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Analysis of flux and energy efficiency for hollow fiber module in direct contact membrane distillation process

Youngkyu Park, Yonghyun Shin, Jihyuk Choi, Yongjun Choi, Sangho Lee*

School of Civil and Environmental Engineering, Kookmin University, Jeongneung-Dong, Seongbuk-Gu, Seoul 136-702, Republic of Korea, Tel. +82-2-910-4529; Fax: +82-2-910-4939; email: sanghlee@kookmin.ac.kr (S. Lee)

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ABSTRACT

Although membrane distillation (MD) holds promise as an emerging desalination technology, relatively few studies were carried out to analyze energy efficiency of MD modules. Accordingly, this study intended to establish an energy balance for a 1 m^2 hollow fiber MD module. Experiments were carried out under a semi-pilot direct contact MD equipment. The feed and distillate temperatures were adjusted from 50°C to 60°C and from 25°C to 35°C, respectively. The feed and distillate flow rates ranged from 0.6 to 1.2 m^3/h. A performance ratio was evaluated from a thermal energy balance in each operation condition. Results showed that the feed flow rate and temperature difference greatly affect water flux (productivity) and performance ratio (energy efficiency). The conductive heat loss through the membrane was found to be substantial, which decreased with a reduction in the temperature difference. The performance ratio was proportional to the single pass water recovery of the MD module, suggesting that the sufficient feed flow rate is required for efficient operation of MD.

Keywords: Direct contact membrane distillation; Performance ratio; Recovery; Energy balance; Membrane module

1. Introduction

As water shortage has become increasingly serious, many countries have been looking for technologies for ongoing and sustainable water supply [1–3]. One of them is seawater desalination that can use seawater as the source of freshwater [4–6]. Although distillation technologies such as multi-stage flash and multi-effect distillation are still being used, reverse osmosis technology is widely applied for seawater desalination. Nevertheless, the energy consumption by the current desalination technologies is still substantial, leading to an increase in operating conditions [6,7]. Accordingly, emerging technologies such as forward osmosis and membrane distillation (MD) have drawn attention as alternatives that may replace the current desalination technologies [8–11].

MD is a thermally-driven process that uses a hydrophobic membrane as an "evaporator" [12]. This implies that the basic principles in conventional distillation can be applied. In MD, the thermal energy (or sensible heat) in the feed solution is used to produce water vapor, which passes through the pores in the hydrophobic membrane [13,14]. Accordingly, thermal energy is transferred from feedwater to distillate together with water vapor [15,16]. In addition, there are other thermal energy losses including conductive heat transfer through the membrane [17]. In order to have high productivity and high energy efficiency, MD membranes should have low thermal conductivity as well as high vapor permeability [16,18].

Although many studies on MD have focused on the improvement of water flux and control of membrane fouling [13,17,19,20], relatively little information is available on the heat transfer and thermal efficiency in a pilot- or full-scale MD modules. Accordingly, this study intended to analyze the energy efficiency and performance in an MD module, which provide insight into optimization of MD module design as well as system optimization. Pilot-scale experiments were carried out using hollow fiber MD modules with the surface area of 1 m^2. Water and energy balances were constructed as a function of operation parameters

* Corresponding author.

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such as feed temperature and flow rate. Factors affecting the MD energy efficiency were also examined.

2. Materials and methods

2.1. MD module

In Table 1, the properties of the MD module are summarized. The membranes were made of polyvinylidene fluoride. The inner and outer diameters of the membrane were 0.8×10^{-3} m and 1.2×10^{-3} m, respectively. The length of the module is 0.45 m and the shell diameter was 0.163 m.

2.2. Pilot-scale MD membrane system

Fig. 1 illustrates the schematic diagram of the pilot-scale MD system used in this study. The system consists of a feed tank, a distillate tank, recirculation pumps, MD modules, a heater, and a cooler. The temperature of the feedwater supplied to the MD module was controlled by the heater and a temperature sensor. The temperature of the distillate flowing into the MD module was controlled by the cooler. Nevertheless, the actual water temperatures were slightly different from the set value. Then, the feedwater was supplied to the MD module. The water vapor passed through the MD membrane and was mixed with the distillate water, resulting in an increase in the distillate temperature. At the same time, the temperature of the feedwater leaving the MD module decreased since the thermal energy was used to evaporate water from the feed solution. The temperatures of feed inlet, feed outlet, distillate inlet, and distillate outlet were monitored, which were used to construct the energy balance. Moreover, the electronic balance was used to measure the changes in the weight of the distillate water, which were used to calculate MD flux.

Table 1
Properties of MD membrane module

Parameters	Values
Shell diameter	0.163 m
Fiber inside diameter	0.8×10^{-3} m
Fiber outside diameter	1.2×10^{-3} m
Pore size	0.1×10^{-6} m
Porosity	0.8
Module length	0.45 m
Membrane area per module	1.0 m^2

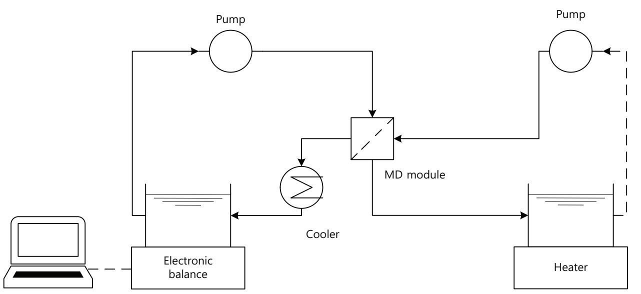


Fig. 1. Schematic diagram of direct contact MD system.

The MD experiments were carried out under various operating conditions. The feed flow and distillate flow rates were adjusted from 0.6 to 1.2 m^3/h. The feed inlet temperature ranged from 49.63°C to 59.72°C and the distillate inlet temperature ranged from 24.8°C to 35.05°C. The feedwater was a 200 mg/L NaCl solution. Details on the experimental conditions were summarized in Table 2.

3. Results and discussion

3.1. MD flux and temperature differences

Fig. 2 shows the variation in flux and temperature difference between feed and distillate in direct contact membrane distillation (DCMD) operation. The feed and distillate temperatures were 59.7°C and 31.8°C, respectively, and the feed and distillate flow rates were 0.9 and 0.6 m^3/h, respectively. The average flux was 4.1 kg/m^2 h with the temperature difference ranging from 18.5°C to 21.5°C. Since the driving force

Table 2
Summary of experimental conditions

Run	Feed flow rate (m^3/h)	Distillate flow rate (m^3/h)	Feed inlet (°C)	Distillate inlet (°C)
1	0.9	0.6	59.7	31.77
2	0.9	0.9	59.7	35.04
3	0.9	1.2	59.26	35.05
4	1.2	0.8	59.54	30.77
5	0.6	0.6	59.72	31.41
6	0.9	0.6	59.69	24.8
7	0.9	0.6	49.84	29.82
8	0.9	0.6	49.74	25.36
9	0.9	0.9	49.63	26.81

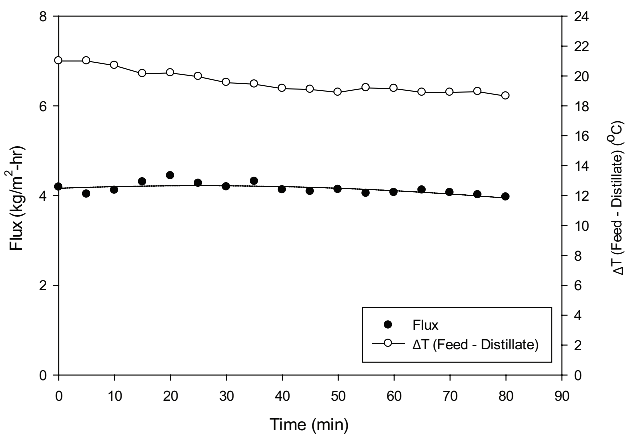


Fig. 2. Water and energy balances for direct contact MD system (conditions: feed temperature, 59.7°C; distillate temperature, 31.8°C; feed flow, 0.9 m^3/h; and distillate flow, 0.6 m^3/h).

of the MD was the vapor pressure difference due to temperature difference, the flux slightly decreased with a decrease in feed flux.

During the MD operation, the thermal energy in the feed inflow to the module was used to produce water vapor. Accordingly, the temperature of the feed outflow from the module became lower than that of the feed inflow. At the same time, the temperature of the distillate outflow became higher than that of the distillate inflow due to thermal energy transferred by the water vapor and heat conduction through the membrane. These results are clearly shown in Fig. 3. According to this, the temperature difference between feed inflow and feed outflow was 8.1°C and the temperature difference between distillate inflow and distillate outflow was 6.4°C.

3.2. Analysis of thermal energy balance

Based on the MD experimental results, the thermal energy balance was established using the following equations. First, the energy supplied to the MD system should be broken down into three terms [13,16,18]:

$$Q_{in} = Q_{out} + Q_{loss} = Q_{flux} + Q_{cond} + Q_{loss} \quad (1)$$

where Q_{in} is the energy input to the MD system, Q_{flux} is the energy used for flux, Q_{cond} is the energy lost by heat conduction through the membrane, and Q_{loss} is the other thermal energy loss from water tank, pipe, and other part. Q_{in} and Q_{flux} are given by [17,18]:

$$Q_{in} = \rho q_{f,in} C_p T_{f,in} - \rho q_{f,out} C_p T_{f,out} \quad (2)$$

$$Q_{out} = \rho q_{d,out} C_p T_{d,out} - \rho q_{d,in} C_p T_{d,in} \quad (3)$$

$$Q_{flux} = J_w H_w A_m = \left(q_{f,in} - q_{f,out}\right) H_w A_m = \left(q_{d,out} - q_{d,in}\right) H_w A_m \quad (4)$$

$$Q_{cond} = Q_{out} - Q_{flux} = \rho q_{d,out} C_p T_{d,out} - \rho q_{d,in} C_p T_{d,in} - J_w H_w A_m \quad (5)$$

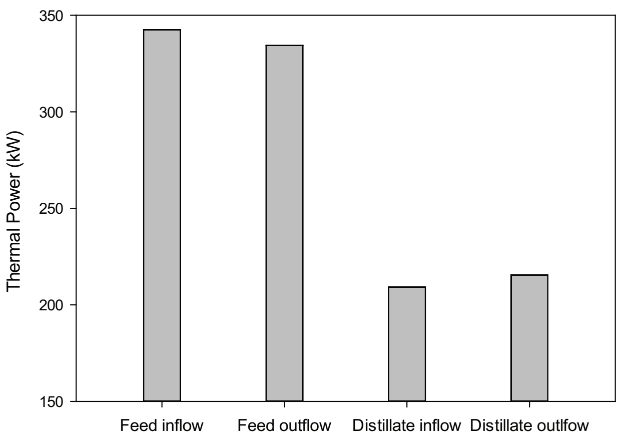


Fig. 3. Water and energy balances for direct contact MD system (conditions: feed temperature, 59.7°C; distillate temperature, 31.8°C; feed flow, 0.9 m^3/h; and distillate flow, 0.6 m^3/h).

where ρ is the water density, $q_{f,in}$ is the feed inflow rate, $q_{f,out}$ is the feed outflow rate, $q_{d,in}$ is the distillate inflow rate, $q_{d,out}$ is the distillate outflow rate, C_p is the heat capacity of water, $T_{f,in}$ is the feed inlet temperature, $T_{f,out}$ is the feed outlet temperature, $T_{d,in}$ is the distillate inlet temperature, $T_{d,out}$ is the distillate outlet temperature, H_w is the latent heat of water vaporization, A_m is the membrane area, and J_w is the distillate flux.

Using Eqs. (2) and (3), the amounts of thermal energy entering into and leaving from the MD module were analyzed. The results are shown in Fig. 3. The test conditions are: the feed inflow temperature of 59.7°C, the distillate inflow temperature of 31.8, the feed inflow rate of 0.9 m^3/h, and the distillate outflow rate of 0.6 m^3/h. Due to the heat transfer through the membrane by conduction and evaporation, the amounts of thermal energy in the inflow and outflow were different in both feed and distillate streams. Nevertheless, the difference in the thermal energy was larger in the feed stream than the distillate stream, indicating that there is also a heat loss ($Q_{loss} = Q_{in} - Q_{out} = Q_{in} - Q_{flux} - Q_{cond}$).

Together with the analysis using Eqs. (4) and (5), water and energy balances for the MD system were obtained as shown in Fig. 4. The net energy supply to the MD system from the feed stream (Q_{in}) was the difference in the thermal energy between the feed inflow and outflow, which corresponds to 8.145 kW. The heat transferred by the flux (Q_{flux}) and the conductive heat loss (Q_{cond}) was calculated to 2.502 and 3.78 kW, respectively. Accordingly, the heat loss (Q_{loss}) was determined to 1.862 kW. These results suggest that the thermal energy used to produce flux by evaporation was not high (<40%). It should be also noted that the Q_{cond} was substantial in this test, indicating that the thermal energy loss in DCMD configuration is significant.

The performance ratio (PR), which is defined as the ratio of the thermal energy used for evaporation to the total thermal energy input, is an index to measure the thermal efficiency for distillation systems. In a single stage distillation, PR is ≤1.0 and in a multi-stage distillation, PR is proportional

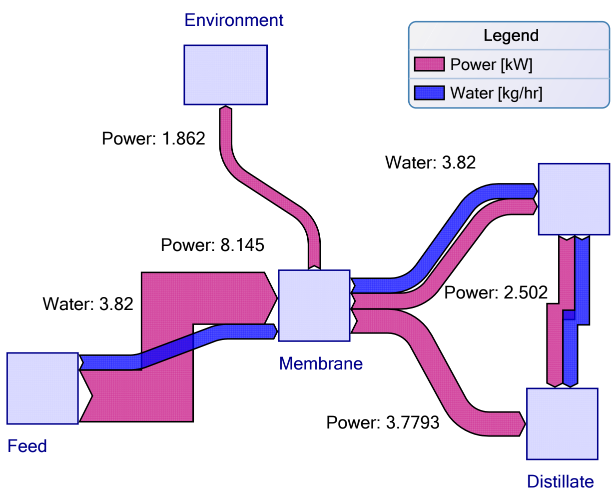
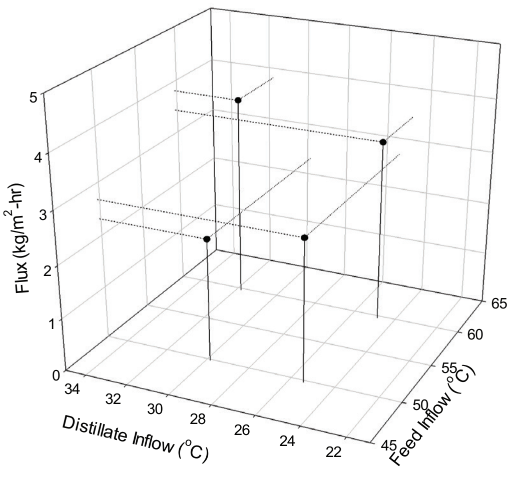
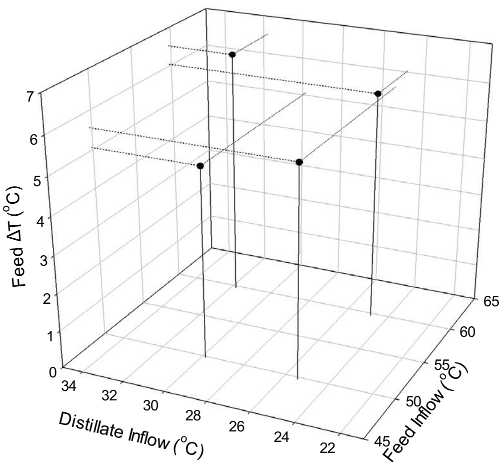


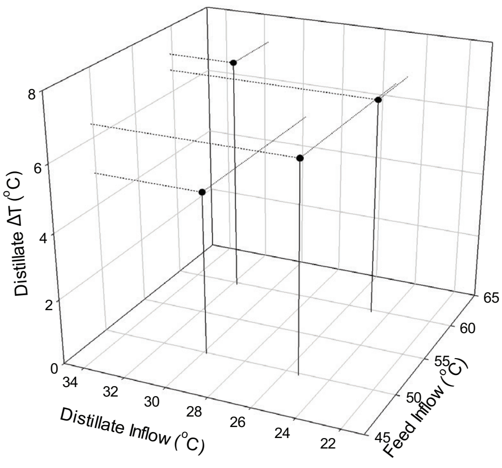
Fig. 4. Water and energy balances for direct contact MD system (conditions: feed temperature, 59.7°C; distillate temperature, 31.8°C; feed flow, 0.9 m^3/h; and distillate flow, 0.6 m^3/h).



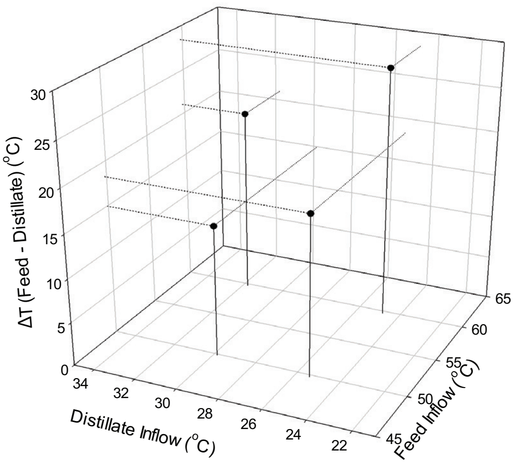
(a)



(b)



(c)



(d)

Fig. 5. (a) Flux, (b) feed ΔT, (c) distillate ΔT, and (d) ΔT between feed and distillate.

to the number of stages. In a single stage DCMD system, PR can be given by:

$$\mathrm{PR} = \frac{Q_{\mathrm{flux}}}{Q_{\mathrm{in}}} = \frac{J_w A_m}{\frac{Q_{\mathrm{in}}}{H_w}} \tag{6}$$

In Fig. 4, the PR was 0.307, suggesting that only 30.7% of the supplied heat was used to evaporate water. Accordingly, it is important to increase PR to reduce the cost for the thermal energy for MD.

3.3. Effect of feed/distillate temperatures and inflow rates

Fig. 5 shows the effect of feed and distillate inflow temperatures on flux, feed ΔT, and distillate ΔT. In these tests, the feed and distillate inflow rates were set to 0.9 and 0.6 m^3/h, respectively. As shown in Fig. 5(a), the flux increases with increasing feed temperature. On the other hand, the effect of distillate temperature on flux was not clear: at low feed temperature, the flux was slightly higher at low distillate temperature. At high feed temperature, the flux was slightly higher at low distillate temperature. This suggests that the feed temperature is an important factor affecting flux rather than distillate temperature.

In MD systems, the flux may be expressed as a function of temperature difference between feed and distillate [13,17]:

$$J_w = \frac{C}{\delta}(p_f - p_d) \tag{7}$$

$$p = \exp\left(a_1 - \frac{a_2}{T_m + a_3}\right) \tag{8}$$

where C is the phenomenological coefficient which measures the ability of the membrane to give MD fluxes, d is the

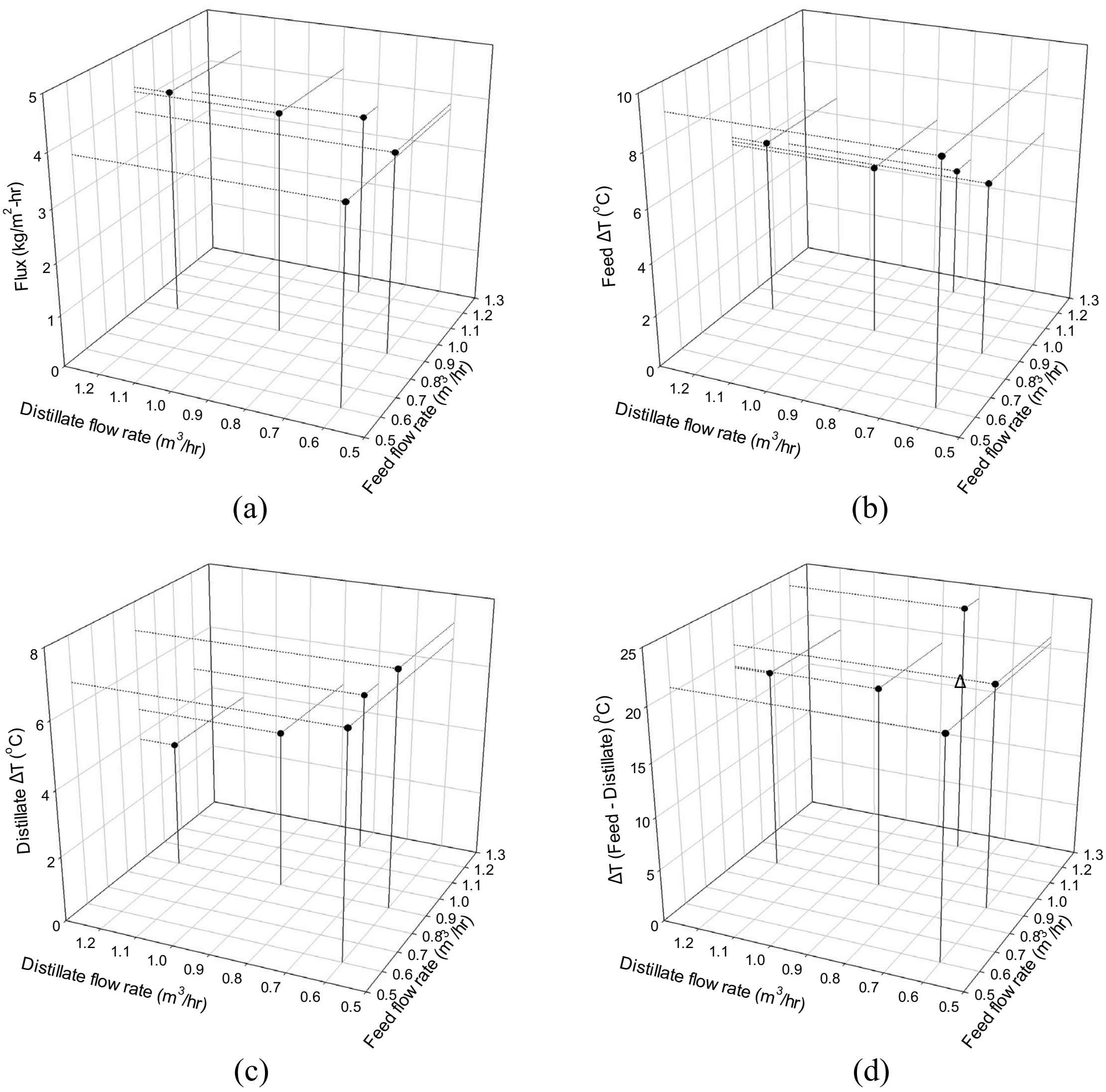


Fig. 6. (a) Flux, (b) feed ΔT, (c) distillate ΔT, and (d) ΔT between feed and distillate.

membrane thickness, p_f is the vapor pressure for feed, p_d is the vapor pressure for distillate, a_1, a_2, a_3 are the Antoine parameters, which are 23.238, 3882.89, and –42.85 K, respectively, for pure water. Accordingly, as the feed temperature increases or the distillate temperature decreases, the difference in vapor pressures between the feed and distillate increases, thereby increasing the flux. However, the vapor pressure is not linearly proportional to the temperature and thus the feed temperature is more important in determining the vapor pressure difference and flux than the distillate temperature.

Figs. 5(b) and (c) show the temperature changes in feed and distillate flows as a function of feed and distillate inflow temperatures. These trends matched the dependence of flux on the temperatures. This is because the changes in temperatures include the use of thermal energy to generate flux. Accordingly, as the flux increases, the change in temperature increases. Of course, the temperature may be changed by heat conduction through the membrane and thermal energy losses.

Fig. 6 shows the effect of feed and distillate inflow rates on flux, feed ΔT, and distillate ΔT. In these tests, the feed and distillate inflow temperatures were set to approximately 60°C and 30°C. With an increase in the feed and distillate flow rates, the flux increased as depicted in Fig. 6(a). This is attributed to an increase in thermal energy supply to the MD module and a decrease in concentration/temperature polarization due to increased shear on the membrane surface. As shown in Fig. 6(b), the feed ΔT, which indicates the amount of thermal energy provided by the feed stream, was higher when the feed inflow rate was lower. On the other hand, the distillate ΔT, which indicates the amount of thermal energy received by the distillate stream, was higher under the condition that the distillate inflow rate was lower. These results suggest that thermal energy flows were sensitive to the feed and distillate flow rates. In other words, the inflow rates of feed and distillate are important operation parameters affecting the efficiency of MD.

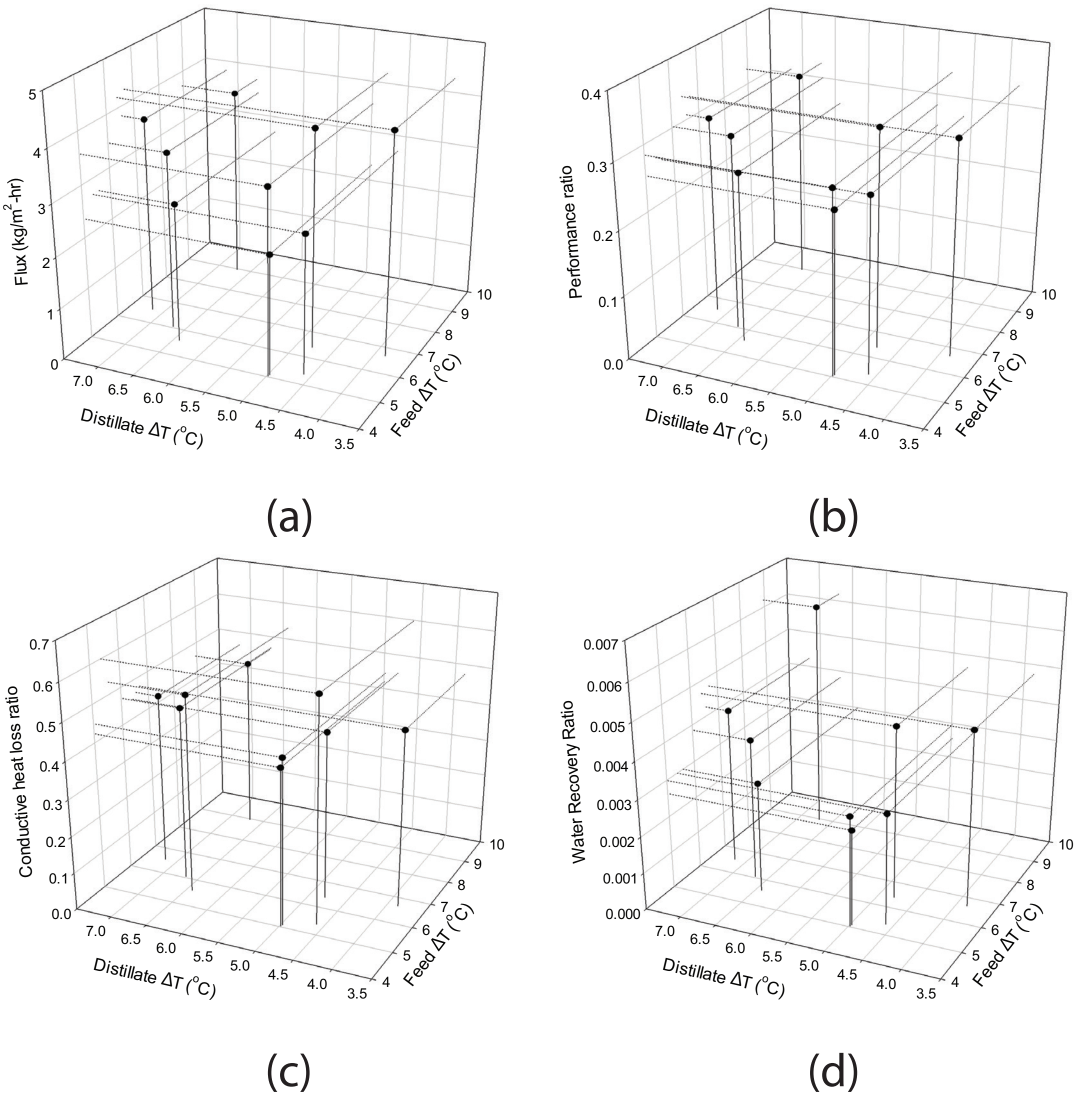


Fig. 7. (a) Flux, (b) performance ratio, (c) conductive heat loss ratio, and (d) water recovery ratio.

3.4. Effect of operation conditions on performance ratio and water recovery

In Figs. 7(a) and (b), the flux and PR were analyzed as a function of feed and distillate ΔT. Since the feed ΔT is the energy input from the feed and the distillate ΔT is the energy gain by the distillate, they can be used as universal parameters to analyze the efficiency of MD under various conditions. The flux increased as the feed ΔT and distillate ΔT increased. This is because the flux is proportional to the energy supplied to the MD module. Similarly, the PR also increased as the feed ΔT and distillate ΔT increased.

It should be noted that PR in a single stage DCMD is closely related to J_w. Rearranging Eq. (6), the following equation can be obtained:

$$\frac{PR}{J_w} = \frac{A_m H_w}{Q_{\text{in}}} \tag{9}$$

If the feed inflow and the membrane area are constant, the ratio of PR to J_w is constant. In other words, PR is proportional to J_w as long as the Q_{in} is fixed. Accordingly, an increase in feed ΔT results in J_w, leading to an increase in PR as shown in the graphs.

Fig. 7(c) shows how the ratio conductive heat loss depends on the feed ΔT and distillate ΔT. The ratio of conductive heat loss was the largest at feed ΔT of 5.5°C and distillate ΔT of 4.6°C. It had the lowest value at feed ΔT of 5.0°C and distillate ΔT of 5.0°C. Within the conditions considered in this study, the ratio of conductive heat loss ranges from 0.42 to 0.6. Nevertheless, it appears that there is no clear relationship between the ratio of conductive heat loss and the temperature differences.

In Fig. 7(d), the water recovery ratio was presented as a function of the feed ΔT and distillate ΔT. Overall, the water recovery was high when the flux and PR were high. As a matter of fact, the water recovery (r) is also dependent on PR:

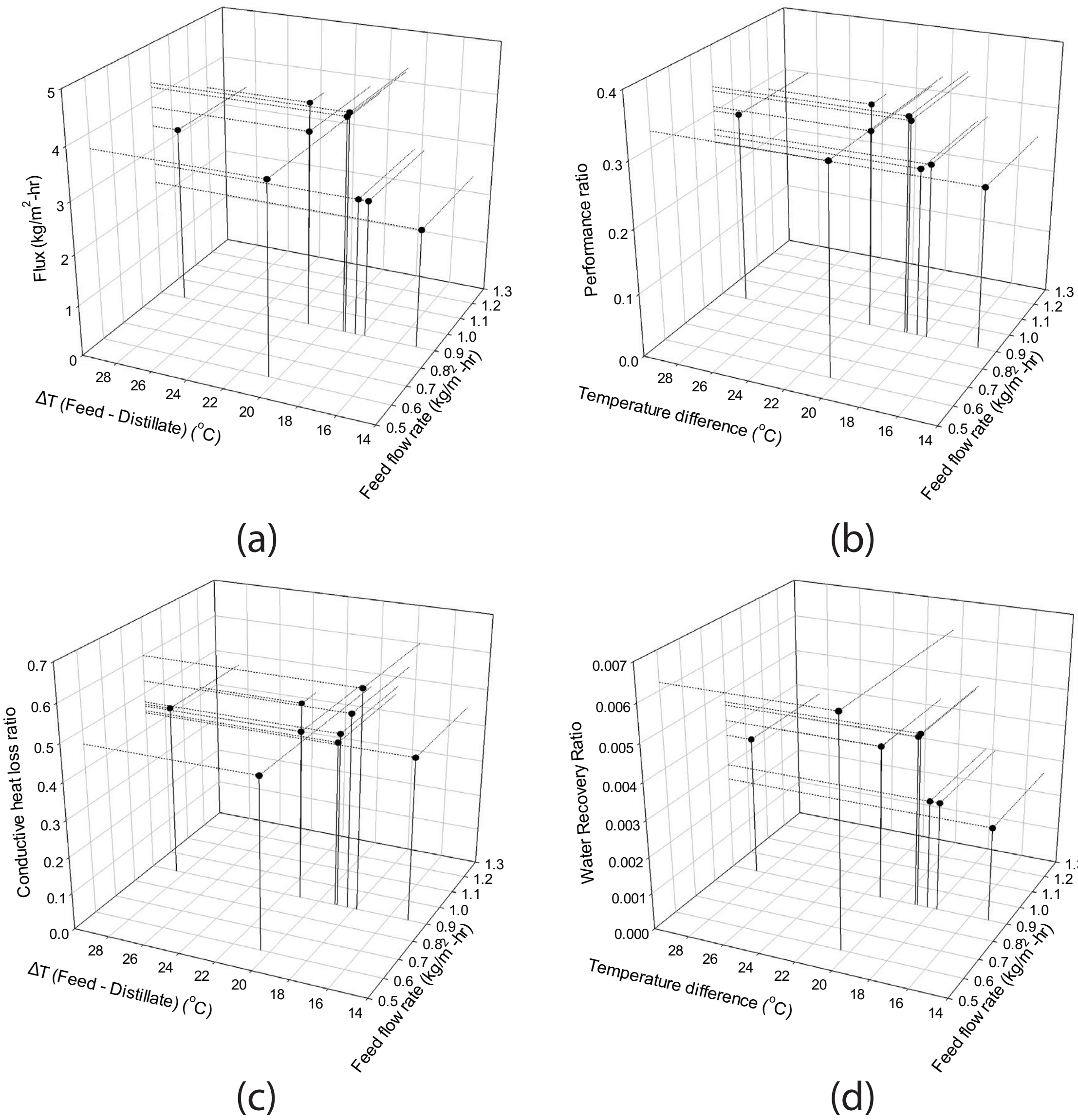


Fig. 8. (a) Flux, (b) performance ratio, (c) conductive heat loss ratio, and (d) water recovery ratio.

$$r = \frac{J_w A_m}{Q_{\text{in}}} = \frac{PR}{H_w} \tag{10}$$

Accordingly, r increases as J_w or PR increases at constant Q_{in}.

In MD systems, the temperature difference between feed and distillate (ΔT_{FD}) is the driving force for producing water vapor. Feed flow rate (Q_{in}) is also an important factor affecting the flux and PR as shown in Eq. (9). Therefore, the flux, PR, conductive heat loss ratio, and the water recovery were estimated as a function of ΔT_{FD} and Q_{in}. As expected, the flux increased as the ΔT_{FD} and Q_{in} increased, which is clearly shown in Fig. 8(a). Similarly, PR also increased with an increase in ΔT_{FD} and Q_{in} as shown in Fig. 8(b). On the other hand, the ratio of conductive heat loss did not clearly depend on ΔT_{FD} and Q_{in}. This is attributed to the competing effects occurring in the MD operation. First, the amount of the conductive heat loss should increase with increasing ΔT_{FD}. However, since the ratio of the conductive heat loss is the relative amount of the heat loss compared with the total amount of heat supply, it is not proportional to ΔT_{FD}. Increasing Q_{in} may result in an increase in the total amount of heat supply but also an increase in the amount of conductive heat loss. Accordingly, the dependence of the ratio of conductive heat loss on ΔT_{FD} and Q_{in} is not simple. As shown in Fig. 8(d), the water recovery decreases with increasing ΔT_{FD} and decreasing Q_{in}, which can be easily explained by Eq. (10).

3.5. Correlation between water recovery and performance ratio

The dependencies of PR on the flux and water recovery ratio were shown in Figs. 9(a) and (b). PR is almost linearly proportional to the flux or water recovery ratio. As pointed out, these trends can be expected from Eqs. (9) and (10).

Accordingly, it is concluded that the thermal energy efficiency in a single stage DCMD can be improved by increasing flux or water recovery ratio. This may require the operation under high feed temperature as shown in Figs. 8(a) and (d). Of course, it should be considered that one of the benefits of MD is its capability of relatively low temperature operation. In general, the thermal energy cost is higher if the feed temperature is higher. Accordingly, it is important to determine the feed temperature by considering not only PR but also the cost of thermal energy.

4. Conclusion

In this study, the energy efficiency in a pilot-scale DCMD system was analyzed through theoretical and experimental approaches. Key performance factors such as flux and PR were examined as a function of operation parameters such as feed temperature and flow rate. The following conclusions were withdrawn:

- Although the temperature difference between feed and distillate is important as the driving force for MD operation, other operation parameters such as feed flow rate and feed temperature were also found to be important. This is because the total thermal energy supplied to the MD module depends on these operation parameters.
- By monitoring the temperature changes in feed and distillate, the energy balance for the MD module could be established. It seems that the conductive thermal energy loss is substantial (0.42–0.6) in a single stage DCMD.
- PR, which represents the thermal energy efficiency, is almost linearly proportional to the flux or water recovery ratio. Accordingly, the thermal energy efficiency in a single stage DCMD should be improved by increasing flux or water recovery ratio.

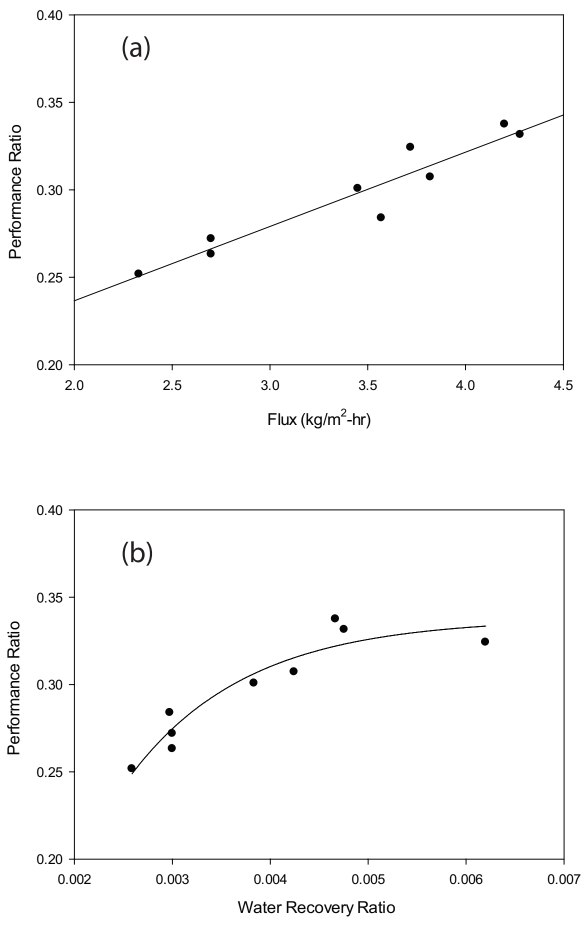


Fig. 9. (a) Performance ratio versus flux (b) performance ratio versus water recovery ratio.

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