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Experimental evaluation for the freshwater production characteristics according to the salinity conditions of vacuum membrane distillation module

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ABSTRACT

This study builds a lab-scale vacuum membrane distillation (VMD) system with 1 m^3/d to analyze the performance characteristics of VMD module, which has a relatively high freshwater production rate and low heating energy consumption during the membrane distillation process and experimentally evaluates freshwater production characteristics of VMD module according to temperature (55, 65, and 75℃), flow rate of (2, 4, 6, and 8 m^3/h), and salinity (25,000, 35,000, and 45,000 ppm) conditions of feed water to the system.

Keywords: Membrane distillation; Vacuum membrane distillation; Vacuum membrane distillation module

1. Introduction

The membrane distillation method which uses temperature differences as driving power and combines the characteristics of the membrane of selective membrane with distillation is able to produce freshwater with relatively low energy. With a higher recovery factor than using a reverse osmosis process, the membrane distillation method is a freshwater production technology which is able to reduce the discharge issue of the brine. The membrane distillation method is roughly segregated into 4 processes, depending on the type of module and operation. The first one is direct contract membrane distillation where the high-temperature solution contacts to membrane surface directly. The second one is air gap membrane distillation where the concentrated surface is away from the membrane surface with an air gap. The third one is sweep gas membrane distillation where the gap between the membrane and concentrated surface is made by sweep gas. And the last one is vacuum membrane distillation (VMD) which creates pressure differences using a vacuum.

The membrane distillation technology has been actively developed in 1980s and caused by the development of material technology of the membrane; however, it has not been actively commercialized and developed to the business model because the system has lower economic benefits and other advantages than the current distillation method and reverse osmosis when the current method is replaced as the membrane distillation method. However, as the price of gas and issue with brine discharge of current osmosis method have increased, the MD method has stood out for being an energy-saving, freshwater production technology, which has received the required heating

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energy from a solar energy system or new and renewable energy since the 2000s, and many studies have already been in progress in advanced countries.

Ying has taken a test to use waste heat which is produced by the vessel engine by installing a VMD system using a hollow fiber membrane on the vessel [1]. Elena has executed an environment to evaluate the use of the flat-type AGMD module of Scarab, Sweden, which supplied required energy using the solar system, the effect of supply temperature, flow rate, salinity, and energy consumption to the freshwater production [2]. Samira performed a validity study for a standalone-type solar energy VMD system, which supplies the system energy for the MD system from a solar collector and electric energy for driving from PV module [3]. Rosalam built experimental equipment of VMD system using geothermal heat and performed a study to evaluate fresh-water production quantity and economic evaluation in comparison with the current freshwater production system [4].

This study builds a lab-scale VMD system with a 1 m^3/d capacity to achieve basic design data of a solar energy, freshwater production system using a VMD module which uses lower energy among the membrane distillation methods and has a relatively high production rate, and analyzes performance characteristics of the VMD module depending on a change in temperature of supply water, flow rate, and salinity. Fig. 1 shows a schematic of VMD module.

2. Materials and methods

2.1. Experimental equipment of VMD module

Table 1 shows the specification of experimental equipment to achieve heat performance characteristics of VMD module. The VMD system in this study is designed and built with an in-house experimental system with 1 m^3/d production capacity. The VMD module in this study uses polyvinylidene fluoride (PVDF) hollow fiber membranes and its total area inside of the module is 5.3 m^2. The experimental system to evaluate VMD module consists of a heated salt water tank to supply heat to the VMD module; 1 EA of 10 kW and 2 EA of 12 kW electric heaters to supply heat, and a 0.2 μm micro filter (MF) filter as a pre-treatment system to remove foreign substances in feed water.

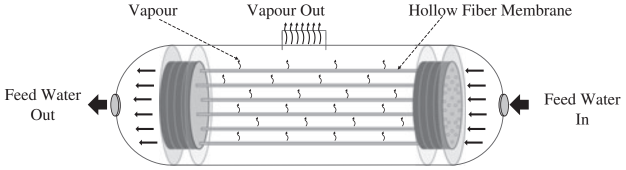

Fig. 1. Schematic of VMD.

Table 1
Configuration of experimental system

Contents	Specification
Seawater tank	0.3 m^3
Electric heater	10 kW 1EA, 12 kW 2EA
Pretreatment MF filter	0.2 μm
Seawater pump	13 m^3/h
Electromagnetic flowmeter	1–45 m^3/h
Condenser	47,120 kcal/h
Vacuum pump	120 LPM 690 mm HG
Pressure transducer	1–20 bar
Vacuum pressure transducer	0–100 kPa
VMD module membrane area	5.3 m^2

To achieve corrosion protection in the experimental system which uses salty water, the entire piping material of HT piping for high temperature is used, and titanium material is used in the pre-treatment system, and a condenser for condensing of vapor. As the VMD module needs a vacuum system, an oil-less reciprocating vacuum to maintain a vacuum in the module interior and vapor piping is used. Fig. 2 shows the VMD system experimental system in this study.

2.2. Experimental method

To check the performance characteristics of the VMD module, the established lab-scale VMD system heats feed water using electric heaters. The heated

Fig. 2. Experimental equipment of VMD system.

seawater is supplied to the VMD module maintaining the water quality with uniform conditions after removing foreign substances passing through a 0.2 μm MF filter. The temperature, pressure, and flow rate are collected by a temperature sensor, a pressure transmitter, and a flowmeter, respectively, and flow rate and pressure are controlled by a valve and a bypass line, respectively. The internal pressure of VMD where the heated feed water is supplied, maintains under 15 kPa of absolute pressure. At this time, feed water temperature and vapor temperature from the VMD module are affected from the pressure inside the module. The vapor, produced in the VMD module, passes through the condenser, and vapor is condensed into liquid from vapor by heat exchange with condensed water. The condensed freshwater is stored in the freshwater tank, and a non-condensable gas is discharged to the outside through a vacuum pump. The system is designed and manufactured to return the collected freshwater to the feed water tank after measuring the weight and water quality of freshwater to maintain the salinity of feed water. Fig. 3 shows a schematic of VMD system.

The performance ratio (PR) (hereinafter PR) which refers to the heat vs. PR of VMD module is represented by the ratio of required heat and actual supplied heat to change phases into vapor for the produced quantity of freshwater, as shown in Eq. (1).

$$\mathrm{PR} = \frac{\dot{m}_{\mathrm{fw}} L_{\mathrm{T}}}{Q} \tag{1}$$

where L_{T} is latent heat of vaporization of water, $\dot{m}_{\mathrm{fw}}$ is quantity of freshwater by the module, and is required quantity of heat, required in VMD module and is able to be represented by temperature differences between inlet and outlet of heated water and flow rate, which is supplied to the VMD module, as shown in Eq. (2).

$$Q = \dot{m}_{\mathrm{fw}} \times C_{\mathrm{p}} \times (T_{\mathrm{in}} - T_{\mathrm{out}}) \tag{2}$$

where L_{T} is flow rate of feed water, C_{p} is specific heat of feed water, T_{in} is inlet temperature of VMD module feed water, and T_{out} is outlet temperature of VMD module feed water.

The temperature differences between VMD module inlet and outlet make a significant impact on the PR value which is a heat PR of VMD module. As the salinity of feed water supplied into the VMD module is increased, thermal conductivity of feed water is decreased, thus, the temperature differences between VMD module inlet and outlet is also decreased. The value of thermal conductivity of feed water according to salinity is as shown in Eq. (3) [5,6].

$$\frac{k_{\mathrm{fw}}}{k_{\mathrm{sw}}} = 0.00022 \times S + 1 \tag{3}$$

$$k_{\mathrm{sw}} = 0.5715(1 + 0.003T - 1.025 \times 10^{-5}T^2 + 6.53 \times 10^{-3}P - 0.00029S) \tag{4}$$

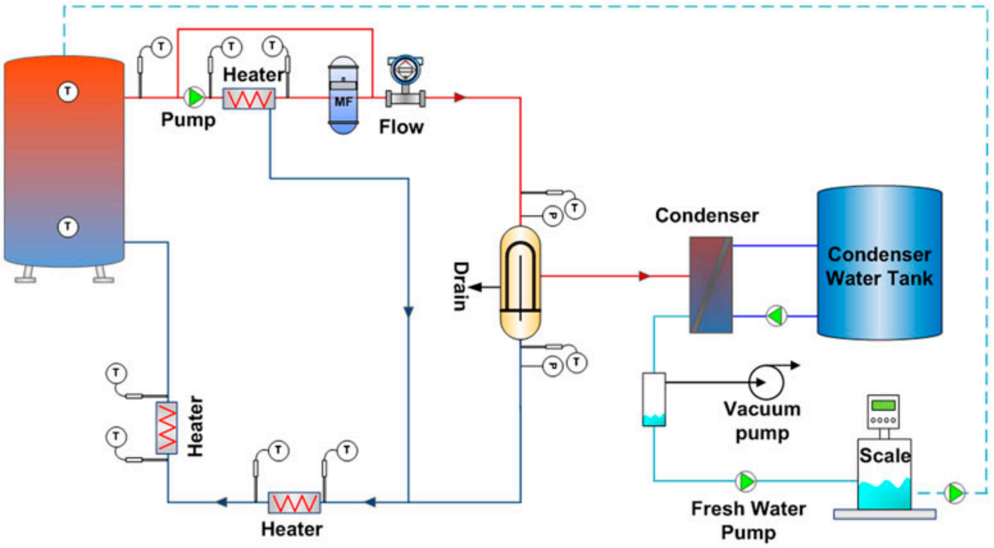

Fig. 3. Schematic diagram of VMD system.

$$k_{\mathrm{fw}} = 0.797015 \times T^{-0.194} - 0.251242 \times T^{-4} + 0.096437 \times T^{-6.385} - 0.0032696 \times T^{-2.134} \quad (5)$$

where T is the feed temperature of salt water, and 0.00022 represents a thermal conductivity ratio of salinity vs. seawater as a constant. k_{sw} is the thermal conductivity of feed water and k_{fw} is the thermal conductivity of freshwater, as calculated by Eqs. (4) and (5).

As the salinity of feed water supplied into VMD module, the boiling point of salt water also increased, therefore, the quantity of heat used to evaporate brine has also increased. The boiling point elevation (BPE) (hereinafter, BPE) value according to the salinity is shown as Eq. (6) [7].

$$\mathrm{BPE} = AS^2 \times BS \quad (6)$$

$$A = -4.584 \times 10^{-4}T^2 + 2.823 \times 10^{-1}T + 17.95 \quad (7)$$

$$B = 1.536 \times 10^{-4}T^2 + 5.267 \times 10^{-2} + 6.56 \quad (8)$$

In Eq. (6), S is salinity of feed water, A and B can be represented by Eqs. (5) and (6) where T is the temperature of feed water.

$$\mathrm{LMH} = \frac{\dot{m}_{\mathrm{fw}}}{A_{\mathrm{m}}} \quad (9)$$

The LMH, which is used as an index of membrane performance of MD module represents the permeate quantity of produced freshwater in the module. LMH value is calculated by the produced freshwater quantity per unit membrane area, as shown in Eq. (9). In Eq. (9), $\dot{m}_{\mathrm{fw}}$ is produced freshwater per unit time, and A_{m} is the membrane area which is used in the VMD module.

3. Result and discussion

The performance evaluation of VMD module shall always be conducted under the same external conditions. The effect of heat loss shall also be considered because the VMD module uses the feed water which has a higher temperature than ambient temperature. Therefore, each experiment has performed under the same external temperature. Additionally, to minimize the experimental error, the temperature, and flow rate of feed water which is supplied to the VMD module has been controlled within an error rate of ±1%.

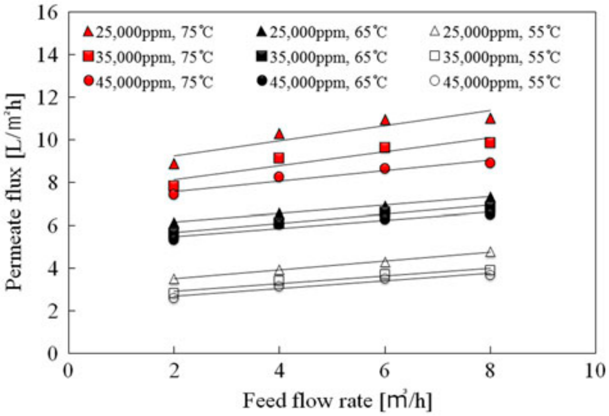

Fig. 4. Permeate flux according to feed flow rate.

Fig. 4 shows the LMH value of VMD module according to salinity, temperature, and flow rate of feed water. The experimental conditions to achieve value according to the feed temperature are 25,000, 35,000, and 45,000 ppm of feed water salinity in reference with TDS, 55, 65, and 75℃ of feed water temperature, 2, 4, 6, and 8 m^3/h of feed flow rate, and the experiment is performed under the same condition of under 15 kPa, absolute vacuum in the VMD module.

Among the results of experiments which use the conditions of 25,000, 35,000, and 45,000 ppm of salinity of feed water under the same condition of 75℃ of feed water temperature and 8 m^3/h of feed flow rate, the LMH value in the experiment which uses 25,000 ppm of feed water salinity is the highest as 11.05.

As the temperature and flow rate are increased, the LMH value which means permeate flux of VMD module membrane is also proportionally increased. This is because the LMH value of VMD module is increased, as the supplied quantity of heat is increased according to increase of temperature and flow rate of feed water to the VMD module.

As the salinity of the feed water is increased, LMH value is also decreased. This is because as the salinity of the feed water is increased, the quantity of heat to produce vapor inside of the VMD module is increased according to an increase of the boiling point of salt water. Therefore, as the salinity of the feed water is increased, the quantity of produced freshwater when the same quantity of heat has been supplied to the VMD module is decreased. This result is identical to the result of studies in the past [8,9].

Fig. 5 shows the BPE value according to the salinity condition of the feed water which is used in this study. It also shows that as the salinity of the feed water is increased, the boiling point is increased

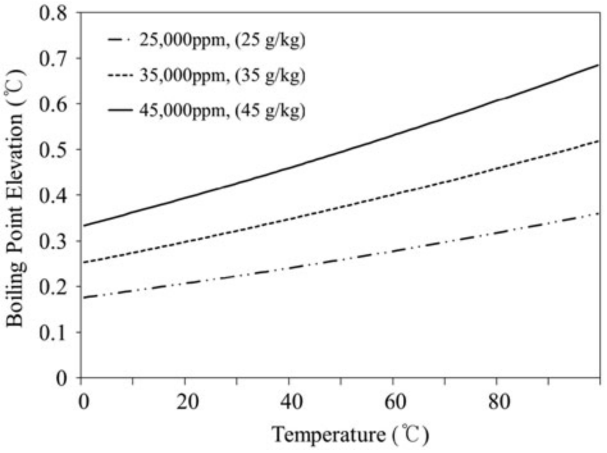

Fig. 5. Boiling point elevation according to salinity.

because the vapor pressure is decreased. Therefore, under the same temperature and pressure conditions, the required heat energy to vaporize the salt water will be increased in proportion to the increase of salinity.

Fig. 6 shows LMH value of the VMD module according to the temperature differences of feed water between inlet and outlet of the VMD module. Under the same flow rate and temperature conditions, as the salinity of the feed water is increased, the temperature differences between inlet and outlet of the VMD module are decreased. This is because the thermal conductivity has been decreased, as the salinity of feed water is increased, so that the temperature differences between the inlet and outlet of the VMD module is decreased. Therefore, the quantity of heat which is supplied to the VMD module will be decreased. When the experiment uses feed water of 55℃ of temperature, 8 m^3/h of flow rate, and 45,000 ppm of salinity, the result shows the lowest temperature differences between the inlet and outlet of the VMD module among all experiments.

Fig. 7 shows the thermal conductivity of feed water according to salinity, and temperature of feed water. As the salinity of feed water is increased, the thermal conductivity is decreased because dissolved electrolyte contents will be increased when salinity of feed water is increased.

Fig. 8 shows the recovery ratio (RR) according to the flow rate, salinity and temperature conditions of feed water. In the VMD module used in this study, the maximum RR value is 2.08%, under the condition of 25,000 ppm of salinity, 75℃ of temperature, and 2 m^3/h of flow rate of feed water, and the minimum RR value appeared as 0.21%, under the condition of 45,000 ppm of salinity, 55℃ of temperature, and 8 m^3/h of flow rate. When the temperature of feed water for the VMD module remains constant, the RR value will be decreased as the salinity and flow rate are increased. Also, when the flow rate and salinity of the feed water for the VMD module remains constant, the RR value will be increased as the temperature of the feed water is increased.

Fig. 9 shows the LMH value according to the heating quantity to the VMD module. The VMD module used in this study requires about 24.2 kWh per hour of quantity of heat to produce 1 m^3/d of freshwater, so that the total quantity of heat in a day will be about 580 kWh. The equation of permeate flux according to heating capacity is $y=0.2707x + 1.2979$. Therefore, the LMH value is proportionally increased as the supplying heat is increased.

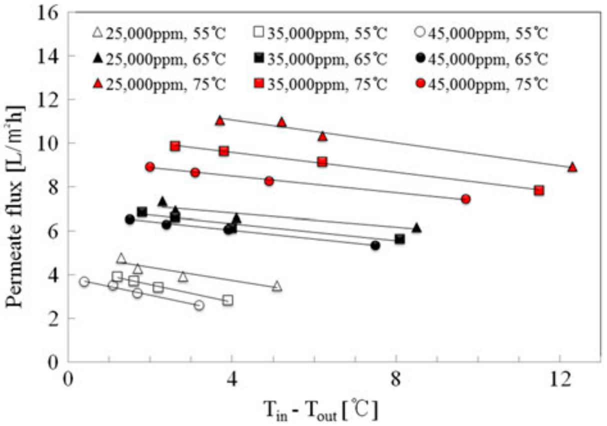

Fig. 6. Permeate flux according to inlet and outlet temperature difference.

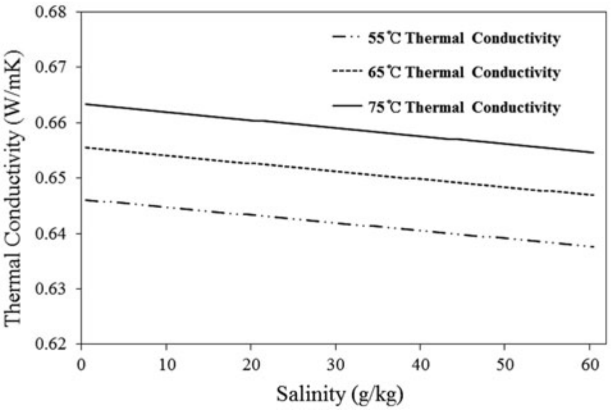

Fig. 7. Seawater thermal conductivity for temperature at a salinity.

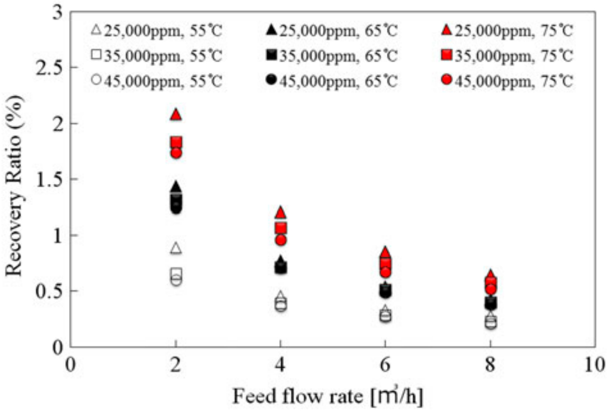

Fig. 8. Recovery ratio according to feed flow rate.

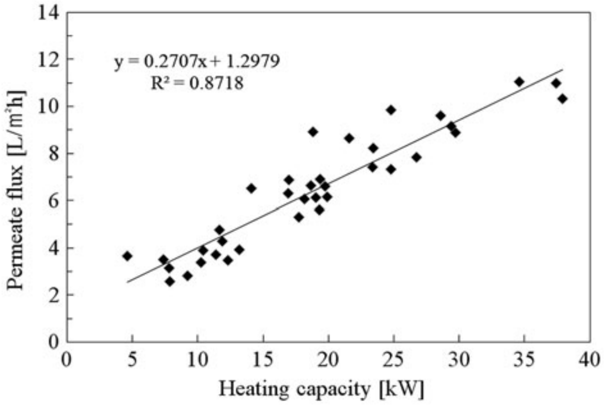

Fig. 9. Permeate flux according to heating capacity.

4. Conclusion

This study creates a VMD system with a 1 m^3/d capacity to achieve the basic data needed to calculate system capacity and optimal design of solar energy which is used in the seawater distillation system using a VMD module and analyzes the performance characteristics of the module according to the change of temperature, flow rate, and salinity of the feed water.

(1) As the temperature and flow rate of feed water which is supplied to the VMD module, value is proportionally increased, and as the salinity of the feed water is increased, value of the VMD module is decreased by the increasing of the boiling point because of the decrease of vapor pressure of the feed water.

(2) As the salinity of the feed water for the VMD module is increased, the thermal conductivity of feed water is decreased, so that temperature differences between inlet and outlet of VMD module will be decreased.

(3) As the salinity and flow rate of feed water are increased, the RR value is decreased, and as the temperature of feed water is increased, the RR value is increased.

(4) The VMD module in this study, which uses PVDF hollow fiber membranes, is analyzed to require 580 kWh to produce 1 m^3 of freshwater per day.

Acknowledgment

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Symbols

A_m	—	membrane area (m^2)
BPE	—	BPE (℃)
C_p	—	specific heat (kJ/kg℃)
k	—	thermal conductivity (W/m℃)
LMH	—	permeate flux ($\ell/m^2/h$)
L_T	—	latent heat (kJ/kg)
$\dot{m}$	—	flow rate (kg/s)
Q	—	heating capacity (kW)
P	—	absolute pressure (pa)
S	—	salinity (g/kg)
T	—	temperature (℃)

Subscripts

fw	—	freshwater
sw	—	feed water
in	—	inlet
out	—	outlet

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