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Freshwater production characteristics of vacuum membrane distillation module for seawater desalination using a solar thermal system by seawater feed conditions

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ABSTRACT

In this study, the thermal performance experiment was conducted by seawater feed conditions of the VMD module prior to building the VMD module to be used in pilot plants in the capacity of 10 m^3/d for seawater desalination using the solar thermal system. For the thermal performance experiment of the VMD module, the lab-scale desalination equipment was designed and made in the capacity of 1 m^3/d and it was used to analyze changes in freshwater production by feedwater salinity, flow rate, and temperature conditions of the VMD module. By the result, it was analyzed that the VMD module used in this study required an average of 580 kWh/d heat capacity to produce 1 m^3/d of freshwater.

Keywords: Membrane distillation; Vacuum membrane distillation module; Solar thermal desalination; Solar collector area

1. Introduction

While water demand has constantly increased due to population increase and industrialization, the water volume available per person has rapidly decreased due to precipitation reduction and desertification caused by climate change. To solve such water shortage problem, certain countries facing water shortage are increasingly introducing seawater desalination plants.

However, concerns are recently being raised on the marine ecosystem impact and the environmental impact caused by brine generated from the seawater desalination process, and the greenhouse gas emission problem is on the rise as well since fossil fuels are used for the thermal energy or the electric energy required for the seawater desalination process.

Consequently, to solve such problems, studies on forms of eco-friendly seawater desalination technology are being conducted in many countries throughout the world. Among those studies, membrane distillation (hereinafter referred to as "MD") is emerging as the next generation freshwater technology that can make up for the shortcomings of existing distillation methods and the reverse osmosis method.

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The membrane distillation obtains the driving force from the temperature (vapor pressure) difference between both sides of the porous and hydrophobic separating membrane. It is the membrane separation process that can produce freshwater from seawater using the selective nature of the separating membrane that allows only the water vapor passing through it from the vapor generated at its seawater feed side. The membrane distillation is operated at a relatively low temperature compared to the existing distillation methods (MED and MSF), and theoretically, its recovery ratio (RR) factor is very high, which indicates that it is a form of freshwater technology that can reduce the brine emission problem.

In the 1980s, with the advances in membrane material technology, studies on membrane distillation related technology were active but there were few commercialization records and projects in the application field, as it lacked the economics or advantages to the existing distillation and reverse osmosis processes. However, as oil prices have risen and the brine emission problem of the existing reverse osmosis process has been intensifying, since the early 2000s, it has been newly highlighted as the eco-friendly energy conservation freshwater technology that obtains the thermal energy necessary for the membrane distillation process from the solar thermal system or the new and renewable energy. Particularly in countries with advanced desalination, studies on solar thermal membrane distillation systems are being actively conducted.

Manna et al. produced a flat plate direct contact membrane distillation (DCMD) with polyvinylidene fluoride (PVDF) material, fed the heat source required for the DCMD from the solar thermal system, and analyzed the feed temperature and flow rate effects to the freshwater production [1]. Koschikowski et al. demonstrated a small-scale standalone solar thermal MD system with a spiral and flat plate DCMD module in the PTFE material, of which the membrane area was approximately 8 m^2, and a solar collector in the area size of 5.9 m^2, and analyzed the freshwater production with respect to solar irradiance [2]. Schwantes et al. evaluated performance on a small-scale MD pilot plant using the solar thermal system and the waste heat, and studied its freshwater production characteristics with respect to insolation and waste heat feed capacity [3]. Abdallah et al. conducted a feasibility study on the solar thermal VMD system prior to demonstration of the standalone solar energy VMD system in which the solar thermal collector feeds the thermal energy to the system and the PV module supplies the electric energy required to drive the system [4]. Sarbatly et al. built a lab-scale experimental VMD system using the geothermal heat on a small scale, conducted a performance evaluation study on the VMD system that used geothermal water, and evaluated its economics compared to the existing freshwater system [5].

In this study, a lab-scale seawater desalination VMD system was built for the study on the freshwater production characteristics of the VMD module prior to building the solar thermal seawater desalination pilot plant in the capacity of 10 m^3/d using the hollow fiber membrane VMD module in the PVDF material, and analyzed the performance characteristics of the VMD module with respect to the feedwater conditions. The purpose of this study was to obtain the basic design data for the solar thermal seawater desalination pilot plant in the capacity of 10 m^3/d using the VMD module.

2. Membrane distillation process

The membrane distillation process is largely divided into four types as illustrated in Fig. 1 depending on the freshwater production method. Typically, these are DCMD where high-temperature solution directly contacts the membrane surface on one side and low-temperature solution directly contacts it on the other side; air gap membrane distillation (AGMD) where a condensing surface is installed on the low-temperature side to increase thermal efficiency and the air gap is maintained between the membrane and the condensing surface; sweep gas membrane distillation (SGMD) that uses inert gas to permeate water vapor through the membrane, moves the water vapor out of the separating membrane module, and condenses it to produce freshwater, and vacuum membrane distillation (VMD) that uses a vacuum to form pressure difference, which permeates water vapor through the membrane, and condenses it on the outside to produce freshwater. Among those, the vacuum membrane distillation (hereinafter referred to as "VMD") uses low pressure close to that of vacuum state. When seawater at the same temperature is fed, VMD is capable of producing vapor than DCMD or AGMD. It is also advantageous because it is operable at a temperature lower than other membrane distillations. However, one of its drawbacks is that additional energy is needed to maintain the vacuum.

2.1. *Seawater desalination MD system using solar thermal system*

The membrane distillation process is the thermal drive type desalination process that evaporates

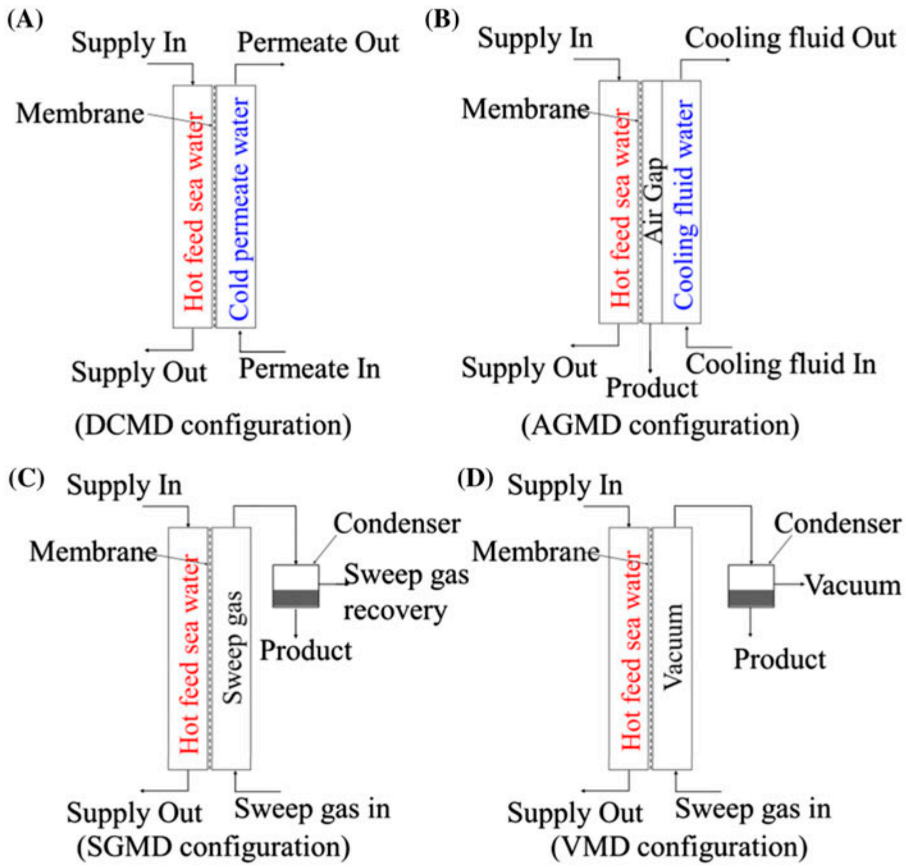

Fig. 1. Different types of membrane distillation: (A) DCMD, (B) AGMD, (C) SGMD, and (D) VMD.

seawater to generate vapor and condenses it to produce freshwater. Since the membrane distillation process evaporates seawater at a temperature lower than the existing thermal drive type desalination process such as MSF and MED, studies have been actively performed on supplying the thermal energy required to evaporate seawater from new and renewable energy sources and under or unutilized thermal energy. Among those, particularly for the solar thermal MD desalination system, pilot plants were already built in several countries at this moment and basic studies for commercialization are underway. Since the solar thermal MD system uses the solar thermal collector to collect the thermal energy required to evaporate seawater, unlike the existing thermal drive type desalination systems that use fossil energy, it can be said that it is the eco-friendly desalination technology without greenhouse gas emission. Fig. 2 illustrates the basic diagram for the solar thermal system-used seawater desalination system using the VMD module.

2.2. *Experimental equipment for vacuum membrane distillation module*

The VMD module used in this study was composed of the hollow fiber membranes in the hydrophobic and porous PVDF material. The strands form of the hollow fiber membranes in the PVDF material were inserted into a cylindrical container in the chlorinated polyvinyl chloride material which is usable at high temperatures. The vapor, which was generated when seawater passed through the membrane tube, passed through pores of the hollow fiber membranes and discharged out of the membrane. 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 the hollow fiber membranes installed in the VMD module used in this study was 5.3 m^2. Fig. 3 illustrates the diagram of the VMD module used in this study.

Considering that it was difficult to apply the actual solar thermal system to the lab-scale experimental

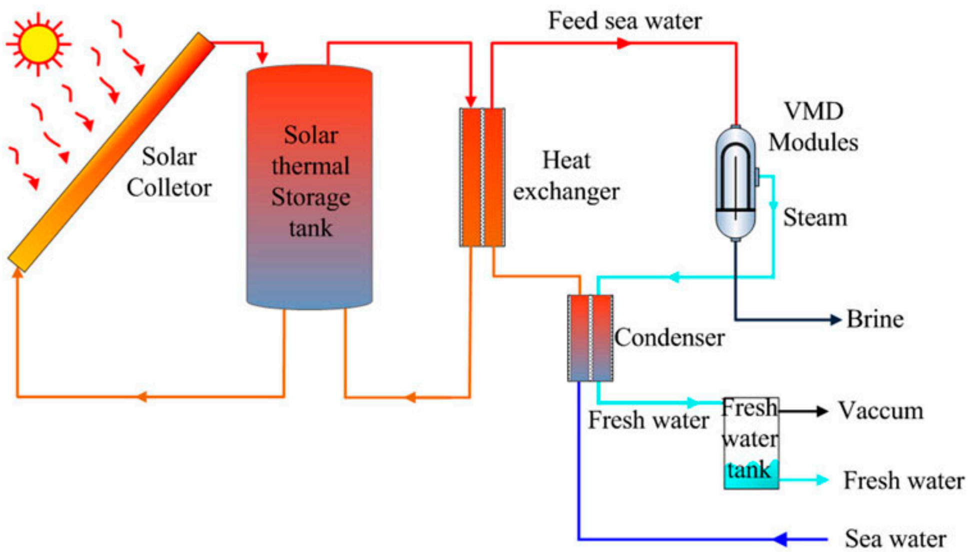

Fig. 2. Diagram for solar thermal system used VMD system.

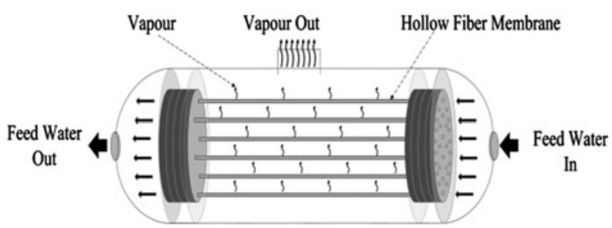

Fig. 3. VMD Module Diagram.

equipment built to derive the freshwater production characteristics of the VMD module, it was designed and produced to use an electric heater for the heat source supplying heat to the VMD module in order to heat seawater. The seawater heated by the electric heater was fed to the VMD module through the 0.2 μm MF filter. At this moment, the temperature, pressure, and flow rate of fed seawater was measured by a temperature sensor, a pressure transducer, and a flow meter, respectively. The equipment was designed to control the flow rate and the pressure by the valve and the bypass line. The seawater that passed through the VMD module was reheated by the electric heater and recollected in the seawater tank again. The vapor generated in the VMD module was condensed into freshwater as it passed through the condenser, and it was stored in the freshwater tank. The experimental equipment was designed to measure the weight and salinity of the freshwater collected in the freshwater tank in order to maintain the seawater fed into the VMD module in a constant salinity and then to return it to the seawater tank. Fig. 4 illustrates the diagram of the experimental equipment for the VMD module and Fig. 5 shows the experimental equipment.

3. Results and considerations

In designing the solar thermal VMD seawater desalination plant, the most important design point was to predict the thermal energy consumption required for the VMD process. The solar thermal system was the most expensive in the solar thermal VMD seawater desalination system. Therefore, calculation of the appropriate size and capacity of the solar thermal system would enable to determine its size in advance by predicting the amount of the thermal energy required for the VMD process. As with conventional thermal drive type seawater desalination systems, the gained output ratio (GOR) value in the dimensionless unit was used to evaluate the thermal performance of the VMD seawater desalination system as well. The GOR value could be expressed with the latent heat energy necessary to evaporate the produced freshwater and the thermal energy consumption used to actually produce freshwater, as shown in Eq. (1) [1–3,5–7].

$$\mathrm{GOR} = \frac{\dot{m}_{\mathrm{dist}} \Delta h_{\mathrm{v}}}{Q_{\mathrm{heat}}} \quad (1)$$

where $\dot{m}_{\mathrm{dist}}$ is the produced freshwater quantity, Δh_{v} is the evaporative latent heat required to evaporate 1 kg of water, and Q_{heat} is the thermal energy amount

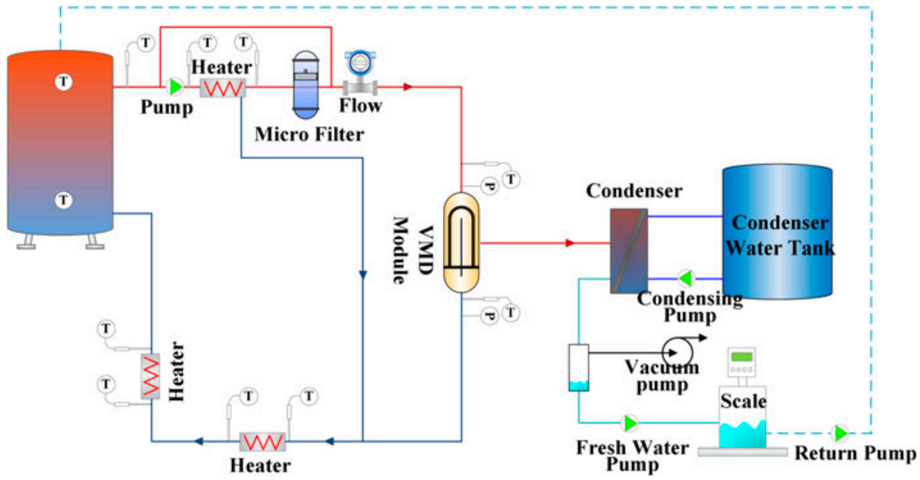

Fig. 4. Experimental equipment to test VMD performance.

Fig. 5. VMD experimental equipment.

supplied when producing freshwater. It was possible to calculate Q_{heat} with the temperature difference and the flow rate of the seawater fed into the VMD module as shown in Eq. (2).

$$Q_{heat} = \dot{m}_{feed} C_p (T_{in} - T_{out}) \quad (2)$$

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

In addition, the LMH value which, along with the GOR value, is used as one of indicators of the membrane in the VMD process was calculated in the freshwater quantity produced per membrane area, as shown in Eq. (3) [1–3,6,7].

$$\mathrm{LMH} = \frac{\dot{m}_{dist}}{A_m} \quad (3)$$

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

3.1. Freshwater production characteristics of VMD module

In order to analyze the freshwater production characteristics of the VMD module with respect to the seawater feed conditions, each experiment should be conducted under the same conditions of the external environment. Since the VMD module generated vapor as it fed seawater whose temperature was higher than the outdoor temperature, the heat loss effect had to be considered. As a result, the same outdoor temperature condition was maintained for each experiment in order to evaluate the performance. In addition, to minimize experiment errors, every error margin of the temperature, flow rate, and pressure of seawater fed into the VMD module was maintained within ±1%.

Fig. 6 shows LMH values of the VMD module with respect to the salinity, temperature, and flow rate of the feedwater. To derive values with respect to the feed temperature, the experimental conditions were chosen to 25,000, 35,000, 45,000, and 55,000 ppm based on TDS for the feedwater salinity, temperature of 55, 65, and 75℃ for the temperature and, 2, 4, 6, and 8 m^3/h for the flow rate. By the nature of the VMD module that operated in the vacuum state, the vacuum pressure in the module was constantly maintained at 15 kPa or less based on the absolute pressure.

By the experiment result, when fed under the same conditions of a 75℃ of temperature and a 8 m^3/h flow rate for the feedwater, the least salinity of 25,000 ppm showed up to 11.05 LMH and the highest salinity of 55,000 ppm showed up to 8.54 LMH, which was analyzed that the difference in the freshwater production was approximately 22% or more depending on the feedwater salinity condition.

It was because the heat capacity required to produce vapor in the VMD module increased, since the higher the feedwater salinity, the higher the boiling point was. Therefore, it appeared that the higher the feedwater salinity fed into the VMD module increased, the less the freshwater quantity was produced for the same heat capacity. Such result was consistent with preceding studies [6,7].

Fig. 7 shows LMH values with respect to the feedwater temperature difference between the inlet and outlet of the VMD module. Under the same flow rate and temperature conditions of the feedwater, the higher the salinity, the narrower the temperature difference between the inlet and outlet of the VMD module was. This is because the higher the feedwater was, the lower the feedwater conductivity, and the temperature difference between the inlet and outlet of the VMD module decreased. As a result, the heat capacity that fed to the VMD module also decreased. Among experimental conditions, it appeared that the temperature difference between the inlet and out of the VMD module was the least of 0.6℃ at a feedwater temperature of 55℃, a flow rate of 8 m^3/h, and a salinity of 55,000 ppm.

Fig. 8 shows RR values with respect to the salinity, temperature, and flow rate of the feedwater. The RR value is generally the ratio of freshwater produced by the VMD module to the feedwater quantity. For the VMD module used in this study, it appeared that the maximum RR value was 2.08% under the experimental condition of the feedwater salinity of 25,000 ppm, a feedwater temperature of 75℃, and a feedwater flow rate of 2 m^3/h, while the minimum RR value was 0.194% under the experimental condition of the feedwater salinity of 55,000 ppm, a feedwater temperature of 55℃, and a feedwater flow rate of 8 m^3/h. On the condition that the temperature of the feedwater that

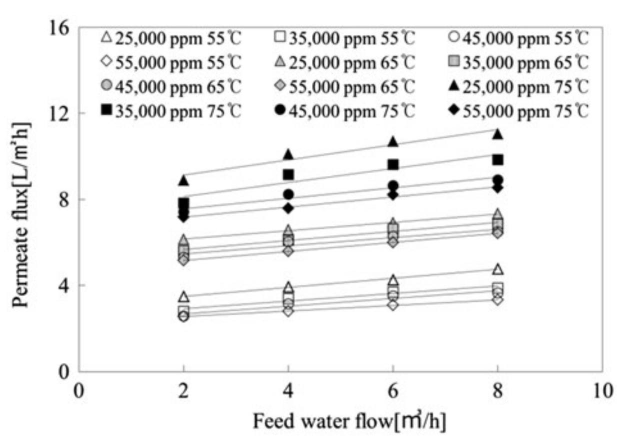

Fig. 6. LMH per feedwater flow rate conditions.

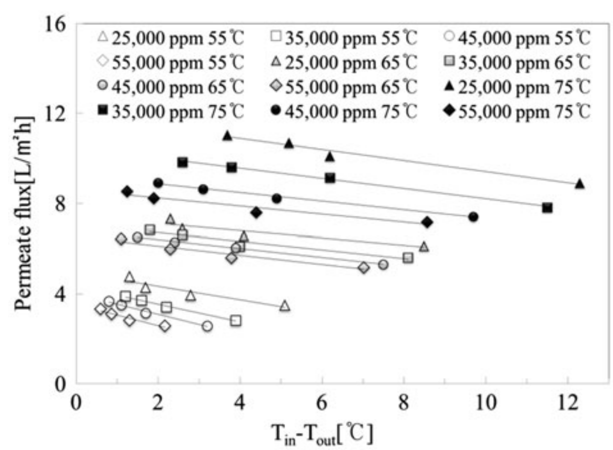

Fig. 7. Temperature difference between VMD module inlet and outlet with respect to feedwater salinity and temperature conditions.

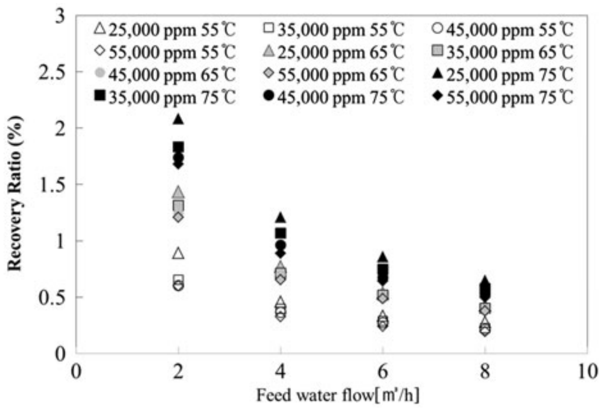

Fig. 8. RR of VMD module per feedwater conditions.

fed into the VMD module was kept constant, the higher the feedwater salinity and flow rate, the lower the RR value was. The RR value decreased because under the same condition, the higher the feedwater salinity, the less freshwater was produced as previously explained and the freshwater production increased relatively less compared to the increased feedwater flow rate.

Fig. 9 shows LMH values with respect to the heating capacity fed to the VMD module. When the VMD module used in this study was used based on the domestic seawater salinity of 35,000 ppm, it appeared that the heating capacity per hour necessary to produce 1 m^3/d of freshwater was approximately 24.2 kWh. Consequently, it appeared that the total heating capacity required to produce 1 m^3 of freshwater a day was approximately 580 kWh/d. The correlation equation of the LMH value according to the heating capacity was $y = 0.2621x + 1.2384$. At this moment, the coefficient of determination R^2 was 0.8964 which meant a relatively low error, and it was believed that it was possible to estimate the freshwater production quantity.

3.2. Calculation of solar collector area for 10 m^3/d VMD seawater desalination plant

It was possible to estimate the area of the solar thermal collector to build a solar thermal VMD seawater desalination pilot plant in the capacity of 10 m^3/d using the correlation equation for the freshwater production characteristics of the VMD module with the heating capacity derived in Section 3.1. To estimate the area of the solar thermal collector, the equation applied is generally used to calculate the efficiency of the solar thermal collector as shown in Eq. (4) [4,7].

$$\eta_c = \frac{Q_c}{I_c \times A_c} \tag{4}$$

where Q_c is the heat capacity obtained from the solar thermal collector, I_c is the insolation, A_c is the area of the solar collector, and η_c is the efficiency of the solar thermal collector.

It is possible to estimate the size of the solar thermal collector for the solar thermal VMD seawater desalination plant in the capacity of 10 m^3/d by applying the insolation, the available time of the solar thermal system, the collector efficiency and the solar fraction to Eq. (4).

Fig. 10 shows areas of the solar collector required for the solar thermal VMD seawater desalination plant in the capacity of 10 m^3/d with respect to the efficiency of the solar thermal collector and the insolation when the VMD module used in this study was

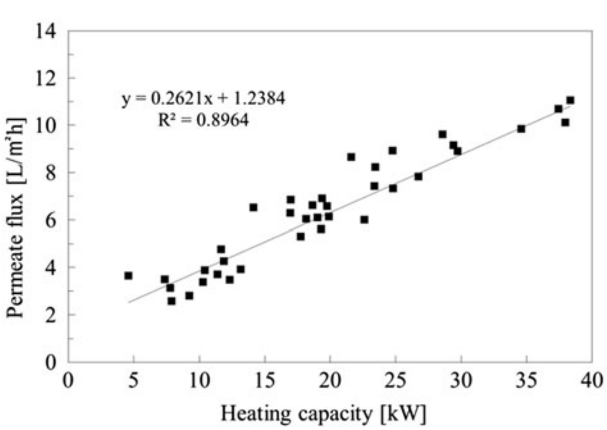

Fig. 9. LMH values of VMD module with respect to feed heat capacity.

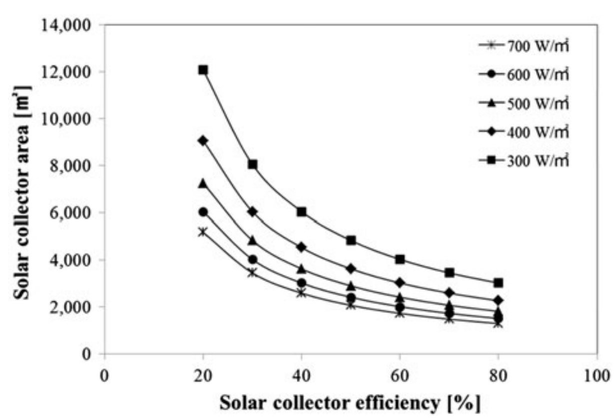

Fig. 10. Solar collector areas required for 10 m^3/d solar thermal VMD seawater desalination plant with respect to solar thermal collector efficiency and insolation.

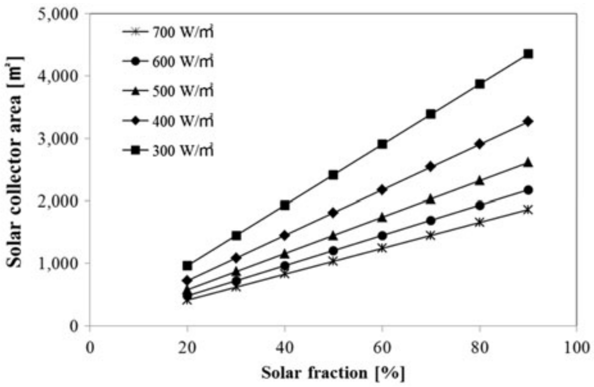

Fig. 11. Solar collector areas required for $10\,m^3/d$ solar thermal VMD seawater.

used. It can be seen that that the higher the efficiency of the collector and the insolation, the smaller the solar collector required for the desalination system, that is, the plant.

Fig. 11 shows the collector areas required for the $10\,m^3/d$ solar thermal VMD seawater desalination plant with respect to the solar fraction under the assumption that the solar thermal collector efficiency is 50%. It can be seen that the higher the solar fraction, the smaller the collector area was required. Under the assumption of the daily average insolation of 500 W/m^3, the collector efficiency of 50% and the solar fraction 50% as well as using the VMD module used in this study, it was analyzed that the solar collector area required to produce freshwater of $10\,m^3/d$ was approximately 1,450 m^3. In the solar thermal VMD seawater desalination system, the solar fraction was the factor that had the greatest effect on the economics of the seawater desalination system. Accordingly, it is planned to further conduct the evaluation study on the economics of the solar thermal VMD seawater desalination system with respect to the solar fraction.

4. Conclusion

In this study, to study the freshwater production characteristics according to the seawater feed conditions of the VMD module prior to building the VMD module used solar thermal seawater desalination plant in the capacity of $10\,m^3/d$, the lab-scale CMD system was built in the capacity of $1\,m^3/d$ and the performance characteristics of the VMD module were analyzed according to the feedwater conditions. In addition, with the analysis result on the performance characteristics of the VMD module, the solar collector area required for the solar thermal VMD seawater desalination system in the capacity of $10\,m^3/d$ was analyzed.

(1) Under the identical conditions of the freshwater flow rate and temperature, it was analyzed that the LMH value, the freshwater production quantity of the VMD module, varied by up to 22% depending on the feedwater salinity condition. In addition, under the same feedwater conditions, the higher the salinity, the smaller the temperature difference between the inlet and outlet of the VMD module, and it appeared that the heat capacity fed to the VMD module also decreased. As a result, the higher the feedwater salinity, the smaller the LMH value, the freshwater quantity produced by the VMD module, was.
(2) The higher the salinity and flow rate of seawater fed to the VMD module, the smaller the RR value was, and the higher the feedwater temperature, the greater the RR value.
(3) For the VMD module used in this study, it was analyzed that the feedwater heating capacity required to produce $1\,m^3/d$ freshwater was 580 kWh/d. Under the assumption of 500 W/m^3 for the daily average insolation, 50% for the collector efficiency, and 50% for the solar fraction, it was analyzed that approximately 1,450 m^3 was required for the solar collection area to build the solar thermal VMD desalination system in the capacity of $10\,m^3/d$.

Acknowledgment

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Nomenclature

A	—	area (m^2)
C_p	—	specific heat (kJ/kg℃)
I	—	insolation (W/m^2)
LMH	—	permeate flux (l/m^2 h)
Δh_v	—	latent heat (kJ/kg)
$\dot{m}$	—	flow rate (kg/s)
Q	—	heating capacity (kW)
T	—	temperature (℃)
η	—	efficiency (%)

Subscript

c	—	collector
dist	—	distillate
feed	—	feed seawater
m	—	membrane
in	—	inlet
out	—	outlet

References

[1] A.K. Manna, M. Sen, A.R. Martin, P. Pal, Removal of arsenic from contaminated groundwater by solar-driven membrane distillation, Environ. Pollut. 158 (2010) 805–811.

[2] J. Koschikowski, M. Wieghaus, M. Rommel, Solar thermal-driven desalination plants based on membrane distillation, Desalination 156 (2003) 295–304.

[3] R. Schwantes, A. Cipollina, F. Gross, J. Koschikowski, D. Pfeifle, M. Rolletschek, V. Subiela, Solar and waste heat driven demonstration plants for desalination, Desalination 323 (2013) 93–106.

[4] S.B. Aballah, N. Frikha, S. Gabsi, Design of an autonomous solar desalination plant using vacuum membrane distillation, the MEDINA project, Chem. Eng. Res. Des. 91 (2013) 2782–2788.

[5] R. Sarbatly, C.K. Chiam, Evaluation of geothermal energy in desalination by vacuum membrane distillation, Appl. Energy 112 (2013) 737–746.

[6] M. Su, 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.

[7] E. Guillen-Burrieza, G. Zaragoza, S. Miralles-Cuevas, J. Blanco, Experimental evaluation of two pilot-scale membrane distillation modules used for solar desalination, J. Membr. Sci. 409–410 (2012) 264-275.