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Improvement of membrane distillation performance through enhancement of the heat retaining capacity of the heat storage tank using phase change material

Seung-Hyun Kim*, Hwan Kyu Lim

Department of Civil and Environmental Engineering, Kyungnam University, 7 Kyungnamdaehak-ro, Masanhappo-gu, Changwon-si, Gyeongsangnam-do, 51767, Korea, Tel. +82 2 3700 0796; Fax: +82 2 3700 0783; email: shkim@kyungnam.ac.kr (S.-H. Kim)

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ABSTRACT

This study was conducted to find the method to improve the membrane distillation (MD) performance though enhancement of the heat retaining capacity of the heat storage tank. For this purpose, phase change material (PCM) such as paraffin and stearic acid was used. It was found in this study that use of PCM was able to enhance the heat retaining capacity of the heat storage tank. The heat retaining capacity was increased by 55% when paraffin was added into the heat storage tank. The beneficial effect was further increased to 114% when paraffin and stearic acid were added together into the heat storage tank. The enhanced heat storage capacity led to the MD performance improvement. When the MD system was driven by the PCM reinforced heat storage tank, distillate production increased, and water recovery increased water from 1.2% (without PCM) to 2.5% (with single PCM), to 3.8% (with dual PCM). PCM was effective in retarding heat transfer from the heat storage tank. The heat transfer coefficient of the heat storage tank decreased from 38 W/m^2 K (without PCM) to 19 W/m^2 K (with single PCM), to 16 W/m^2 K (with dual PCM) when MD was in operation. The energy efficiency of the MD system improved due to reduced heat transfer. Performance ratio of the MD system increased from 0.19 (without PCM) to 0.24 (with single PCM), to 0.35 (with dual PCM).

Keywords: Phase change material; Membrane distillation; Heat storage tank; Paraffin; Stearic acid

1. Introduction

Membrane distillation (MD) is a hybrid desalination technology of conventional thermal and membrane technology. MD runs on thermal energy, but evaporation occurs at membrane. MD has several advantages over conventional desalination technologies. The main advantages are low operating pressure and temperature. MD does not need high operating pressure like membrane technology, either high operating temperature like thermal technology [1,2]. Therefore, MD has drawn much attention from the desalination community, but its commercialization has progressed slowly mostly due to economic reason. MD is economically competitive only when inexpensive energy source is available [3].

Consequently, there have been attempts to combine MD technology with renewable energy source, that is, solar power [3–5]. The solar powered MD system consists of solar collector, heat storage tank, and MD module. The solar collector captures the solar energy while sunlight is available. The captured energy is stored in the heat storage tank filled with water. The stored energy is then used to drive the MD system. It is important, therefore, for the heat storage tank, which is the energy source of the MD system, to retain the heat energy as long as possible because heat energy is quickly dissipated from the heat storage tank through heat transfer.

This study was conducted to find the method to improve the MD performance through enhancement of the heat retaining capacity of the heat storage tank. For this purpose, phase change material (PCM) such as paraffin and stearic acid was used in this study in order to enhance the heat retaining

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* Corresponding author.

capacity of the heat storage tank. PCM is a substance that absorbs and releases heat energy during the phase change. PCM absorbs heat when its phase changes from solid to liquid. As the temperate decreases, PCM changes its phase from liquid to solid, and releases the absorbed heat energy. Therefore, use of PCM is able to enhance the heat retaining capacity of water in the heat storage tank. The enhanced heat retaining capacity is expected to lead to the MD performance improvement.

2. Experiments

2.1. Materials

2.1.1. PCM

There are organic or inorganic PCM depending on its chemical nature. Organic PCM generally undergoes less volume change and is less corrosive than inorganic PCM, and possesses less latent heat energy than inorganic PCM (Wikipedia). Both inorganic PCM and organic PCM were used in this study. Inorganic PCM of paraffin and organic PCM of stearic acid were selected due to their melting temperatures. Since MD experiment was conducted at 40°C–75°C, which will be explained later, *n*-paraffin (hereinafter paraffin) with melting point of 58.4°C and stearic acid with melting point of 71°C was selected.

Table 1 shows thermal characteristics of PCM used in this study. Melting point, latent heat, and specific heat of paraffin were measured using the differential scanning calorimeter (DSC, TA Instruments, New Castle, DE, USA). The latent heat and the specific heat of paraffin were measured by DSC Q20 and Q25, respectively. These results were analyzed using the software of TA Instruments Universal Analysis 2000 (Water LLC). Other thermal characteristics of paraffin such as thermal conductivity and density were collected from references (Abhat [6] and Kim [7]). All thermal characteristics of stearic acid were provided by the manufacturer (Daejung, Republic of Korea). Paraffin manufactured by Junsei Chemical Co., Ltd., (Japan) was used in this study.

Fig. 1 shows analytical results of thermal characteristics of paraffin measured by the DSC. There were two peaks (minor at lower temperature and major at higher temperature) both for the exothermic and endothermic reactions in Fig. 1. During the exothermic reaction, two peaks occurred around 40°C and at 58.4°C. According to the analytical result, 30.2 kJ/kg was released at 40°C and 147.9 kJ/kg at 58.4°C, and total exothermic latent heat became 178.1 kJ/kg. During the endothermic reaction, 150.9 kJ/kg was released at 53.8°C and 27.1 kJ/kg below 40°C, and total endothermic latent heat became 178.0 kJ/kg. The minor peak, which is believed to be caused by impurities, was ignored in this study because the MD operation was terminated at 40°C, and the minor peak occurred around or below 40°C. Once the minor peak was ignored, the exothermic latent heat of paraffin became 147.9 kJ/kg at 58.4°C. Liquid paraffin freezes to solid at 53.8°C, and its corresponding endothermic latent heat became 150.9 kJ/kg.

2.1.2. Heat storage tank

Three different heat storage tanks were used in this study. They are the heat storage tank with water alone (control tank), the tank with water and single PCM of paraffin (PCM tank), and the tank with water and dual PCM of paraffin and stearic acid (dual PCM tank). Fig. 2 shows pictures

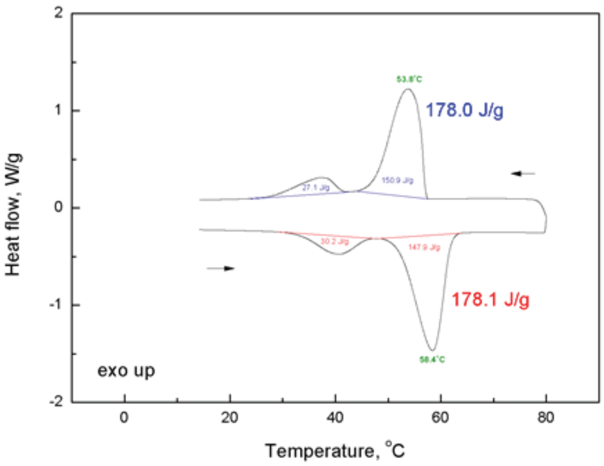

Fig. 1. Analytical results of thermal characteristics of paraffin measured by the differential scanning calorimeter.

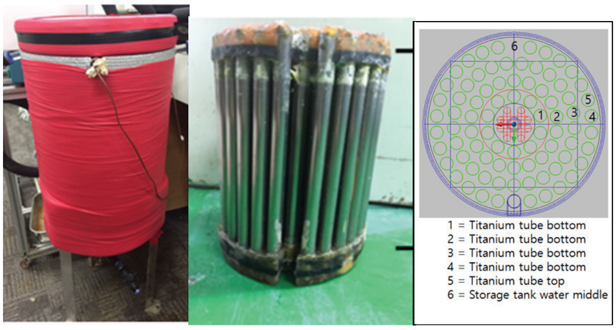

Fig. 2. Pictures of the heat storage tank, titanium tubes, and location of thermocouples inside the tank.

Table 1
Thermal characteristics of PCM used in this study

PCM	Melting point, °C	Latent heat, kJ/kg	Thermal conductivity, W/m·K	Density, kg/L	Specific heat, kJ/kg °C
n-paraffin	53.8–58.4	178.1 (178.0)[a]	0.21 [6]	0.80 (0.78)[b] [7]	2.1
Stearic acid	71	203	0.33 (0.16)[b]	0.94	2.0 (2.3)[b]

[a] Value in parenthesis indicates latent heat of endothermic reaction.

[b] Value in parenthesis indicates thermal conductivity, density, and specific heat of liquid PCM.

of the heat storage tank, and PCM containing titanium tubes together with location of six thermocouples inside the heat storage tank. Five thermocouples were used to monitor the PCM temperature, while one to monitor the water temperature. Temperatures were monitored every minute using data acquisition system (Agilent 34970A).

The diameter of the heat storage tank diameter was 0.265 m, and its length was 0.43 m. Eighty-one titanium tubes (outside diameter of 19 mm, inside diameter of 17 mm, 310 mm long) were used for PCM filling. Those titanium tubes were positioned to surround the electric heater located at the center, as shown in Fig. 2. After the filling, both ends of titanium tubes were finished with epoxy resin to prevent water contact from PCM. The amount of water used for the heat storage tank was 10 L. The amount of PCM was 4.5 kg. The 4.5 kg of paraffin was added to the PCM tank, while 3.5 kg of paraffin, and 1.0 kg of stearic acid were added to the dual PCM tank. The electric heater (3 kW) was used to heat water and PCM in the heat storage tank instead of solar energy, and the heater was switched off once the temperature of water and PCM in the tank reached 75°C. The electric consumption was measured by the wattmeter.

2.2. Methods

2.2.1. Membrane distillation experiment

Fig. 3 shows the experimental setup used in this study. The MD experiment was conducted at configuration of direct contact MD. Feed water was sodium chloride solution at 1,000 mg/L, and cold water was distillate. The heat storage tank was also used as the feed water tank. Feed water was fed to the MD system, and the MD brine was returned to the heat storage tank, as shown in Fig. 3. Initial temperature of feed water and cold water was set to 75°C and 20°C, respectively. Feed water temperature gradually decreased due to the circulation, while cold water temperature was maintained at 20°C using a chiller. The flow rates of feed water and cold water were set to 1 L/min. The energy source of the MD system was the heat storage tank, and the MD experiment was terminated when the feed water temperature dropped to 40°C. The heat retaining capacity of the heat storage tank was represented by the sensible and latent energy stored by water (10 kg) and PCM (4.5 kg) in the tank.

Hollow fiber membrane (Econity, Republic of Korea) was used for the MD module in this study. The fiber was made of polyvinylidene difluoride (PVDF), and its average pore size was 0.1 μm. The MD module consisted of 15 fibers (1.2 mm outside diameter, 0.215 m long), and the corresponding membrane area was 0.01216 m^2. The MD performance was evaluated by water production, water recovery, water flux, and energy efficiency. Distillate produced by the MD system was collected in the permeate tank, and the amount of collected distillate was measured by the balance, as shown in Fig. 3. Water recovery was a ratio of the amount of distillate produced to the initial amount of water (10 L). Average water flux of the MD system was calculated using the amount of distillate, the duration of MD operation, and the membrane area. Performance ratio (PR) was used to evaluate the energy efficiency of the MD system. PR was calculated as a ratio of energy required to produce the distillate to actual thermal energy, or a ratio of total latent heat of evaporation of the product water to input thermal energy [3].

3. Results and discussion

3.1. Energy required for the heat storage tank

The energy input to the heat storage tank by the electric heater and the energy required to heat water and PCM in the

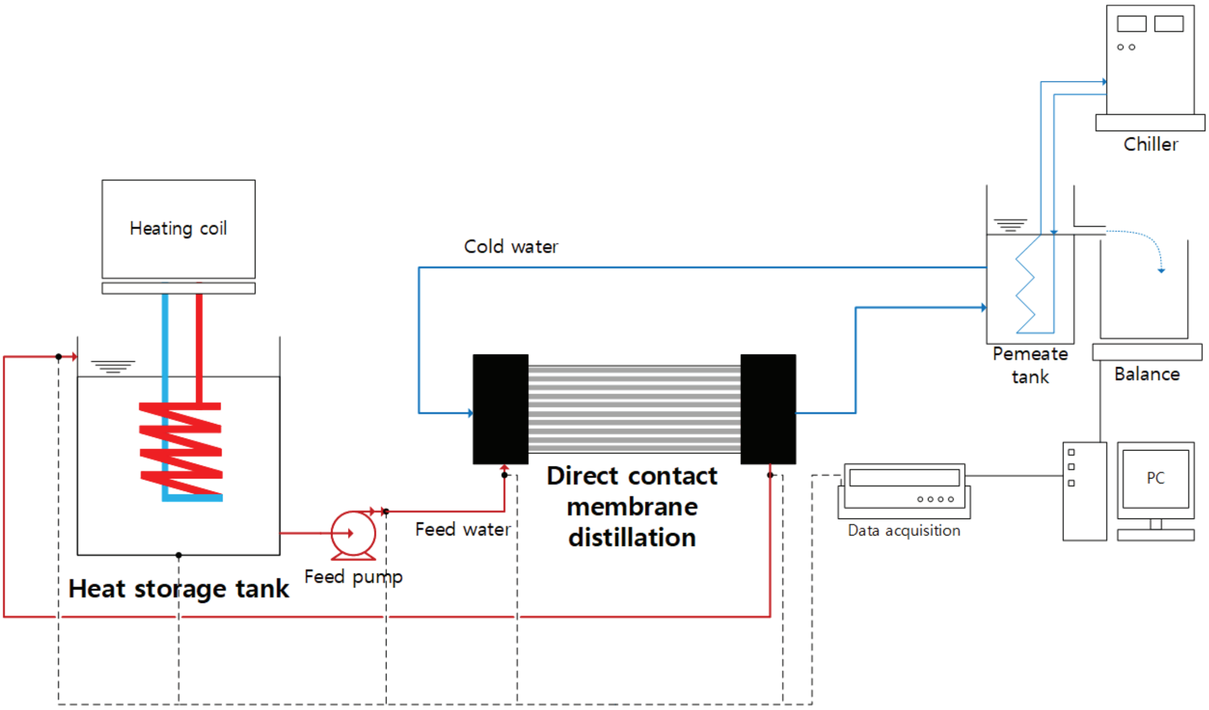

Fig. 3. Experimental setup used in this study.

tank to the predetermined temperature of 75°C are shown in Table 2. The electric heater was operated for 17 min to heat water in the control tank. The wattmeter reading was 0.7 kWh, which corresponded to 2,520 kJ of energy consumption. The energy required to raise the water temperature from 20°C to 75°C was calculated as 2,310 kJ. This amount of energy (2,310 kJ) corresponded to 92% of the energy input (2,510 kJ), indicating that 92% of energy input was utilized to heat water in the control tank, and the remaining 8% was dissipated through heat transfer.

The longer operation (45 min) of the electric heater was required for the PCM tank. The wattmeter reading was 1.36 kWh, which corresponded to 4,896 kJ of energy consumption. The sensible energy required to raise the paraffin temperature (4.5 kg) from 20°C to 75°C was calculated as 520 kJ and its latent energy was calculated as 801 kJ. This means that 3,631 kJ of energy (2,310 kJ for water and 1,321 kJ for paraffin) was required to heat water and paraffin in the PCM tank to 75°C. The 3,631 kJ corresponded to 74% of the energy input (4,896 kJ). This result indicates that the control tank (92%) was more effective than the PCM tank (74%) in terms of the energy utilization. It was due to lower thermal conductivity of paraffin. As shown in Table 1, the thermal conductivity of paraffin (0.21 W/m K) was substantially lower than that of water (0.658 W/m K at 333 K) [8]. Consequently, more energy was required to heat paraffin than water.

The duration of the electric heater for the dual PCM tank (44 min) was similar to that for the PCM tank (45 min). The wattmeter reading was 1.4 kWh, which corresponded to 5,040 kJ of energy consumption. The sensible energy required to heat 3.5 kg of paraffin to 75°C was calculated as 404 kJ and its latent energy was calculated as 623 kJ. The corresponding sensible and latent energy of 1.0 kg of stearic acid was calculated as 125 and 203 kJ, respectively. This means that 3,665 kJ of energy (2,310 kJ for water, 1,027 kJ for paraffin, 328 kJ for stearic acid) was required to heat water, paraffin, and stearic acid in the dual PCM tank to 75°C. The 3,665 kJ corresponded to 73% of the energy input (5,040 kJ). The energy utilization of the dual PCM tank was similar to that of the PCM tank.

3.2. *Heat transfer through the heat storage tank*

Fig. 4 shows the change in water temperature of the heat storage tank. The water temperature of the tank gradually decreased with time as heat transfer progressed. Since the MD operation was terminated at 40°C as mentioned above, the temperature decrease was monitored up to 40°C. It took 840 min for water in the control tank to cool from 75°C to 40°C, whereas the corresponding cooling time was much longer (1,300 min) for the PCM tank. Unlike the control tank, there is a slope change in the cooling line for the PCM tank. The change occurred around 55°C as shown in Fig. 4, which approximately corresponded to the freezing point of paraffin (53.8°C). As paraffin changed its phase from liquid to

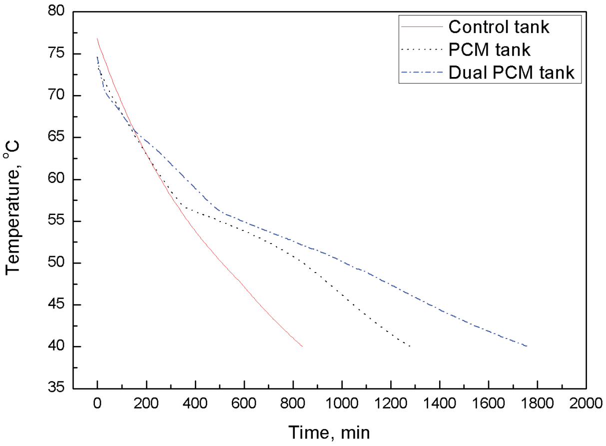

Fig. 4. Change in water temperature in different heat storage tank.

Table 2
Energy balance for different heat storage tanks

Description			Control tank[a]	PCM tank[a]	Dual PCM tank[a]
Energy input, kJ			2,520 (0.7 kWh)	4,896 (1.36 kWh)	5,040 (1.4 kWh)
Energy required for water, kJ			2,310	2,310	2,310
Energy required for PCM, kJ	Paraffin	Sensible	–	520	404
		Latent	–	801	623
		Sub-total	–	1,321	1,027
	Stearic acid	Sensible	–	–	125
		Latent	–	–	203
		Sub-total	–	–	328
	Total		–	1,321	1,355
Total energy used, kJ			2,310 (0.92)[b]	3,631 (0.74)[b]	3,665 (0.73)[b]
Energy required from 40°C to 75°C, kJ			1,470	2,480	2,537
Heat transfer coefficient of the heat storage tank, W/m^2 K			3.2 (38)[c]	3.5 (19)[c]	2.6 (16)[c]

[a] Control tank indicates the heat storage tank with water alone; PCM tank indicates the heat storage tank with PCM; dual PCM tank indicates the heat storage tank with dual PCMs.

[b] Values in parenthesis indicate the efficiency of energy utilization.

[c] Values in parenthesis indicate the heat transfer coefficients of the heat storage tanks when the MD was in operation.

solid, its latent heat was released, which slowed down the cooling. Consequently, the heat retaining capacity of the heat storage tank was enhanced. The heat transfer coefficients of the control tank and the PCM tank were then compared in order to check whether PCM helped retard heat transfer from the heat storage tank. These coefficients were calculated based on the energy available from 40°C to 75°C. As shown in Table 2, the heat transfer coefficients of both tanks were similar (3.2 W/m^2 K for the control tank and 3.5 W/m^2 K for the PCM tank). This result indicates that addition of paraffin was unable to retard heat transfer from the tank.

It was then decided to add two PCMs to maximize the heat retaining capacity of the heat storage tank. Organic PCM of stearic acid was selected because its melting point (71°C) is higher than that of paraffin (58.4°C) but lower than 75°C. Addition of paraffin and stearic acid further delayed the cooling, as shown in Fig. 4. It took 1,800 min for water in the dual PCM tank to cool from 75°C to 40°C. Fig. 4 shows that there were two slope changes in the cooling line for the dual PCM tank: one around 70°C and another one around 55°C. These temperatures approximately corresponded to the freezing points of stearic acid (71°C) and of paraffin (53.8°C). The latent heat was released during phase changes of stearic acid and paraffin, which helped delay the cooling progress. This result indicates that use of dual PCM was beneficial to maximize the heat retaining capacity of the heat storage tank. Addition of paraffin and stearic acid even retarded heat transfer from the heat storage tank. As shown in Table 2, the heat transfer coefficient of the dual PCM tank (2.6 W/m^2 K) was slightly lower than that of control tank (3.2 W/m^2 K).

3.3. MD experiments

The MD experimental results are summarized in Table 3. Table 3 shows the energy available to drive the MD operation, the duration of MD operation, the amount of distillate produced, water recovery, water flux, and PR of the MD system. As shown in Table 3, 1,470 kJ of energy was available to drive the MD system driven by the control tank, which was able to sustain the MD operation for 72 min. This indicates that the MD operation expedited heat transfer. As mentioned before, water cooling (75°C to 40°C) in the control tank took 840 min without the MD operation. However, heat was quickly transferred out with the MD operation, and water cooled from 75°C to 40°C within 72 min. The heat transfer acceleration by the MD operation was explicitly noted in the increased heat transfer coefficients. The heat transfer coefficient of the control tank increased from 3.2 to 38 W/m^2 K when the MD system was in operation. Both evaporation and the MD brine circulation into the heat storage tank are believed to contribute to the accelerated heat transfer. When the MD system was driven by the control tank as an energy source, 120 g of water was produced. Water recovery was 1.2%. The average flux was calculated to be 8.2 kg/m^2 h. PR of the MD system was calculated as 0.19.

Table 3
Summary of MD experimental results

Description	Control tank	PCM tank	Dual PCM tank
Energy available, kJ	1,470	2,480	2,537
Operation duration, min	72	239	290
Water produced, g	120	257	382
Water recovery, %	1.2	2.6	3.8
Average water flux, kg/m^2·h	8.2	5.3	6.5
Performance ratio (PR)	0.19	0.24	0.35

The MD operation was sustained longer (239 min) when an energy source of the MD system was switched from the control tank to the PCM tank. It was understandable considering an increase in the amount of energy available to drive the MD system. The amount of available energy for the PCM tank was 2,480 kJ, while it was 1,470 kJ for the control tank, as shown in Table 3. Consequently, more distillate was produced (257 g) and water recovery increased to 2.6%. However, water flux was reduced to 5.3 kg/m^2 h. Use of PCM was beneficial for distillate production. When the MD system was driven by the PCM tank, the amount of energy available increased by 69%, but the MD operation was extended by 232% and water production increased by 114%. Beneficial effect of PCM was also noted in heat transfer reduction from the heat storage tank. The heat transfer coefficient of the heat storage tank was decreased by half (19 W/m^2 K vs. 38 W/m^2 K), when the energy source of the MD system was switched from the control tank to the PCM tank. Retarded heat transfer resulted in improved energy efficiency of the MD system. PR of the MD system driven by the PCM tank was calculated as 0.24. These results clearly indicate that use of PCM contributed to the MD performance improvement. Addition of paraffin into the heat storage tank increased water production as well as improved the energy efficiency of the MD system.

Addition of paraffin and stearic acid further improved the MD performance. Although the amount of energy available for both systems was similar (2,480 kJ vs. 2,537 kJ), the MD operation was longer (290 min) with use of dual PCM, compared with the operation with use of single PCM. Consequently, use of dual PCM resulted in more water production (382 g), and higher water recovery (3.8%). Average flux was also higher (6.5 kg/m^2 h). The enhanced heat retaining capacity led to improved MD performance. The dual PCM tank retained heat energy more effectively than the PCM tank, as shown in Fig. 4. Use of dual PCM was also effective in delaying heat transfer from the heat storage tank when the tank was used to drive the MD system. The heat transfer coefficient of the dual PCM tank (16 W/m^2 K) was lower than that of the PCM tank (19 W/m^2 K). The energy efficiency of the MD system improved due to reduced heat transfer. PR of the MD system driven by the dual PCM tank was calculated as 0.35.

4. Conclusion

This study was conducted to improve the MD performance through enhancement of the heat storage tank using PCM. The heat storage tank was used as an energy source to drive the MD system. PCM such as paraffin and stearic acid was used for this purpose. According to this study, use of PCM was able to enhance the heat retaining capacity of the heat storage tank. Addition of paraffin enhanced the heat retaining capacity of the heat storage tank by 55%. Such beneficial effect was maximized by use of dual PCM. The heat retaining capacity of the heat storage tank was increased by 114%, when paraffin and stearic acid were added together. The enhanced heat retaining capacity of the heat storage tank led to the MD performance improvement. When the MD system was driven by the PCM reinforced heat storage tank, the MD operation was sustained longer, and more water was produced. Water recovery increased from 1.2% (without PCM) to 2.5% (with single PCM), and 3.8% (with dual PCM). Use of PCM was also effective in retarding heat transfer when the heat storage tank was used to drive the MD system. The heat transfer coefficient of the heat storage tank decreased from 38 W/m^2 K (without PCM) to 19 W/m^2 K (with single PCM), and to 16 W/m^2 K (with dual PCM). Retarded heat transfer led to the improved energy efficiency of the MD system. PR of the MD system increased from 0.19 (without PCM) to 0.24 (with single PCM), and to 0.35 (with dual PCM).

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