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Energy efficiency evaluation of a compact direct contact membrane distillation system using thermoelectric modules

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ABSTRACT

Energy efficiency of a compact direct contact membrane distillation (DCMD) system using a thermoelectric module (TEM) applicable for water production was evaluated in this study. The TEM acts as a heat pump by suppling energy required for the feed side in the DCMD system by absorbing and transferring heat from the condensate side. The TEM coupling improved the energy efficiency of the DCMD system, and the specific energy consumption decreased from 4.8 kWh/kg (conventional DCMD system) to 2.4 kWh/kg (cooling enhanced DCMD-TEM system). The energy balance around the DCMD system showed that the TEM coupling reduced the temperature polarization effect, which led to the improvement of energy efficiency. The temperature polarization coefficient increased from 0.23 (conventional DCMD system) to 0.39 (CEDCMD-TEM system).

Keywords: Direct contact membrane distillation (DCMD); Thermoelectric module (TEM); Specific energy consumption; Temperature polarization coefficient

1. Introduction

Direct contact membrane distillation (DCMD) is the most commonly used configuration for MD applications due to its simplicity [1–7]. Hot feed is in direct contact with cold condensate through a thin hydrophobic membrane at this configuration [1,3,4,8]. Disadvantage of the DCMD is low energy efficiency [3,6,9]. This configuration tends to have high conduction loss [1,2,6,9]. Since the feed loses energy due to evaporation and conduction during operation, water temperature decreases as the feed leaves a membrane module. On the other hand, water temperature increases on the condensate side. A heater and a chiller are therefore employed to maintain the constant temperatures at the feed and the condensate. Unfortunately, a heater and a chiller consume a substantial amount of energy, which makes the conventional DCMD system energy inefficient. Inclusion of a heater and a chiller also makes the DCMD system bulky. A chiller can be eliminated from the conventional DCMD system when cooling water is available. However, a chiller should be provided to the DCMD system when cooling water is unavailable.

There was an attempt to negate a heater and a chiller from the conventional DCMD system [10]. A compact wastewater distillation system applicable to the space mission was searched in their study. They proposed the thermoelectric membrane distillation (TMD) system, at which the thermoelectric module (TEM) was embedded at the hydrophobic membrane surface. This design allowed simultaneous retentate heating and permeate cooling without a heater and a chiller. Although this proof-of-concept of TMD design was validated, the study lacked the performance evaluation such as energy efficiency because this study was aimed to develop an engineering design concept. There was another study combining TEM with MD, which was applied for space cooling and water production [11]. They hybridized TEM with SGMD (sweeping gas membrane distillation) process (T-SGMD) in order to reduce the cooling load of

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the system. It was found in their study that the coupling of TEM to the SGMD allowed less energy consumption and more condensate production. The T-SGMD system was thoroughly evaluated in this study with varying operation parameters such as feed temperature, membrane area, presence of recycling, and module configuration. This study was more focused on cooling improvement. The SGMD process was mainly used to improve the cooling efficiency with minimal condensate production.

The energy efficiency of a compact DCMD system for water production is evaluated in this study. The TEM replaced a heater and a chiller. The TEM is a small device based on the thermoelectric effect, which is the direct conversion of temperature differences to electricity, or vice versa [12]. The TEM consists of a hot side and a cold side like the DCMD system, and it can act as a heat pump transferring heat from a cold side to a hot side when an electric current is applied to the device. When the TEM is coupled to the DCMD system, the TEM can absorb heat accumulated at the condensate side, and transfer the absorbed heat to the feed side. This indicates that the TEM can replace a heater and a chiller from the DCMD system. It is expected that the TEM coupling can make the DCMD system energy efficient because the TEM can replace a heater and a chiller. This hypothesis is tested in this study. The TEM coupled DCMD system operates on electrical energy, unlike the conventional DCMD system, which requires on thermal energy and electrical energy. The energy efficiency of the DCMD system was therefore evaluated by the specific energy consumption (SEC), which is the ratio of the energy input to the distillate produced.

2. Materials and methods

2.1. Membrane and module

Hydrophobic hollow fiber membrane made of polyvinylidene fluoride (PVDF) (Econity, Republic of Korea) was used in this study. The outside and inside diameters of fiber are 1.2 and 0.7 mm, respectively. Membrane characteristics were provided by the Econity. Average pore size of fiber is 0.1 µm. The porosity is 60%. The contact angle is 120°. The liquid entry pressure (LEP) is 1.8 bar. Long fibers (1.2 m) were used for an experiment. Twenty fibers were put into a membrane module so as to have a membrane area of 0.09 m^2. The module has an outside diameter of 36 mm, and its thickness is 3 mm.

2.2. Thermoelectric module

Characteristics of TEM (TEC1-12715, DC12V), which made of Bi_2Te_3 are provided by the manufacturer. They are shown in Table 1. The width and length of TEM are 40 mm, and its thickness is 1.5 mm. The TEMs are installed in a water block, as shown in Fig. 1.

The Seebeck coefficient (α) relates an applied electric voltage to the temperature difference, as shown in Eq. (1). According to preliminary experiments, the Seebeck coefficient was found 0.06 V/K. The endothermic and exothermic heat fluxes of the TEM can be calculated using Eqs. (2) and (3) [13]. The power requirement of TEM can be estimated by the difference of the exothermic and the endothermic fluxes, as shown in Eq. (4).

Table 1
Characteristics of the thermoelectric module used in this study

Description		Values
Q_{max}, W	Cold side	142
	Hot side	180
I_{max}, A		11.8
V_{max}, V		12
T_{max}, °C		90
ΔT_{max}, °C		67
Thermal conductivity, W/m K		1.5
Electric resistance, ohm		0.89

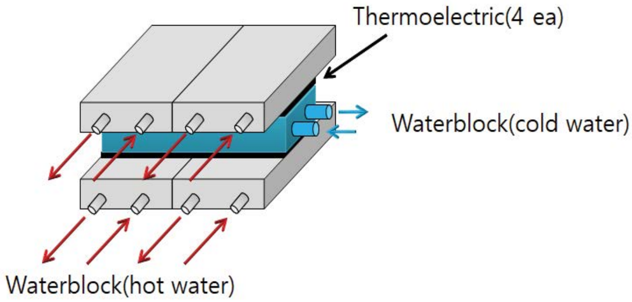

Fig. 1. Schematic of water block including TEMs used in this study.

$$V = \alpha \cdot \Delta T \tag{1}$$

$$q_C = \alpha \cdot T_C \cdot I - 0.5 \cdot I^2 \cdot R - \kappa \cdot \Delta T \tag{2}$$

$$q_H = \alpha \cdot T_H \cdot I + 0.5 \cdot I^2 \cdot R - \kappa \cdot \Delta T \tag{3}$$

$$W = q_H - q_C \tag{4}$$

where V is the voltage, V; α is the Seebeck coefficient, V/K; q_C is the endothermic heat flux, W; q_H is the exothermic heat flux, W; T_C is the temperature of cold side of TEM, K; T_H is the temperature of hot side of TEM, K; ΔT is the temperature difference between the cold side and the hot side, K; I is the direct current, A; R is the electric resistance of TEM, ohm; κ is the thermal conductivity of TEM, W/m K; W is the power requirement of TEM.

2.3. Conventional DCMD system

Schematic of the conventional DCMD system is shown in Fig. 2. The water bath (Jeio Tech, BW-05G, Republic of Korea) was used to maintain the feed temperature at 70°C, while a chiller (Daeho chiller, DH-1A, Republic of Korea) was used to maintain the condensate temperature at 20°C. Four thermocouples (T/C wire, *k*-type, Republic of Korea) were installed in order to monitor the temperature change along membrane at the feed and condensate sides. Monitored temperatures were sent to the data collector

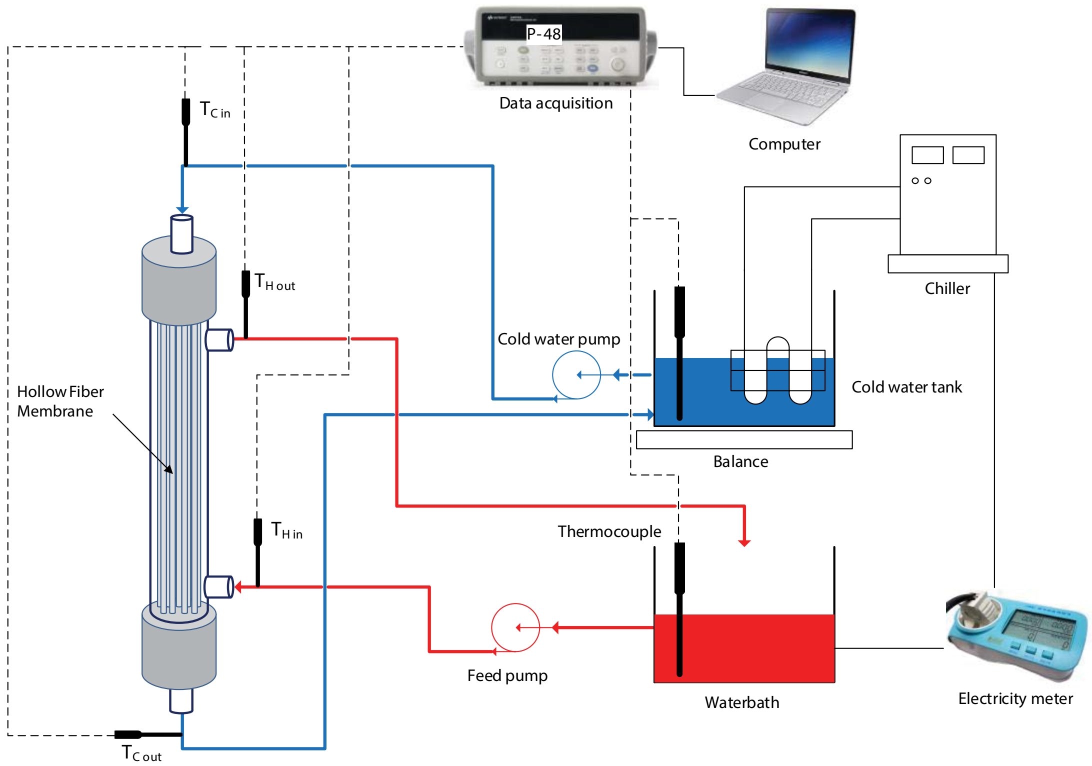

Fig. 2. Schematic of the conventional DCMD system.

(Agilent, 34970A, U.S.A.) every minute. The volume of the condensate tank is 2 L. The feed and the condensate was circulated at the flow rate of 1 L/min. The amount of the condensate was measured every minute by a balance (AND, EK-6100i). The energy consumption of the system was measured by the watthour meter (Seojun Electric, SJPM-C16, Republic of Korea).

2.4. DCMD-TEM system and CEDCMD-TEM system

The DCMD-TEM system is shown in Fig. 3a. A difference of the DCMD-TEM system from the conventional DCMD system is inclusion of TEMs instead of a heater and a chiller. Four TEMs replaced a heater and a chiller in the DCMD-TEM system. The switching power supply (NES-350-12) converted the alternating current to the direct current. It was found out during the operation of the DCMD-TEM that the water temperature kept increasing at the feed and condensate sides, which will be explained later. Therefore, two TEMs were added and cooling was enhanced (cooling enhanced DCMD-TEM system, CEDCMD-TEM). Fig. 3b) shows the CEDCMD-TEM system. A difference of the CEDCMD-TEM system from the DCMD-TEM system was the number of TEMs. There were four TEMS in the DCMD-TEM system, and six TEMs in the CEDCMD-TEM system.

2.5. Experiments

The sodium chloride solution (2,000 mg/L) was used as the feed and the tap water as the condensate. The electric conductivity of tap water was about 33 µS/cm. The period of the DCMD operation was an hour. After an hour of operation, the amount of distillate produced and the energy consumed were measured. The energy efficiency of the DCMD system was evaluated by the SEC, which is the ratio of the energy input (kWh) to the distillate produced (kg), and the system energy efficiency (η_{sys}), which is the proportion of the energy used for the distillate production to the energy input.

3. Results and discussion

3.1. Conventional DCMD system

Operational results of the conventional DCMD system are shown in Fig. 4. The temperatures of the feed and the condensate were maintained constant during the operation. The feed entered the membrane module at 63.9°C, and left the module at 55.6°C. The condensate temperature increased from 28.3°C to 34.5°C. The temperature change along the membrane module was 8.3°C at the feed side and 6.2°C at the condensate side, respectively. Average temperature difference between the hot feed and the cold condensate was calculated 28.4°C (59.8°C/31.4°C). The energy consumptions of a heater and a chiller were measured 0.88 and 0.75 kWh, respectively. The amount of distillate produced was recorded 0.3417 kg for an hour of operation, which corresponded to the distillate flux of 3.8 kg/m²/h. The SEC of the conventional DCMD system was therefore calculated 4.8 kWh/kg. Assuming the heat of evaporation of water as 2,400 kJ/kg, the gained output ratio (GOR) of the conventional DCMD system was calculated 0.26.

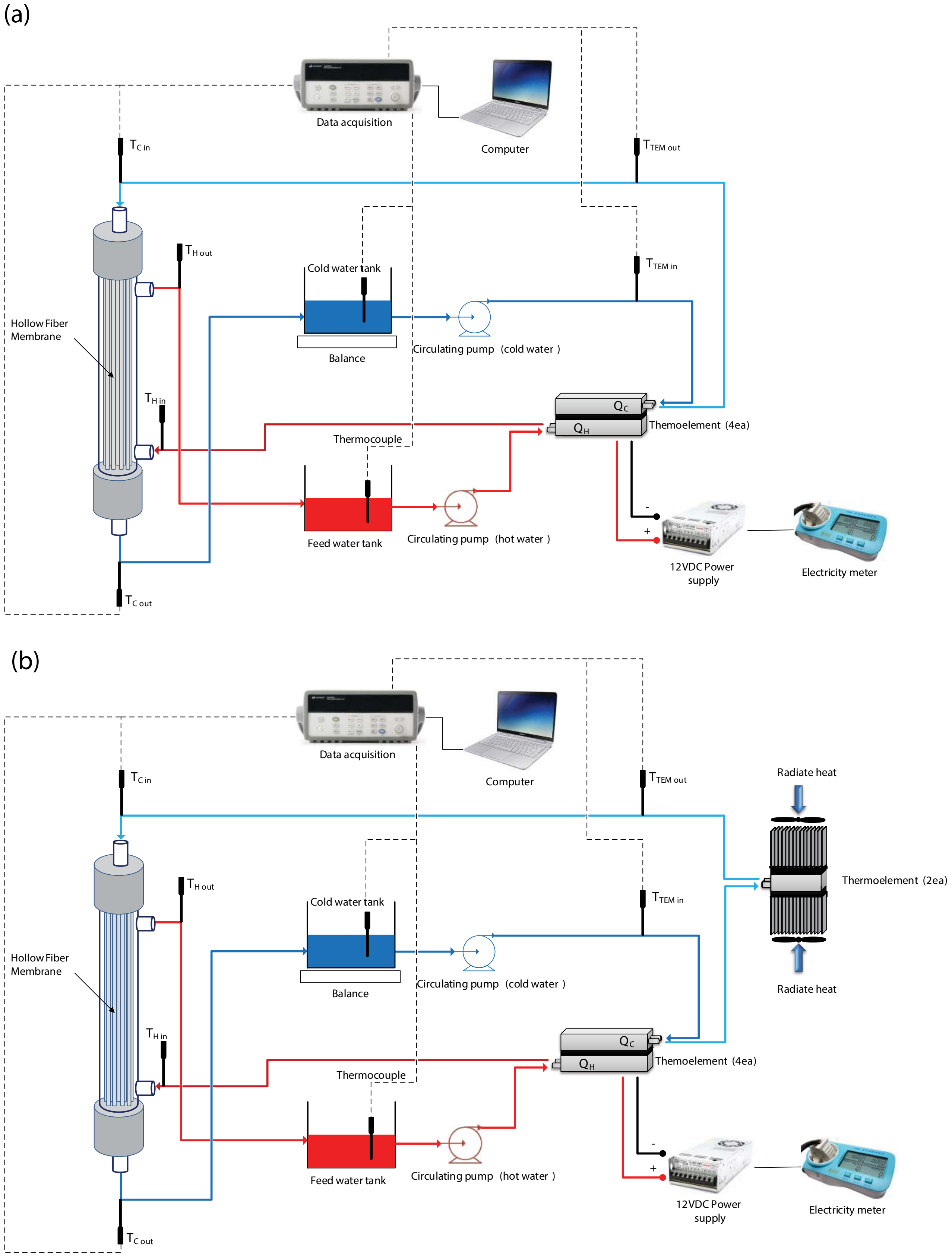

Fig. 3. (a) Schematic of the DCMD-TEM system and (b) schematic of the CEDCMD-TEM system

Energy was balanced around the conventional DCMD system. The results are summarized in Table 2. The energy input was 1.63 kWh. The energy requirement for the distillate production was calculated 0.23 kWh, based on the amount of the distillate produced (0.3417 kg/h) and the heat of evaporation of water (2,400 kJ). This result indicates that the energy put into the distillate production was minimal, and the energy efficiency of the conventional DCMD system became 0.14. There were four kinds of energy loss; heating loss (Q_{heat}), cooling loss (Q_{cool}), conduction loss (Q_{cd}), and the system loss (Q_{sys}). The heating loss (0.30 kWh), which is related to the efficiency of a heater, was calculated by subtracting the heating requirement (0.58 kWh) from the energy consumption of a heater (0.88 kWh). The energy requirements of heating and cooling (0.43 kWh) were calculated using the water temperature change at the feed side (8.3°C), and the condensate temperature change (6.2°C), respectively. The energy consumption of a chiller (0.75 kWh) became the cooling loss. The system loss (0.15 kWh) was calculated by subtracting the energy requirement of cooling (0.43 kWh) from that of heating (0.58 kWh). The remaining loss was regarded as the conduction loss (0.20 kWh).

The conduction loss was also calculated using Eq. (5). Since temperatures at membrane surfaces were not known, bulk temperature difference (28.4°C) between the feed and the condensate was used for the calculation. The calculation showed the conduction loss of 0.87 kWh, which was substantially higher than the value (0.20 kWh) mentioned above. This is due to the temperature polarization effect (TPC). The smaller value (0.20 kWh) could be the conduction loss based on the transmembrane temperature difference, while larger value (0.87 kWh) based on the bulk temperature difference. The temperature polarization coefficient (TPC) of 0.23 was calculated using these two values. The transmembrane temperature change became 6.5°C at TPC of 0.23.

$$q_{\text{cd}} = \kappa_m \cdot \Delta T \cdot (\text{MA}/\delta) \tag{5}$$

$$\kappa_m = (1 - \varepsilon)\cdot\kappa_s + \varepsilon\cdot\kappa_g \tag{6}$$

$$\kappa_g = 2.72 \times 10^{-3} + 5.71 \times 10^{-5} T \tag{7}$$

$$\text{TPC} = \frac{\left(T_{\text{mh}} - T_{\text{mc}}\right)}{\left(T_h - T_c\right)} \tag{8}$$

where q_{cd} is the conduction loss rate, W; κ_m is the thermal conductivity of membrane, W/m K; κ_s is the thermal conductivity of polymer (PVDF), W/m K; κ_g is the thermal conductivity of water vapor, W/m K; ΔT is the transmembrane temperature change, K; MA is the membrane area, m^2; δ is the membrane thickness, m; ε is the membrane porosity; T_{mh} is the temperature at membrane surface of the hot side; T_{mc} is the temperature at membrane surface of the condensate side; T_h is the temperature at the feed (bulk); T_c is the temperature at the condensate (bulk).

Table 2 shows that most of the energy added was lost through cooling and heating in the conventional DCMD system. It is therefore important to increase the energy efficiency of a chiller (0.57) and a heater (0.66). If their efficiencies could be improved to 1.0, the SEC of the conventional DCMD system would decrease from 4.8 to 3.0 kWh/kg. The corresponding GOR would increase from 0.26 to 0.39.

3.2. DCMD-TEM system

The number of TEMs required for the DCMD system was calculated based on the system cooling requirement. The energy requirement of cooling for the DCMD system was 0.43 kWh, as mentioned above. According to Table 1, the maximum amount of heat absorbable by single TEM is 142 Wh. It was therefore determined to employ four TEMs for the DCMD-TEM system. Operational results of the DCMD-TEM system are shown in Fig. 5. It was noted that both temperatures of the feed and the condensate kept increasing in the DCMD-TEM system, unlike the conventional DCMD system. The feed temperature entering a membrane module increased from 60.7°C to 67.4°C after 1 h of operation, while the feed temperature leaving the module increased from 47.8°C to 54.3°C. The condensate temperature entering the module increased from 27.5°C to 43.3°C, and the condensate temperature exiting from the module increased from 39.6°C to 50.7°C. The temperature changes along the module were 13.1°C at the feed side, and 7.4°C at the condensate side, respectively. Average temperature difference between the hot feed and the cold condensate was 13.9°C (60.9°C/47.0°C). The energy consumption of the DCMD-TEM system was measured 0.5 kWh, which indicates that single TEM consumed 0.125 kWh of energy. The distillate production (0.2969 kg) decreased, compared

Table 2
Summary of the energy balance calculation for different DCMD systems

Description		Conventional DCMD system	DCMD-TEM system	CEDCMD-TEM system
Energy input, kWh		1.63	0.50	0.75
Distillate production, kWh		0.23	0.20	0.21
Loss, kWh	Heating	0.30	–	–
	Cooling	0.75	–	0.20
	TEM	–	0.10	0.15
	Conduction	0.20	0.17	0.18
	System	0.15	0.03	0.01
	Sum	1.4	0.30	0.54

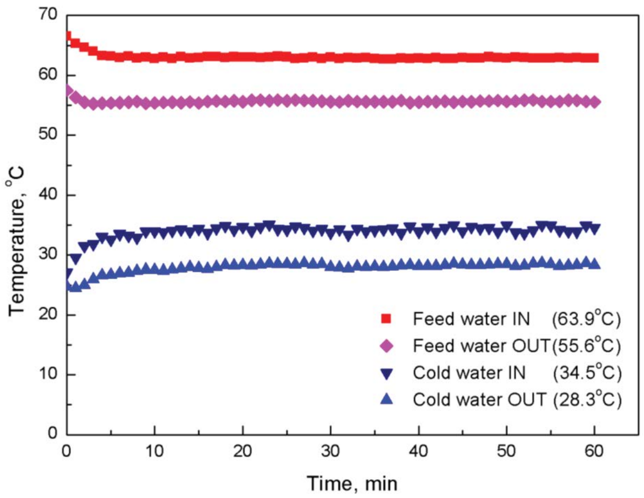

Fig. 4. Operational results of the conventional DCMD system.

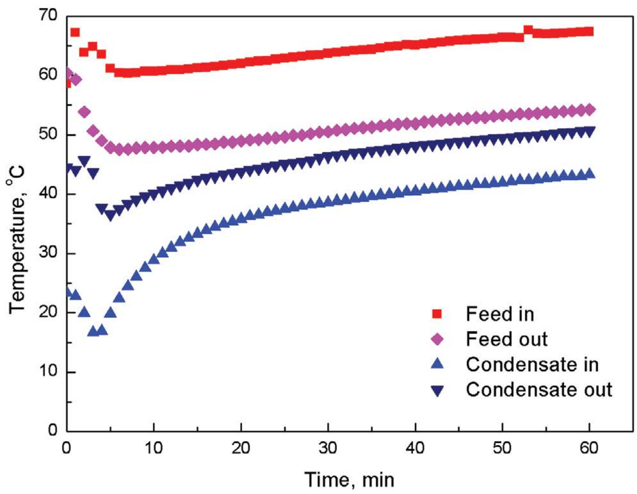

Fig. 5. Operational results of the DCMD-TEM system.

to the conventional DCMD system (0.3417 kg) probably due to smaller temperature difference (13.9°C vs. 28.4°C). The distillate flux and the SEC were calculated 3.3 kg/m^2/h and 1.7 kWh/kg, respectively.

The DCMD-TEM system utilized energy more effectively than the conventional DCMD system. Energy associated with the distillate production was calculated 0.20 kWh, and total energy loss was 0.30 kWh. The energy efficiency of the DCMD-TEM system (0.4) was higher than that of the conventional DCMD system (0.23), indicating higher energy efficiency of the DCMD-TEM system. There were three heat losses in the DCMD-TEM system; TEM loss, conduction loss and system loss. The TEM loss was calculated by subtracting the energy requirement of TEMs (0.40 kWh) from the energy consumption (0.50 kWh). The power requirement of TEM was calculated using Eqs. (2)–(4). The calculation showed that the endothermic flux at the cold side of TEM was 122 W, and the exothermic flux was 222 W. Subsequently, the power requirement of single TEM was 100 W. Since four TEMs were employed for the DCMD-TEM system, the TEM loss became 0.10 kWh. The transmembrane temperature change at the DCMD-TEM system was calculated using the amount of distillate produced assuming the distillate production was proportional to the transmembrane change. The calculation showed the transmembrane temperature change of 5.6°C, which was then used to calculate the conduction loss (0.17 kWh). The remaining loss became the system (0.03 kWh), which indicates that the DCMD-TEM system significantly reduced the system loss. The TPC (0.4) was then calculated using the calculated transmembrane temperature difference and bulk temperature difference (13.9°C).

3.3. CEDCMD-TEM system

In order to stabilize the water temperature inside the membrane module, cooling was enhanced using two TEMs, as mentioned earlier. Operational results of the CEDCMD-TEM system are shown in Fig. 6. Cooling enhancement was able to keep temperatures of the feed and the condensate constant. The feed entered the membrane module at 55.7°C, and left at 45.6°C. The condensate entered the module at 31.2°C and left at 39.7°C. The temperature changes along the membrane module were 10.1°C at the feed and 8.5°C at the condensate, respectively. Average temperature difference between the hot feed and the cold condensate was 15.2°C (50.7°C/35.5°C). The energy consumption of the CEDCMD-TEM system was measured 0.75 kWh. The amount of distillate produced was 0.3082 kg during an hour of operation. The SEC of the CEDCMD-TEM system was calculated 2.4 kWh/kg.

The energy balance of the CEDCMD-TEM system was similar to that of the DCMD-TEM system. The only

Table 3
Comparison of energy utilization for different DCMD systems

Description	Conventional DCMD system	DCMD-TEM system	CEDCMD-TEM system
Thermal efficiency	0.53	0.54	0.53
Temperature polarization coefficient (TPC)	0.23	0.40	0.39
Energy efficiency	0.14	0.40	0.28
Specific energy consumption (SEC), kWh/kg	4.8	1.7	2.4
Gained output ratio (GOR)	0.26	0.79*	0.60*

*GOR was calculated based on the heating energies of 0.25 kWh (DCMD-TEM system) and of 0.38 kWh (CEDCMD-TEM system).

difference is addition of the cooling loss. Energy associated with the distillate production was 0.21 kWh, and total energy loss was 0.53 kWh. The energy efficiency of the CEDCMD-TEM system (0.28) was lower than the DCMD-TEM system. The calculated power requirement of single TEM in the CEDCMD-TEM system (100 W) was same as that in the DCMD-TEM system. Since six TEMs were employed for the CEDCME-TEM system, the TEM loss became 0.15 kWh. Since two TEMs were used for cooling, the cooling loss became 0.20 kWh. The calculation using the amount of distillate produced led to the calculation of the transmembrane temperature change at the DCMD-TEM system of 5.9°C, which was then used to calculate the conduction loss (0.18 kWh). The system loss became 0.01 kWh. The TPC of the CEDCMD-TEM system (0.39) was very similar to that of the DCMD-TEM system (0.40).

3.4. Energy utilization

Comparison result of energy utilization performances of three different DCMD systems is presented in Table 3. All systems showed similar thermal efficiency (0.53–0.54), which is specified as the ratio of latent heat of vaporization to the sum of latent heat and conduction loss [14,15]. A difference was noted in the TPC. The TPC was low (0.23) for the conventional DCMD system, while it was higher (0.39/0.40) for the TEM coupled DCMD systems. An increase in the TPC led to high energy efficiency, which is the ratio of energy utilized for the distillate production to the energy input. The energy efficiency of the conventional DCMD system was 0.14, while those of DCMD-TEM system and the CEDCMD-TEM were 0.40 and 0.28, respectively. However, operation of the DCMD-TEM system was unstable, and temperature kept increased, as mentioned above. Cooling enhancement (CEDCMD-TEM system) was able to suppress the temperature increase, indicating that sufficient cooling should be provided for the TEM coupled DCMD system. Improved performance of energy utilization was reflected in the SEC. The SEC decreased from 4.8 to 2.4 kWh/kg (CEDCMD-TEM system). The GOR of the TEM coupled system was calculated, based on the assumption that equal amount of energy was used for heating and cooling (0.38 kWh). This was a reasonable assumption, considering the minimal system loss (0.01 kWh). The TEM coupling increased the GOR from 0.26 to 0.60. Improved energy efficiency through the TEM coupling to the DCMD system suggests economic benefit. Since the SEC of the CEDCMD-TEM system is half of that of the conventional DCMD system, the TEM coupling could reduce the energy cost by half. It could also contribute to the capital cost reduction because the TEM cost significantly less than cost of a heater and a chiller.

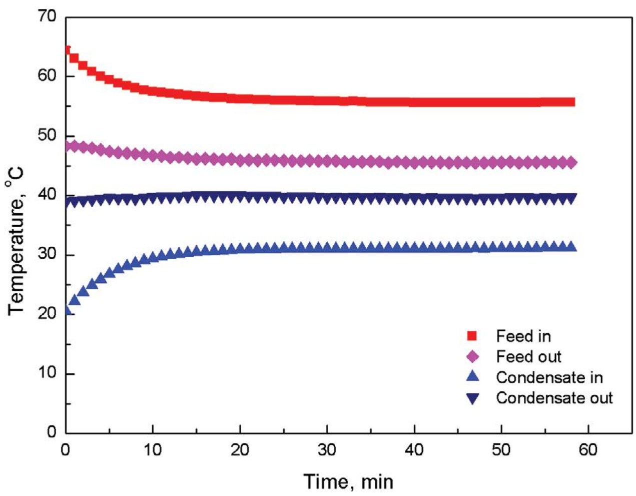

Fig. 6. Operational results of the cooling enhanced DCMD-TEM system.

4. Conclusions

Energy efficiency of a compact DCMD system using a small electrical device of TEM applicable for water production was evaluated in this study. The TEM coupling to the DCMD system contributed to the improvement of the energy efficiency of the DCMD system. The TEM coupling decreased the SEC by half from 4.8 kWh/kg (conventional DCMD system) to 2.4 kWh/kg (CEDCMD-TEM system). Increased TPC (0.23–0.39) contributed to the improvement of the energy efficiency. Since TEM can act as a chiller and a heater, these bulky devices were precluded from the TEM-coupled DCMD system. Such preclusion allowed the DCMD system to be compact.

Acknowledgments

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