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Operation optimization of vacuum membrane distillation using the shipboard waste heat

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ABSTRACT

Membrane distillation (MD) is investigated as an alternative to solve the high power costs and environmental pollution caused by reverse osmosis, which is a widely used water purification technology today. MD is driven by the difference in vapor pressure that occurs between the surfaces of hydrophobic porous membranes. It is operated at a relatively low temperature compared with the existing evaporation process, and theoretically, most of the inorganic ions can be removed, and it is not affected by feed water. MD is broadly classified into four types; among them, vacuum membrane distillation (VMD) has the lowest heat loss as well as the highest performance. Therefore, VMD is considered a process optimized when using engine waste heat generated from marine vessels and in the environment of low directness. Nevertheless, the performance of the VMD process varies according to the characteristics and forms of membrane modules used in the process, and membrane performance degrades when operated for a long time due to the direct vacuum pressure on a membrane. Therefore, this study aimed to find ways to maximize the performance of VMD system by identifying the optimum operating conditions through experiments under various operating conditions, and to reflect the findings in the design of the VMD plant process to secure its safety. The experiments of this study were carried out in a lab scale. Also, the types of membranes, feed water temperature, flow rate of feed water and vacuum pressure were set as the parameters of operating conditions, and the effect of each of them on VMD performance was analyzed. Water flux increased along with an increase in the temperature of the feed water. In case of the types of membranes, the membrane module of Capillary type showed the highest water flux. Three types of membrane modules displayed >99% salt rejection. Changes in performance according to flow rate and vacuum pressure were also investigated. It was judged that VMD performance can be maximized if optimum operating conditions determined through this experiment are applied to the design of freshwater plant for marine vessels.

Keywords: Membrane distillation; Vacuum membrane distillation; Capillary membrane; Desalination; Water treatment

1. Introduction

The desalination technology is widely studied in the Middle East and other parts of the world as a way to secure the alternative water resources. The demand for desalination facility to supply the water to the vessels navigating open seas and offshore plants docked in the offshore for a long period is increasing. The desalination system for ships and offshore plants is categorized as the key unit to be developed along with the ship engine, propelling system, marine pollution protection system and high performance energy recovery system by the marine equipment industry. Currently,

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the multi-stage flash distillation (MSF) process and reverse osmosis (RO) process have been commercialized as the desalination systems for ships and offshore plants [1]. The MSF process consumes a large amount of energy because it must heat the inlet water to 100°C or higher to generate the steam and requires a large ground [2]. The RO process generates the freshwater by pressurizing the feed water to higher than osmotic pressure, thus requires high operating cost and shows low recovery rate of 40%–50% [1]. Moreover, it requires heavy integration in a limited space such as a ship. The membrane distillation (MD) process was developed to overcome such technical limitations. As the MD process is actuated by the difference of steam pressure between the porous and hydrophobic membranes, the decrease of actuating force by osmotic pressure of feed water is lower than the RO process [3,4]. Therefore, the MD process uses very porous and hydrophobic membranes [5]. An MD process is mainly divided into the direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), vacuum membrane distillation (VMD) and sweep gas membrane distillation (SGMD) processes according to how the vapor pressure on the side of penetration from the membrane module is decreased [3,4]. The direct contact membrane distillation (DCMD) process generates the steam pressure using the cold water, which is widely used for lab-based MD research since it is easy to manufacture [6,7,8]. However, the heat loss is high, and flux is low while the transmitted vapor must be separated again [6,7,8]. The AGMD places a cold air layer on the penetration side to generate the vapor pressure and condense the vapor penetrating through the hydrophobic membrane [6,7,9]. Unlike the DCMD process, the pure water penetrating through the membrane does not have to be separated again, and the catalyst used to reduce the temperature of air gap can be utilized widely [9]. On the other hand, it has a lower permeate flux than other processes [9,10,11]. VMD has less heat loss and higher flux than other processes [8,9]. However, it is vulnerable to wetting as no optimized module has been developed [6,8,12,13]. This study focused on the VMD system, which can generate high performance under the environment of limited installation such as a ship, and intended to optimize the process using the hollow-fiber membrane. The performances under the various operating conditions using the tube and capillary module having similar characteristics as the hollow-fiber membrane were analyzed to deduce the optimized operating condition in the lab-scale equipment. It also proposed the module layout plan to increase the freshwater production and energy efficiency of the MD process.

2. Materials and methods

2.1. Membrane

This study used the hydrophobic and porous module of hollow fiber, tubular and capillary types according to the shape. The effective membrane area of each tested type was 0.035 m^2. Table 1 shows the structures of the membranes.

2.2. VMD system

A lab-scale VMD system was fabricated. Figs. 1 and 2 show the architecture of the lab testing equipment. The system consists of the feed water tank, produced water tank, gear pump to circulate the feed water, vacuum pump, heat exchanger for cooling, cooler to condense the produced steam through heat exchanger, electric heater to heat the feed water, electronic scale to measure the produced flux and hydrophobic membrane module.

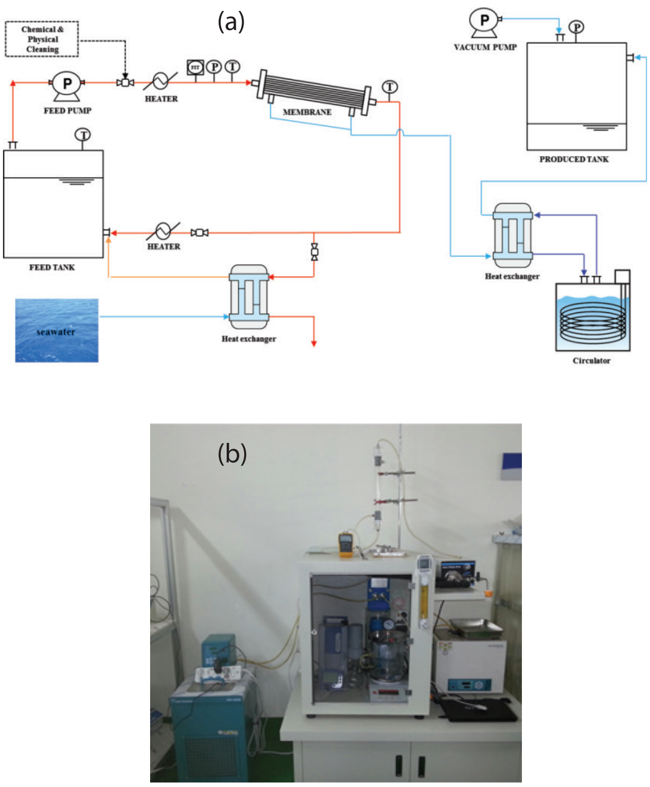

Fig. 1. Laboratory-scale single-stage module VMD system: (a) schematic diagram and (b) photography of the system.

Table 1
Property of the MD membrane

Item	Tubular	Capillary	Hollow fiber
Nominal pore size (μm)	0.2	0.2	0.2
Surface property	Polypropylene	Polypropylene	Polyvinylidene fluoride
Porosity (%)	70	70	70
Module shell size (mm)	20	20	20
Effective area (m^2)	0.035	0.035	0.035
Inner diameter (mm)	5.5	1.8	0.6

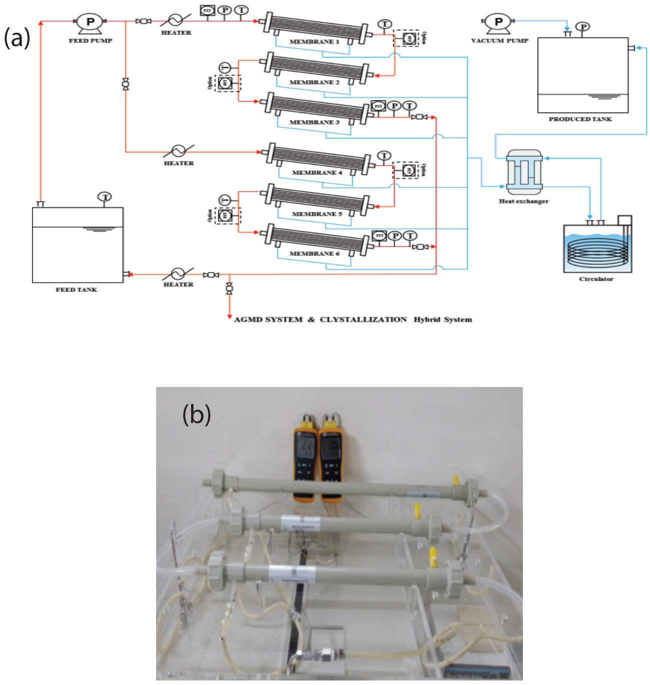

Fig. 2. Laboratory-scale multi-stage modules VMD system: (a) schematic diagram and (b) photography of the system.

2.3. Operating condition

As shown in Fig. 3, a VMD system can be an in-out type of feed water circulating inside the membrane or an out-in type of feed water circulating outside the membrane. Since the feed water circulates outside the membrane, the out-in type generates additional heat loss from the module since the feed water circulates outside. Also, there is the possibility of wetting at the edge of membrane where vacuum occurs after a prolonged operation since the vacuum is directly set inside the membrane. Therefore, this study conducted the test in out-in mode. However, there was a concern that it would be more vulnerable to membrane pollution since the feed water circulates inside. Therefore, the performance according to the membrane diameter was analyzed. Moreover, the test was conducted under various conditions of feed water temperature, flow rate and membrane module shape. The feed water used in the test was produced using 35,000 mg/L NaCl aqueous solution to replicate the seawater. The inlet temperature of feed water was maintained at 60°C–80°C using the electric heater and temperature sensor, and feed water was circulated at 0.4–1.0 L/min using the pump. The vacuum pressure of the penetrated side of membrane was set to 40–100 mbar. Table 2 shows the detailed test conditions.

2.4. VMD evaluation performance

To evaluate the performance after the test, a scale was installed on the produced water tank to measure the flux and recovery rate using the amount of produced water, and the electrical conductivity was measured using the electric conduction system to check the sale removal rate.

The flux (J, kg/m²·h) in the MD process can be calculated as shown in Eq. (1):

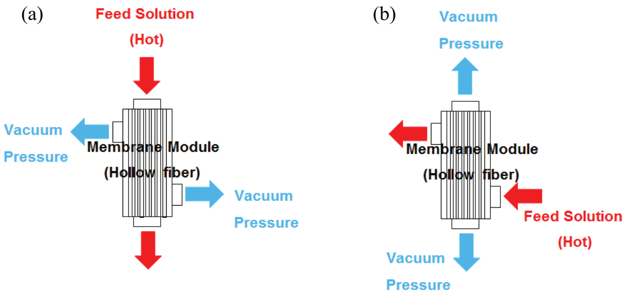

Fig. 3. Operating type: (a) in-out and (b) out-in.

Table 2
Summary of experimental conditions on MD system

Item		Condition
Operation type		Vacuum MD
Membrane		Tubular, capillary, hollow fiber
Feed solution		35,000 mg/L NaCL 2 L
Flow rate		0.4, 0.6, 0.8, 1.0 L/min
Vacuum pressure		40, 60, 80, 100 mbar
Temperature	Feed	60°C, 70°C, 80°C
	Cool	15°C

$$J = \frac{V \times d}{S \times t} \tag{1}$$

where V is the volume of freshwater (L); d is the density of freshwater (kg/L); S is the effective membrane area of process (m^2); and t is the operating time of VMD process. The salt concentration of raw water (C1, mg/L) is calculated with $Hg(NO_3)$ titration while the salt concentration of freshwater (C2, mg/L) is calculated with measurement of electric conductivity. The salt rejection factor (η, %) is calculated as shown in Eq. (2):

$$\eta = \frac{C1 - C2}{C1} \text{ x } 100\% \tag{2}$$

3. Results and discussion

3.1. Effect of feed flow type method

3.1.1. Comparison of water flux and salt rejection

To verify the performance with the hollow-fiber membrane, the performances according to temperature in the in-out mode and out-in mode were checked. The PVDF material hydrophobic membrane with 0.22 μm pores from Econity (Korea) was used. The feed temperature was set to 50°C, 60°C and 70°C. Fig. 4 shows the same flux in both operating modes and that the flux increased as the temperature increased. The salt rejection rate was >99.9% in all conditions.

3.1.2. Comparison of heat losses

The out-in mode showed higher temperature decrease than the in-out mode at the beginning of operation and longer period to stabilize to the feed operating temperature before the test began. To confirm it, a temperature sensor was installed at the inlet and outlet side of the membrane module, and measured the temperature in real time. As shown in Table 3, it was confirmed that the temperature drop in the feed was higher in the out-in mode than the in-out mode. The temperature decreases of 1°C, 1.6°C and 2°C were observed at the feed temperature of 50°C, 60°C and 70°C, respectively. Such result confirmed that there was the additional heat loss for the out-in mode due to the temperature outside the membrane module when considering only the heat loss inside the membrane module and disregarding the heat loss from the whole system. Therefore, it was judged that the in-out mode was more advantageous from the viewpoint of heat loss.

The test result confirmed that the in-out mode was more advantageous from the heat efficiency viewpoint for the hollow-fiber type membrane module. However, the in-out mode can cause severe membrane pollution according to total dissolved solids (TDS) of high concentration of feed water after a prolonged operation since the feed water is circulated into the hollow-fiber membrane. A previous study reported that the performance of MD process increased as the circulation flow of feed water increased. However, the circulating flow is limited by the diameter of the hollow-fiber membrane. The reason is that the operating pressure of circulating flow must be set to 0 bar to reduce the possibility of wetting because of the characteristics of hydrophobic membrane in the MD process. If a hydrophobic membrane is applied by the pressure higher than liquid entry pressure (LEP), the hydrophobic membrane loses its characteristic and becomes hydrophilic. If it is operated at 0 bar or higher even when the pressure is below LEP, the characteristics of hydrophobic membrane will be lost, and the wetting may occur as the membrane becomes more polluted after prolonged exposure. Therefore, the study to prevent such phenomenon must be conducted, and the inner diameter of the hollow-fiber membrane becomes an important factor in the case of in-out operation.

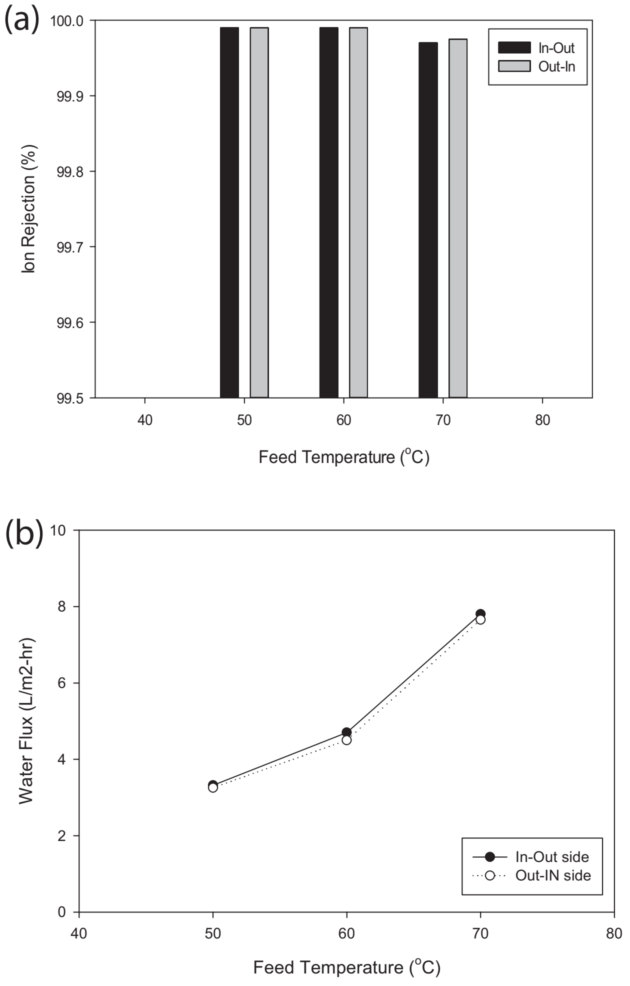

Fig. 4. Effect of operating type method in VMD: (a) flux and (b) salt rejection (experimental conditions: membrane = hollow fiber PVDF 0.22 μm; Q_{feed} = 0.8 L/min; vacuum pressure = 100 mbar; T_{feed} = 50°C, 60°C, 70°C; $T_{cooling}$ = 15°C; feed water = deionized [D.I.] water).

3.2. Evaluation of performance according to type

This study compared the performance of hollow fiber, capillary and tubular membranes with different diameters under various operating conditions. Table 1 shows the characteristics of the three types of membranes in details.

3.2.1. Performance according to feed temperature

The performances according to the feed temperature at each of type types of membrane were compared. The feed temperature was set to 60°C, 70°C and 80°C while the flow rate and vacuum were set to 0.8 L/min and 100 mbar, respectively. As shown in Fig. 5, the test showed that the performance change was sensitive to the temperature condition of feed water in VMD. The flux sharply increased as the feed temperature increased. The capillary type membrane module showed the highest flux. After the operation, the freshwater samples were collected to measure the electric conductivity. The result showed that all three types of membrane modules had 99.9% or higher salt rejection rate. The performance of MD process tends to be proportional to steam pressure, and the steam pressure of water can be expressed as a function of temperature and salt concentration. Therefore, it can be

Table 3
Effect of operating type on loss heat in MD system (experimental conditions: membrane = hollow fiber PVDF 0.22 μm; Q_{feed} = 0.8 L/min; vacuum pressure = 100 mbar; T_{feed} = 50°C, 60°C, 70°C; $T_{cooling}$ = 15°C; feed water = deionized water)

Feed temperature	Operation type	Feed inlet	Feed outlet	Feed dT
50	In-out	48.3	44.4	3.9
	Out-in	48.2	43.3	4.9
60	In-out	57.6	51.5	6.1
	Out-in	57.3	49.6	7.7
70	In-out	67.7	59.5	8.2
	Out-in	67.5	57.3	10.2

Note: dT – differential temperature.

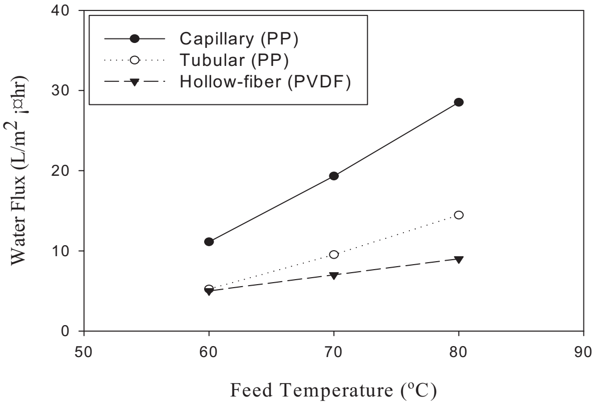

Fig. 5. Effect of feed temperature on flux in VMD (experimental conditions: membrane = tubular, capillary, hollow fiber; Q_{feed} = 1.0 L/min; vacuum pressure = 100 mbar; T_{feed} = 60°C, 70°C, 80°C; $T_{cooling}$ = 15°C; feed water = D.I. water).

judged that increased temperature increase is the result of performance increase from higher steam pressure in accordance with the Antoine equation as shown in Eq. (3):

$$\log P = A - \frac{B}{C+T} \tag{3}$$

where P is the vapor pressure (mmHg); A, B and C are constants (8.07131 mmHg; 1,730.63°C and 233.426°C, respectively); and T is the temperature (°C).

3.2.2. Vacuum pressure

Fig. 6 shows the change of flux at different vacuum in VMD. The vacuum levels were set to 40, 60, 80, 100, 120 and 140 mbar for operation, while the feed water temperature was set to 70°C and feed water flow was circulated at 0.8 L/min. The flux sharply increased at a vacuum level of 100 mbar, and then the increase became insignificant. After the operation, the freshwater samples were collected to measure the electric conductivity. The result showed that all three types of membrane modules had 99.9% or higher salt rejection rate. In the VMD process, the performance change varies according to the vacuum level, which also affects the operating cost and wetting of membrane. Therefore, it is judged that there is a need to select the optimum vacuum condition for the operation.

3.2.3. Feed flow rate

Fig. 7 shows the change of flux according to flow rate in the VMD process. The feed water temperature was set to 70°C while the vacuum level was set to 100 mbar and flow rates were set to 0.4, 0.6, 0.8 and 1.0 L/min. The system was operated not to violate the pressure limit. The test showed that the performance increased as the flow rate increased and the salt rejection rate was 99.9% or higher. Such result is judged to be the result of VMD performance improving from the decreased concentration boundaries formed at both side of the membrane and lowered concentration polarity as the flow rate of the feed water into the membrane module increases.

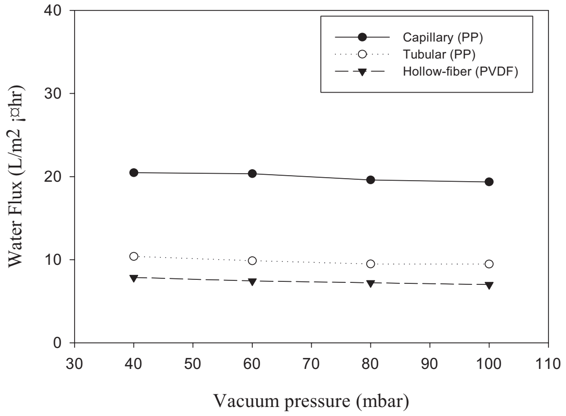

Fig. 6. Effect of vacuum pressure on flux in VMD (experimental conditions: membrane = tubular, capillary, hollow fiber; Q_{feed} = 1.0 L/min; vacuum pressure = 40, 60, 80, 100 mbar; T_{feed} = 70°C; $T_{cooling}$ = 15°C; feed water = D.I. water).

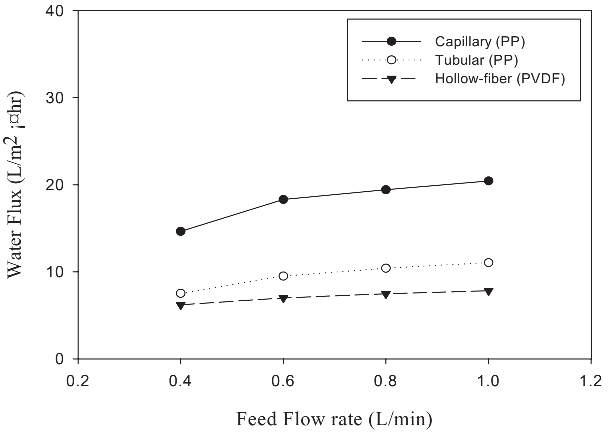

Fig. 7. Effect of flow rate on flux in VMD (experimental conditions: membrane = tubular, capillary, hollow fiber; Q_{feed} = 0.4, 0.6, 0.8, 1.0 L/min; vacuum pressure = 100 mbar; T_{feed} = 70°C; $T_{cooling}$ = 15°C; feed water = D.I. water).

3.3. Evaluation of multistage VMD system performance

Fig. 8 shows the comparison of a VMD system with a single module and a VMD system with three modules connected in series. The capillary membrane was used, and the feed water temperature, feed water flow rate and vacuum level were set to 60°C, 0.8 L/min and 100 mbar, respectively. The effective membrane areas of the single-stage module system and three-stage module system were 0.035 and 0.105 m^2, respectively. The operation result showed that the single-module system had higher average flux than the three-stage module system. The result is attributed by the gradual decrease of feed water temperature as it passes from the first stage to the third stage, and thus the steam pressure decreases. However, the amount of freshwater produced during the operation was 1.8 times higher in the three-stage module than the single-stage module. It is judged that the heat efficiency can be increased by connecting multiple membranes in series under the same heat energy and feed water circulating flow condition.

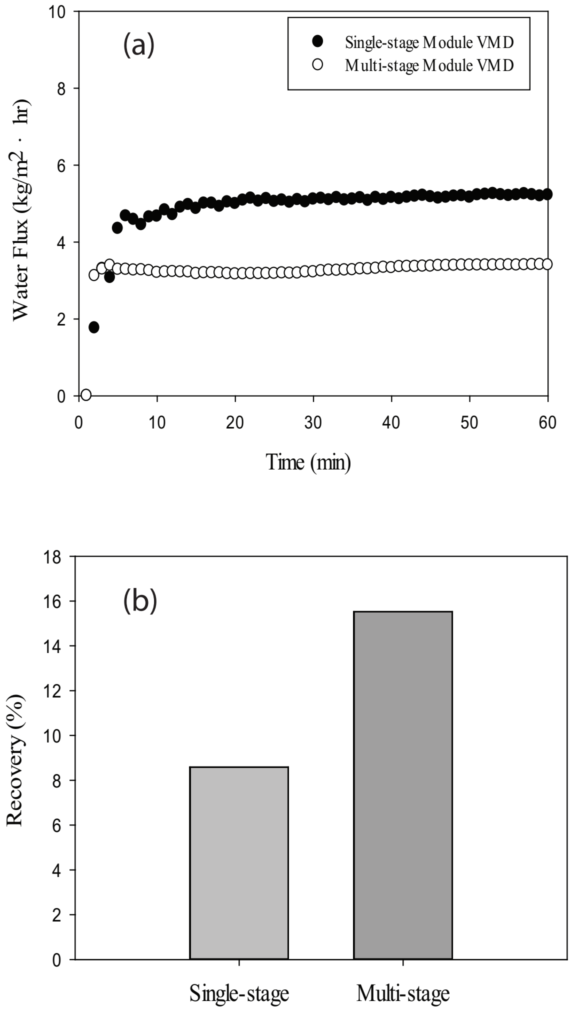

Fig. 8. Single module vs. multi modules (experimental conditions: membrane = tubular, capillary, hollow fiber; Q_{feed} = 1.0 L/min; vacuum pressure = 100 mbar; T_{feed} = 60°C; T_{cooling} = 15°C; feed water = D.I. water).

4. Conclusions

This study compared the performances under various operating conditions to provide insight for actual VMD plant design and optimization. Following conclusions were drawn:

- The in-out and out-in modes showed the same performance in the MD system using the hollow-fiber membrane, and the heat loss was higher in the out-in mode than the in-out mode. In the case of out-in mode, it was judged that there was the additional heat loss outside the membrane module.
- The comparison of performances of hollow fiber, capillary and tubular membrane modules under the same operating condition showed that the capillary membrane module had the highest performance. The performance changed according to the inner diameter size in the hollow-fiber membrane module.
- The comparison of performance under the various conditions of feed water temperature, feed water flow rate and vacuum level showed that the VMD performance increased as the temperature was higher, the flow rate was higher and the vacuum level was lower. However, the optimum operation condition with consideration to energy efficiency and operating cost must be deduced during the actual plant design and reflected in the operation.
- The comparison of the single-stage module system and the three-stage module system showed that the performance gradually deteriorated as the feed water temperature decreased as the water passed from the first stage to the third stage. Although the average flux of the three-stage module system was lower than the single-stage module system, the three-stage module produced 1.8 times more freshwater in the same period.
- It is judged that the economic and efficient operation can be expected if the result of this study is reflected in actual VMD desalination plant design.

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