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Application of membrane distillation in the management of thermal effluents from power plants

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ABSTRACT

Thermal effluents discharged from thermal power plants are problematic because of their adverse impact on receiving environments. Accordingly, it is necessary to develop technologies to mitigate the effect of thermal effluents on the aquatic environment. In this study, membrane distillation (MD) was applied to treat thermal effluents for the first time. Because MD can be operated by utilizing temperature difference between feed and product, it may produce freshwater from thermal effluents and reduce their temperature by transferring latent heat. To examine its feasibility, experiments were carried out in a semi-pilot direct contact MD equipment under various operating conditions. Based on real thermal effluent conditions, synthetic feed solutions were prepared. A series of experiments were conducted to measure flux, performance ratio, and temperature of the feed using a semi-pilot hollow fiber MD system during the treatment of the synthetic thermal effluents by MD. Results showed that MD hold potential to reduce the volume and temperature of the thermal effluents, thereby mitigating their possible impact.

Keywords: Thermal effluents; Membrane distillation (MD); Performance ratio (PR); Hollow fiber MD system

1. Introduction

In thermal power plants, thermal effluents are generated from the cooling processes and released into sea or river [1]. Thermal power plants should use a large amount of cooling water to cool down the engines and equipments for power generation [2–5]. The cooling water absorbs the waste heat of the power generation process and is discharged as thermal effluents with a high temperature. Only 40% of the energy input for electric power generation in a thermal power plant is converted into electricity, with another 40% discarded as waste heat in thermal effluents, and the rest is discarded as exhaust gas [6].

The influence of thermal effluents on the aquatic environment has received extensive attention over the last decades. Thermal effluents from power plants are discharged at about 7°C higher than the cooling water [7,8]. They have possible impact on receiving environments, including a decrease in the level of dissolved oxygen of water and adverse changes on aquatic animals such as fish and other aquatic organisms. Accordingly, it is necessary to mitigate the adverse effect of thermal effluents by reducing their volume and temperature. Unfortunately, few works have been carried out for the treatment of thermal effluents.

One of technologies that holds potential for thermal effluent treatment is membrane distillation (MD). MD is a thermally driven process using a porous hydrophobic membrane and a promising technology as a desalination process [9]. The thermal energy (or sensible heat) in the feed solution is used to produce water vapor in MD [10,11], and the thermal energy is transferred from feedwater to distillate together with water vapor [12,13].

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Compared with conventional water treatment techniques, MD has several unique advantages such as the possibility to concentrate high-salinity feedwaters and to use low-grade waste heat sources [10]. MD can utilize heat sources of low grade such as waste heat from industrial plants and solar heat due to its capability of low-temperature operation [14–17]. There are also other advantages of MD including easy scale-up, easy automation, reduction in chemical usage, high productivity/size ratio, high productivity/weight ratio, high simplicity in operation, and high flexibility [18].

In light of these aspects, this study examined MD as an innovative technology to mitigate the impact of thermal effluents. Because MD is operated by utilizing temperature difference between feed and product, it can produce freshwater from thermal effluents and reduce their temperature by transferring latent heat. The MD process is eco-friendly because (1) it can reduce the adverse impact of thermal effluent, and (2) it can use extra heat in thermal effluents. To assess the feasibility of MD, a series of experiments were conducted under various conditions using a semi-pilot hollow fiber MD system. Key performance parameters such as flux, recovery, and performance ratio (PR) were measured. To the best of our knowledge, this is the first study to apply a semi-pilot-scale MD process for the treatment of thermal effluents.

2. Materials and methods

2.1. MD module

Experiments were carried out using pilot-scale hollow fiber MD membrane modules (Econity, Korea). The detailed properties of the MD module were summarized in Table 1. The membrane was made of polyvinylidene fluoride. The shell diameter of membrane module was 0.29 m, and the length of the module of membrane was 0.84 m. The inner diameter and outer diameter of the membrane were 8×10^{-4} and 12×10^{-4} m, respectively. Moreover, the porosity was 0.8, and the membrane area per module of membrane was 7.6 m^2.

2.2. Pilot-scale MD system

The schematic diagram of the pilot-scale MD system is illustrated in Fig. 1. The operation mode was direct contact membrane distillation (DCMD). This MD system consisted of feed and distillate tanks, the MD module, temperature sensors, a heater, a cooler, and circulating pumps. The temperature of the feedwater and the distillate supplying to the MD module was controlled by using the heater, the cooler, and the temperature sensor.

In this system, MD was operated using heat in the feedwater. Thus, feed temperature was initially set to a given value, and no extra heat was supplied during the experiment. On the other hand, the distillate inlet temperature was maintained constant through the experiments. As a result, the temperature difference between feed and distillate decreased with time.

In the membrane module, the feedwater passed through the shell side and the distillate water entered to the tube side

Table 1
Properties of MD membrane module

Parameters	Membrane
Membrane material	Polyvinylidene fluoride (PVDF)
Shell diameter	0.29 m
Module length	0.84 m
Fiber inside diameter	8×10^{-4} m
Fiber outside diameter	12×10^{-4} m
Pore size	1×10^{-7} m
Porosity	0.8
Membrane area per module	7.6 m^2

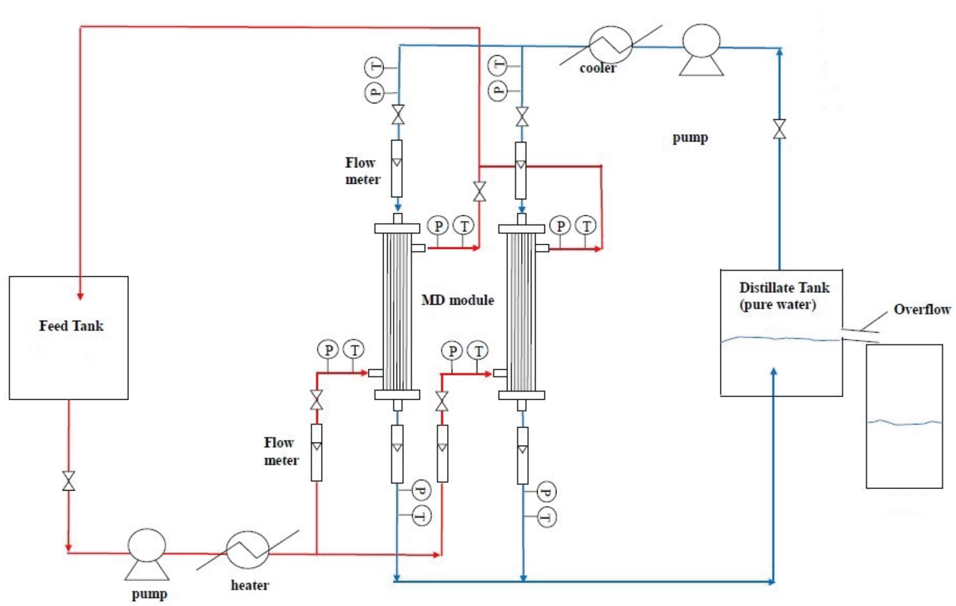

Fig. 1. Schematic diagram of the pilot-scale MD system.

Table 2
Summary of experimental conditions

Run	Feed flow rate (m^3/h)	Distillate flow rate (m^3/h)	Initial feed inlet (°C)	Average distillate inlet (°C)
1	0.9	0.6	41.5	33.2
2	0.9	0.6	36.1	28.7
3	0.9	0.6	33.3	24.9
4	0.9	0.6	28.7	20.9
5	0.9	0.6	24.4	17.1
6	1.8	1.2	40.4	32.6
7	1.8	1.2	36.1	28.8
8	1.8	1.2	31.9	24.9
9	1.8	1.2	28	20.9
10	1.8	1.2	24.6	17.3

(outside-in). The temperatures of feed inlet, feed outlet, distillate inlet, and distillate outlet were periodically measured and recorded. An electronic balance was used to measure the changes in the weight of the distillate water for the calculation of MD flux.

DCMD mode experiments were carried out based on the conditions summarized in Table 2. The feed flow rates were controlled from 0.9 to 1.8 m^3/h. The distillate flow rates were adjusted from 0.6 to 1.2 m^3/h. The simulated thermal effluents were prepared using a 35,000 mg/L NaCl solution. The initial feed inlet temperature ranged from 24.4°C to 41.5°C. The distillate inlet temperature ranged from 17.1°C to 33.2°C. To achieve similar conditions to real thermal effluents, the temperature differences between the feed and the distillate were maintained at 7.0°C–8.4°C.

3. Results and discussions

3.1. Changes in MD flux

There were two hydrodynamic conditions in this study: the low flow rate condition (feed flow: 0.9 m^3/h; distillate flow: 0.6 m^3/h) and the high flow rate condition (feed flow: 1.8 m^3/h; distillate flow: 1.2 m^3/h). Fig. 2 shows the changes in flux and the temperature difference between the feed and distillate as a function of operation time under the low flow rate condition. Because the feed temperature was not regulated, it decreased with time, leading to a reduced flux. Initially, the flux was approximately 0.33 kg/m^2 h with the initial temperature difference between feed and distillate of 7°C–8°C and decreased with time. The temperatures of feed and distillate did not significantly affect the flux as long as the temperature differences were similar.

The low flux values in this experiment are not surprising, because the driving force (vapor pressure difference) was small. For instance, the vapor pressures at 41.5°C and 33.2°C are 0.080 and 0.051 bar, respectively. Thus, the vapor pressure difference is only 0.029 bar, which resulted in 0.33 kg/m^2 h. This corresponds to the vapor permeability of 1.14 kg/m^2 h bar.

The variations in flux and temperature difference with time at the high flux rate condition are illustrated in Fig. 3. The results were similar to those at the low flow rate condition. The overall trends were similar in both cases. But the flux was slightly lower than that under the low flow rate condition. This suggests that an increase in flow rate is not effective to increase flux during the treatment of the synthetic thermal effluents.

3.2. Changes in feed temperature difference

When MD is applied to treat thermal effluents, it should not only produce water but also reduce the temperature of the feedwater. This implies that MD should be used as a special type of a heat exchanger. To investigate the efficiency of heat change by MD, the feed temperature differences between feed inlet and feed outlet were analyzed. If the feed temperature difference is larger, the heat exchange efficiency is higher. The results are shown in Fig. 4. With an increase in the feed inlet temperature, the feed temperature difference increased. Under the low flow rate condition (Fig. 4(a)), the initial feed temperature differences ranged from 4.8°C to 6.6°C and decreased to 1.8°C–3.3°C after 30 min. Under the high flow rate condition (Fig. 4(b)), they ranged from 5.7°C to 6.4°C and decreased to 1.8°C–2.7°C.

It should be noted that feed temperature difference was not zero during the MD experiments. As shown in Figs. 2 and 3, the flux became zero after a certain operation time. The reduction in feed temperature in MD is attributed to the transfer of latent heat and conduction through the membrane. If flux is zero, there is no transfer of latent heat. However, the conductive heat transfer still exists, leading to a further decrease in feed temperature. This implies that MD can work as a heat exchanger even with low-flux conditions.

3.3. Analysis of thermal efficiency

In addition to flux and temperature difference, thermal efficiency was also analyzed for each experiment. To calculate thermal efficiency, the energy balance should be established. The energy supplied to the MD system consists of three terms [10,19,20]:

$$Q_{\text{in}} = Q_{\text{out}} + Q_{\text{loss}} = Q_{\text{flux}} + Q_{\text{cond}} + Q_{\text{loss}} \tag{1}$$

where Q_{in} is the energy supplied 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 pipes, water tanks, and other parts. Q_{in} and Q_{flux} are given by [9,20]:

$$Q_{\text{in}} = \rho q_{f,\text{in}} C_p T_{f,\text{in}} - \rho q_{f,\text{out}} C_p T_{f,\text{out}} \tag{2}$$

$$Q_{\text{out}} = \rho q_{d,\text{out}} C_p T_{d,\text{out}} - \rho q_{d,\text{in}} C_p T_{d,\text{in}} \tag{3}$$

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

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

where r is the water density, $q_{f,\text{in}}$ is the feed inflow rate, $q_{f,\text{out}}$ is the feed outflow rate, $q_{d,\text{in}}$ is the distillate inflow rate, $q_{d,\text{out}}$ is the distillate outflow rate, C_p is the heat capacity of water, $T_{f,\text{in}}$ is the feed inlet temperature, $T_{f,\text{out}}$ is the feed

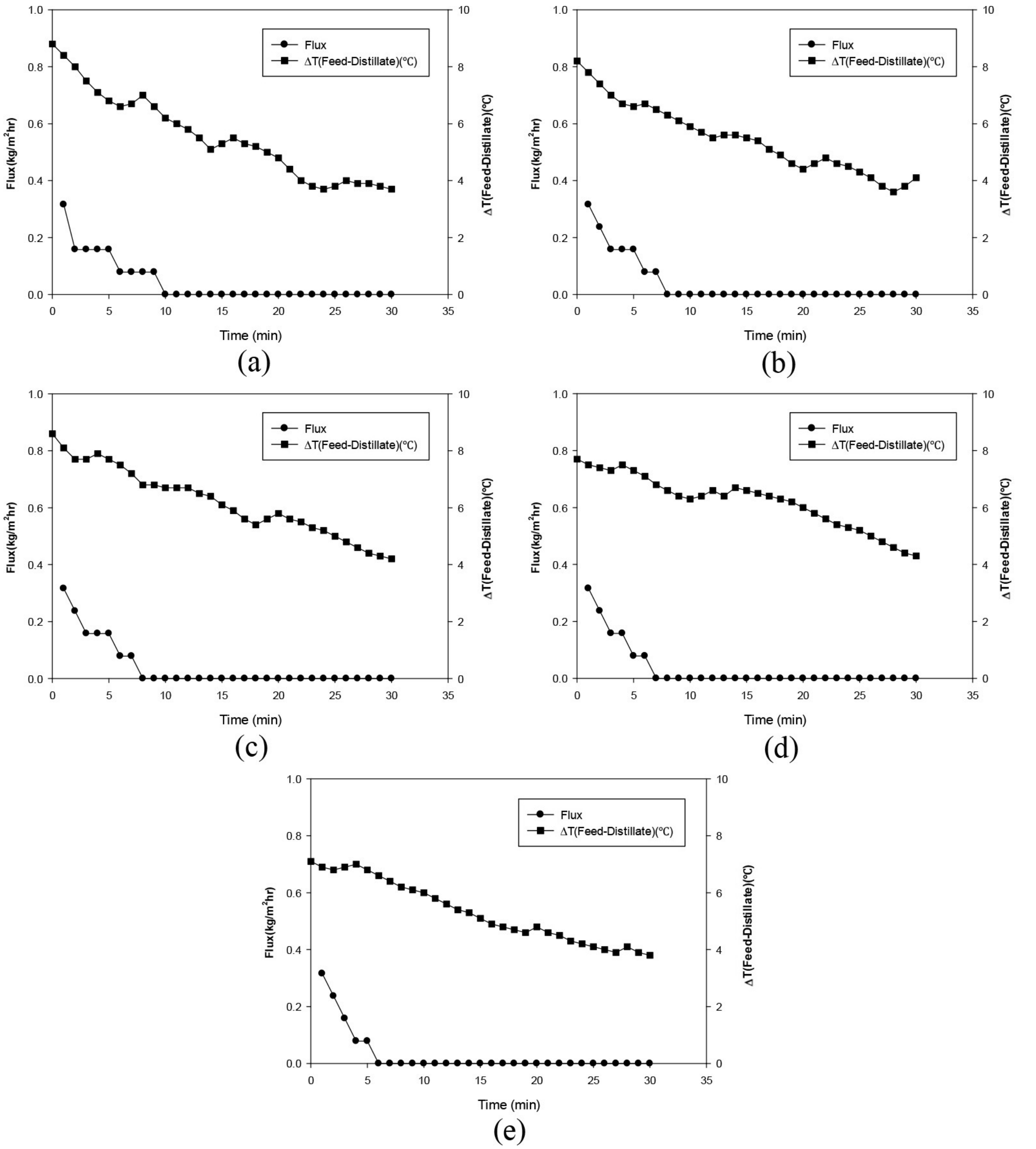

Fig. 2. Variations in flux and temperature difference under different feed and distillate temperatures at low flow rate conditions (conditions—feed flow: 0.9 m³/h; distillate flow: 0.6 m³/h): (a) 41.5°C–33.2°C, (b) 36.1°C–28.7°C, (c) 33.3°C–24.9°C, (d) 28.7°C–20.9°C, and (e) 24.4°C–17.1°C.

outlet temperature, $T_{d,\mathrm{in}}$ is the distillate inlet temperature, $T_{d,\mathrm{out}}$ 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.

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. Accordingly, it is important to increase PR to reduce the cost for the thermal energy for MD. In a single-stage distillation, PR is less or equal to 1.0 and in a multi-stage distillation, PR is proportional to the number of stages. In a single-stage DCMD system, PR can be given as follows:

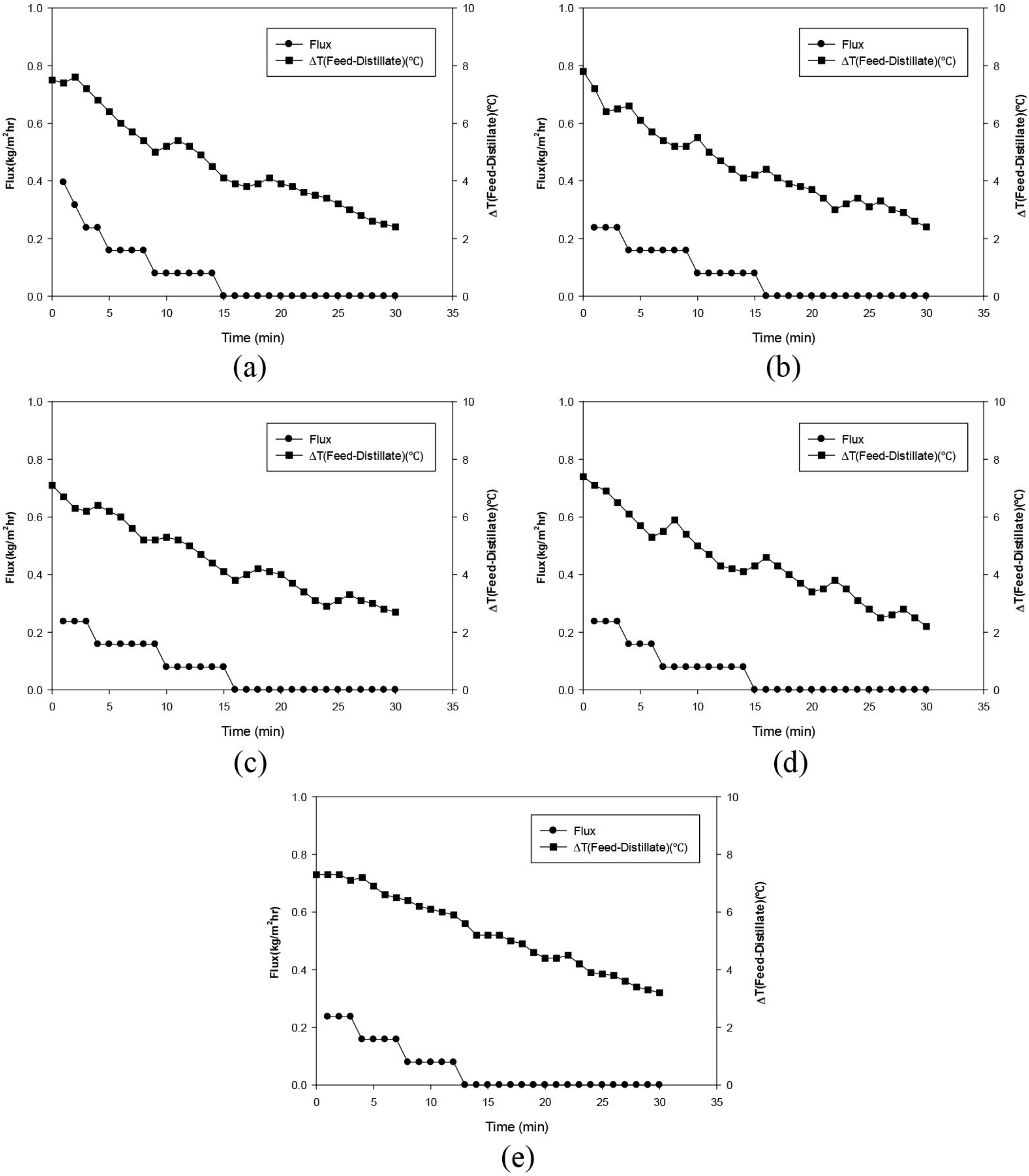

Fig. 3. Variations in flux and temperature difference under different feed and distillate temperatures at high flow rate conditions (conditions—feed flow: 1.8 m^3/h; distillate flow: 1.2 m^3/h): (a) 40.4°C–32.6°C, (b) 36.1°C–28.8°C, (c) 31.9°C–24.9°C, (d) 28°C–20.9°C, and (e) 24.6°C–17.3°C.

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

The results of average flux and PR in each case were shown in Table 3 and Fig. 5. The PR ranged from 0.062 to 0.168 while the flux ranged from 0.130 to 0.174 kg/m^2 h. With decreasing temperature difference between the feed and

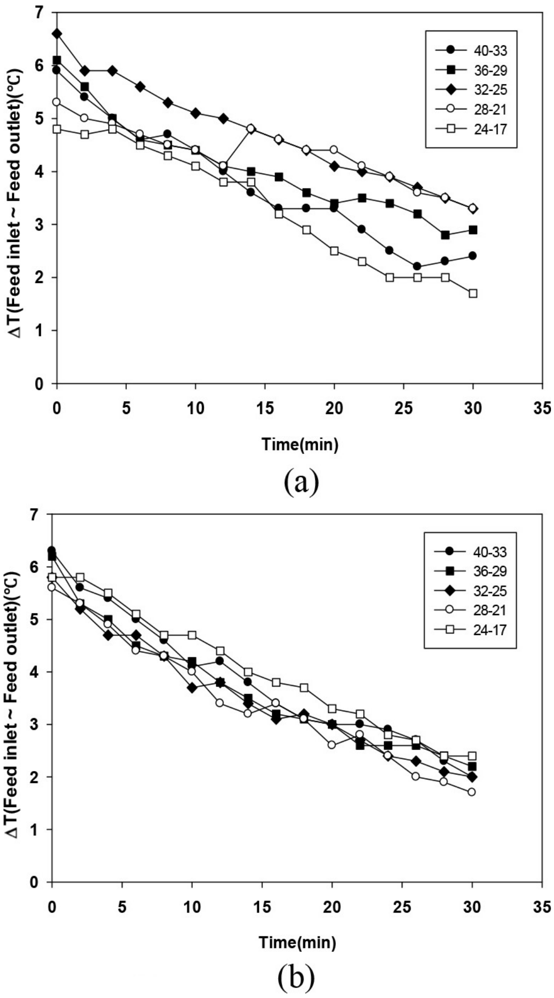

Fig. 4. Temperature differences between feed inlet and feed outlet over time in each experimental condition: (a) 0.9–0.6 m^3/h and (b) 1.8–1.2 m^3/h.

Table 3
Results of flux and performance ratio in each experimental condition

Run	Flux (kg/m²·h)	PR
1	0.174	0.156
2	0.171	0.150
3	0.169	0.146
4	0.163	0.149
5	0.158	0.143
6	0.164	0.079
7	0.142	0.078
8	0.142	0.078
9	0.130	0.070
10	0.125	0.059

distillate, water flux from MD significantly decreased, and PR also decreased. This is attributed to a low second law efficiency at low-feed temperature conditions.

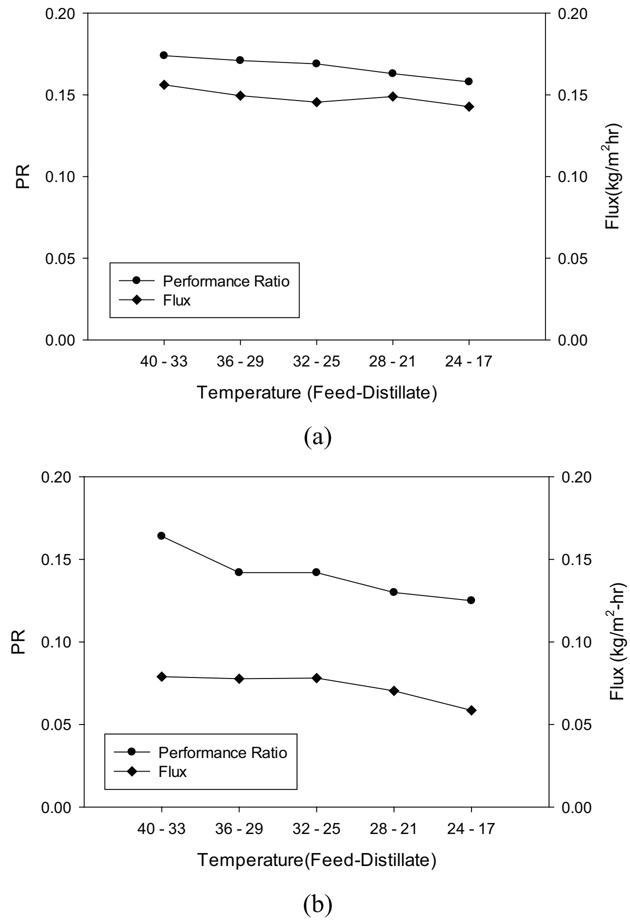

Fig. 5. Effect of feed and distillate temperatures on PR: (a) low flow rate condition (0.9–0.6 m^3/h) and (b) high flow rate condition (1.8–1.2 m^3/h).

The recovery of distillate from the experiments was always lower than the theoretical recovery calculated from the total thermal energy in the feedwater. It is evident from the results that the difference between experimental and theoretical recoveries becomes larger with a decrease in PR.

4. Conclusions

The feasibility of MD application for the treatment of thermal effluents by utilizing its thermal energy was investigated in this study. The following conclusions were drawn:

1. With the initial temperature difference of about 7°C between feed and distillate, the initial MD flux ranged from 0.25 to 0.33 kg/m² h. This suggests that MD may have potential to produce fresh water from thermal effluent using such a small temperature difference.
2. As the MD operation continued, the temperature difference decreased with the operation time, leading to a reduction in MD flux. The average flux was measured in the range of 0.125–174 kg/m² h. Increasing flow rates of feed and distillate did not increase flux
3. The temperature differences between feed-inlet and feed-outlet in each experimental condition decreased

from about 7°C to 2°C for 30 min. This implies that MD works as a heat exchanger as well as a desalination process in the presence of a heat sink.

4. The calculated PR values were in the range from 0.059 to 0.156. Because the temperature difference was low, the second law efficient was low, resulting in low PR values. However, PR may be improved by recovering and reusing thermal energy as it has been performed in other distillation systems.

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