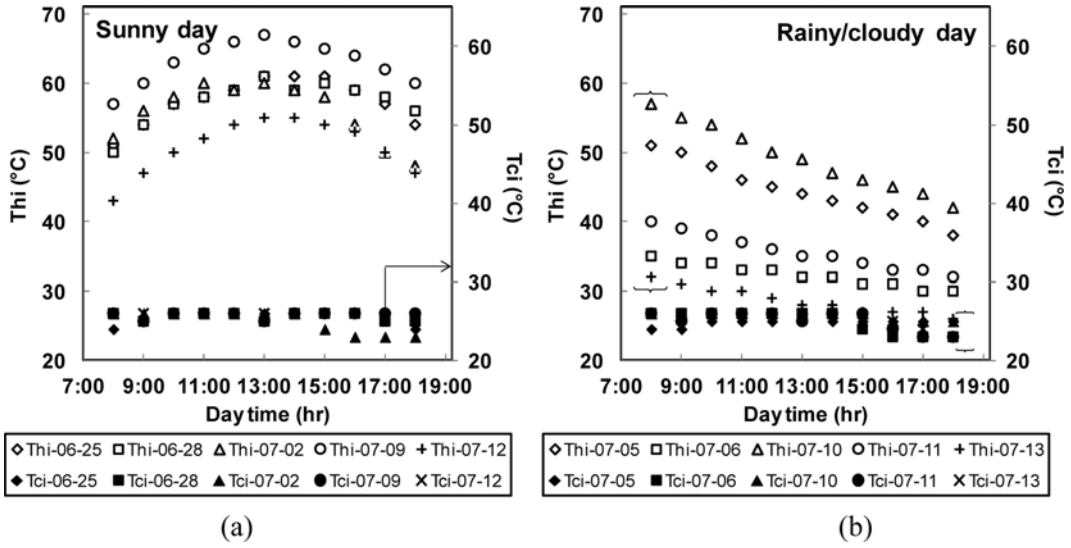

Fig. 6. System inlet temperature variation with time for different sunny (a) and rainy/cloudy (b) days (Hot and cold side flow rate of 4.5 L/min, operation 1).

be expressed by the equations with the variation of time as:

$$Thi = -0.303t^2 + 8.548t + 1.158$$

$$Tci = -0.028t^2 + 0.642t + 22.501$$

where t is the time within one day.

6. Long-term Performance (Operation 2): Membrane Fouling

Due to its high permeation flux and hydrophobicity, the C07 membrane was selected for the long term during operation 2 (08/01/2010-01/23/2011) to investigate membrane long-term performance during seawater desalination. Based on the short-term experimental results the operating temperatures for the feed and permeate streams were set at 65 °C and 25 °C, respectively, and feed and permeate flow rates were set at 2.5 L/min. Fig. 7 shows permeation flux and salt rejection percentage as a function of time using real seawater. After 150 days, the permeate flux decreased from 28.48 to 26.50 L/m²hr. In addition, membrane salt rejection was >99.8% after 150 days, without any chemical cleaning process. By comparison of these results with our previous studies [26], the effect of the fouling layer was dependent on the operating conditions. In particular, feed temperature and feed flow rate were found to significantly influence flux reduction. In our previous study, the permeate flux dropped from 23.76 L/m² h to 14.36 L/m² h over one month at the following conditions: hot side inlet temperature of 60 °C, cold side inlet temperature of 20 °C, and hot and cold side flow rate of 0.6 L/min for PTFE pore size 0.22 μm membranes. Consequently, more particles were retained at the membrane surface in the previous study. Therefore, the fouling effect under low temperature and low flow rate conditions was greater [26]. Unlike the previous reports, it can be a future promising alternative for water desalination with sustainable manner.

Table 4 lists insolation values for different months at one location in South Korea and its energy requirements for solar and electrical energy by month for the present module. During the year, December and January had the lowest average insolation values. Even so, more than 75.1% of total energy requirement was supplied by

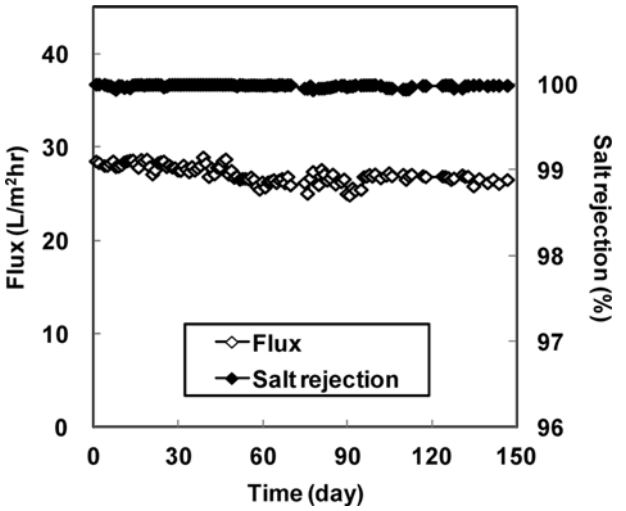

Fig. 7. Permeation flux and salt rejection rate as functions of time for seawater desalination over 150 day (Hot side inlet temp. of 65.0 °C, cold side inlet temp. of 25.0 °C, flow rates in both sides were 2.5 L/min, operation 2).

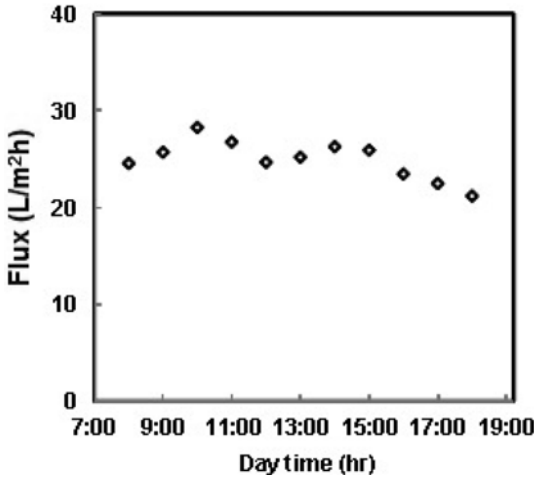

Fig. 8. Effect of time on flux during operation 1 (C07 membrane, hot and cold side flow rates were both 4.5 L/min, experimental results obtained on 07/02/2012).

solar energy during the daytime. In particular, in September, 95.3% of energy requirement was supplied by solar energy. We predicted that from March to June, 100% of the energy requirement could be supplied by the solar heater during daytime (average insolation values for March: 4.60 KWh/m^2/day, April: 5.03 KWh/m^2/day May: 4.69 KWh/m^2/day, June: 4.71 KWh/m^2/day).

7. Effect of Time with Flux on Mass Transfer

The driving force for mass transfer across the membrane is the water vapor pressure difference between feed and permeate side. Fig. 8 shows the flux versus time for operation 1 (Hot and cold side flow rate 4.5 L/min) in seawater desalination. It indicates that the flux is maximum at 11.00 a.m. due to temperature reaching a maximum. Fig. 7 shows the effect of the time versus flux for operation 2, which slightly decreases after 150 days.

CONCLUSIONS

A solar energy assisted DCMD system was developed for seawater desalination. Different pore size PTFE membranes were characterized and used. The C02 membrane showed the highest LEP values but lowest permeate flux. The C12 membrane showed the highest flux, but rejection of salt percentage decreased under high flow rate conditions. Accordingly, the C07 membrane was selected for the solar-DCMD process. The weather was found to play an important role in solar energy harnessing. For operation 1, we tested the solar-DCMD system on sunny and rainy/cloudy days in the summer rainy season. Based on the experimental results obtained, we derived equations for feed and cold side inlet temperature variation with time. The solar-DCMD system was run continually for more than 150 days for the C07 membrane under operation 2, and can be a promising alternative method for future water needs in a sustainable manner. In the daytime, more than 77.3% of the heating energy was supplied by solar energy for the whole year. In particular, in September, 95.3% of the heating energy was supplied by solar energy. Taking advantage of integrating the renewable solar energy with DCMD process will be an alternative method for desalination in a sustainable manner.

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Table 4. Energy consumption of solar-DCMD system for the long-term experiments

Month	Aug.	Sep.	Oct.	Nov.	Dec.
*Insolation (kw/m^2/day)	3.85	4.22	4.23	3.34	3.28
Daytime					
Heating energy (kJ)	0.66×10^9	0.64×10^9	0.66×10^9	0.64×10^9	0.66×10^9
Energy by solar (kJ)	0.54×10^9 (81.8%)	0.61×10^9 (95.3%)	0.61×10^9 (92.4%)	0.51×10^9 (79.7%)	0.51×10^9 (77.3%)
Energy by electric (kJ)	0.10×10^9 (18%)	0.03×10^9 (4.7%)	0.05×10^9 (7.6%)	0.13×10^9 (20.3%)	0.15×10^9 (22.7%)
Night time					
Heating energy (kJ)	1.11×10^9	1.07×10^9	1.11×10^9	1.07×10^9	1.11×10^9

*Values were obtained from reference [49]

of Commerce, Industry and Energy (MOCIE) through the Regional Innovation Centre (RIC).

NOMENCLATURE

T_c : cold side temperature
T_h : hot side temperature
t : time
τ : temperature polarization coefficient
ε : membrane porosity
ξ : membrane tortuosity
δ : membrane thickness
r : membrane pore radius

REFERENCES

1. H. M. Ettouney, H. T. El-Dessouky, R. S. Faibish and P. J. Gowin, *Chem. Eng. Progr.*, **98**, 32 (2002).
2. R. A. Kerr, *Science*, **281**, 1128 (1998).
3. M. Thomson, M. S. Miranda and D. Infield, *Desalination*, **153**, 229 (2002).
4. J. M. Ortiz, E. Expósito, F. Gallud, V. García-García, V. Montiel and A. Aldaz, *J. Membr. Sci.*, **274**, 138 (2006).
5. F. Banat and N. Jwaied, *Desalination*, **230**, 27 (2008).
6. J. Koschikowski, M. Wieghaus, M. Rommel, V. S. Ortin, B. P. Suarez and J. R. B. Rodríguez, *Desalination*, **248**, 125 (2009).
7. H. E. S. Fath, *Desalination*, **116**, 45 (1998).
8. M. Mulder, *Basic principles of membrane technology*, 2nd Ed., Kluwer Academic Publishers, Netherlands (1996).
9. A. O. Imdakm and T. Matsuura, *J. Membr. Sci.*, **262**, 117 (2005).
10. L. F. Greenlee, D. F. Lawler, B. D. Freeman, B. Marrot and P. Moulin, *Water Res.*, **43**, 2317 (2009).
11. V. Calabrò, B. L. Jiao and E. Drioli, *Ind. Eng. Chem. Res.*, **33**, 1803 (1994).
12. T. Y. Cath, V. D. Adams and A. E. Childress, *J. Membr. Sci.*, **228**, 5 (2004).
13. K. W. Lawson and D. R. Lloyd, *J. Membr. Sci.*, **124**, 1 (1997).
14. B. Li and K. K. Sirkar, *Ind. Eng. Chem. Res.*, **43**, 5300 (2004).
15. M. S. El-Bourawi, Z. Ding, R. Ma and M. Khayet, *J. Membr. Sci.*, **285**, 4 (2006).
16. F. A. Banat and J. Simandl, *Sep. Sci. Technol.*, **33**, 201 (1998).
17. C. Charcosset, *Desalination*, **245**, 214 (2009).
18. A. Burgoyne and M. M. Vahdati, *Sep. Sci. Technol.*, **35**, 1257 (2000).
19. A. M. Alklaibi and N. Lior, *Desalination*, **171**, 111 (2004).
20. B. Zhu, J. H. Kim, Y.-H. Na, I. S. Moon, G. Connor, S. Maeda, G. Morris, S. Gray and M. Duke, *Membranes*, **3**, 155 (2013).
21. J. Zhang, S. Gray and J.-D. Li, *Desalination*, **323**, 142 (2013).
22. C. K. Yoo, D. S. Kim, J.-H. Cho, S. W. Choi and I.-B. Lee, *Korean J. Chem. Eng.*, **18**, 408 (2001).
23. S.-T. Hwang, *Korean J. Chem. Eng.*, **28**, 1 (2011).
24. M. Manickam, T. O. Kwon, J. W. Kim, M. Duke, S. Gray and I. S. Moon, *Desalination Water Treat.*, **13**, 362 (2010).
25. K. He, H. J. Hwang and I. S. Moon, *Korean J. Chem. Eng.*, **28**, 770 (2011).
26. K. He, H. J. Hwang, M. W. Woo and I. S. Moon, *J. Ind. Eng. Chem.*, **17**, 41 (2011).
27. H. J. Hwang, K. He, S. Gray, J. Zhang and I. S. Moon, *J. Membr. Sci.*, **371**, 90 (2011).
28. E. Curcio and E. Drioli, *Sep. Purif. Rev.*, **34**, 35 (2005).
29. S. Al-Obaidani, E. Curcio, F. Macedonio, G. Di Profio, H. Al-Hinai and E. Drioli, *J. Membr. Sci.*, **323**, 85 (2008).
30. M. Gryta and M. Tomaszewska, *J. Membr. Sci.*, **144**, 211 (1998).
31. S. A. Kalogirou, *Prog. Energy Combust. Sci.*, **30**, 231 (2004).
32. M. Khayet, M. P. Godino and J. I. Mengual, *Int. J. Nuclear Desalination*, **1**, 30 (2003).
33. L. Martínez-Díez, F. J. Florido-Díaz and M. I. Vázquez-González, *Desalination*, **126**, 193 (1999).
34. S. A. Avlonitis, K. Kouroumbas and N. Vlachakis, *Desalination*, **157**, 151 (2003).
35. L. M. Camacho, L. Dumée, J. Zhang, J.-d. Li, M. Duke, J. Gomez and S. Gray, *Water*, **5**, 94 (2013).
36. K. W. Lawson and D. R. Lloyd, *J. Membr. Sci.*, **124**, 1 (1997).
37. F. Banat, R. Jumah and M. Garaibeh, *Renew. Energy*, **25**, 293 (2002).
38. P. A. Hogan, F. A. G. Sudjito and G. L. Morrison, *Desalination*, **81**, 81 (1991).
39. T.-C. Chen and C-D. Ho, *J. Membr. Sci.*, **358**, 122 (2010).
40. J. B. Gálveza, L. García-Rodríguezb and I. Martín-Mateosc, *Desalination*, **246**, 567 (2009).
41. A. S. Jonsson, R. Wimmerstedt and A. C. Harrysson, *Desalination*, **56**, 237 (1985).
42. G. L. Liu, C. Zhu, C. S. Cheung and C. W. Leung, *Heat Mass Transfer*, **34**, 329 (1998).
43. A. Fahmi, A. Al-Rub, F. Banat and K. Bani-Melhem, *Sep. Sci. Technol.*, **38**, 3645 (2003).
44. M. M. A. Shirazi, A. Kargari, M. Javad and A. Shirazi, *Desalination Water Treat.*, **49**, 368 (2012).
45. M. Khayet, *Adv. Colloid Interface Sci.*, **164**, 56 (2011).
46. A. M. Alklaibi and N. Lior, *Desalination*, **171**, 111, (2004).
47. E. Drioli, V. Calabrd and Y. Wu, *Pure Appl. Chem.*, **58**, 1657 (1986).
48. R. B. Saffarini, E. K. Summers, H. A. Arafat, J. H. Lienhard, *Desalination*, **286**, 332 (2012).
49. J. D. Kang and K. Y. Heack, *J. Korean Sol. Energy Soc.*, **27**, 11 (2007).