Solar-powered multi-stage direct contact membrane distillation system: modeling and simulation

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Abstract

This paper presents a theoretical analysis of the monthly average daily and hourly performances of a solar-powered multi-stage direct contact membrane distillation (SMDCMD) system with an energy recovery scheme and dynamic operating system. Mid-latitude meteorological data from Busan, Korea is employed, featuring large climate variation over the course of one year. The number of module stages used by the dynamic operating scheme changes dynamically based on the inlet feed temperature of the successive modules, which results in an improvement of the water production, thermal efficiency, and solar fraction. The simulations of the SMDCMD system are carried out to investigate the spatial and temporal variations in the feed and permeate temperatures and permeate flux. The monthly average daily water production increases from 0.37 m^3/day to 0.4 m^3/day and thermal efficiency increases from 31% to 45% when comparing systems both without and with dynamic operation in December. The water production with respect to collector area ranged from 350 m^2 to 550 m^2 and the seawater storage tank volume ranged from 16 m^3 to 28.8 m^3, and the solar fraction at various desired feed temperatures from 50 °C to 80 °C have been investigated in October and December.

Keywords: Dynamic operating system, desalination, direct contact membrane distillation, heat and mass transfers, multi-stage concept, solar-powered system (Busan, Korea)

1. Introduction

The membrane distillation (MD) process for seawater desalination is an emerging non-isothermal membrane separation process which transports water vapor through a microporous hydrophobic membrane. The driving force of the MD process is the difference in partial vapor pressure, generated by the temperature gradient between the feed and permeate sides of the membrane. The MD process can achieve the near 100% rejection of non-volatile electrolytes and it also has several advantages such as lower requirement of operating temperature than conventional thermal processes and hydraulic pressure, lower effect of salinity on the permeate flux, and lack of the corrosion thanks to the characteristics of polymer membrane materials [1−14]. Typically there are four types of MD processes: direct contact membrane distillation (DCMD), sweeping gas membrane distillation (SGMD), air gap membrane distillation (AGMD), and vacuum membrane distillation (VMD). Most studies have been conducted on the DCMD process due to its simple configuration in which the condensation of water vapor is carried out inside the membrane module, as well as its potentially high flux [xx]. The major challenge of the DCMD process is to reduce the energy consumption resulting from a higher conductive heat loss; thus many researchers have attempted to reduce the specific thermal energy consumption. Firstly, heat recovery systems have been applied in MD processes to reuse the residual thermal energy from the feed and permeate [1,4,9,15,16]. The heat recovery scheme has a significant influence on the energy consumption of the system. The heat energy is recovered from the retentate via heat exchanger, thus the preheating energy for inlet feed seawater can be reduced. Secondly, the membrane has been developed to reduce conductive heat loss and to increase permeate flux. The composite configuration is one of several commercial membranes used to improve the permeate flux and reduce conductive heat loss [1,17−20]. Composite membranes consist of an active layer of hydrophobic polymer casted on a thicker supporting layer of a hydrophilic or hydrophobic polymer. The active layer is thinner than the support layer to prevent heat loss through conduction and to reduce the mass transfer resistance. Thirdly, thermal energy supply, which has low or negligible cost, is required for economic operation of the MD process [1]. Alternative energy sources have been studied as free energy suppliers for MD processes [1,21−27]. Solar energy, which is environmentally friendly and sustainable, is harvested through the solar collector and can be utilized to preheat the feed seawater for MD process.

Numerous experimental and theoretical studies on solar-assisted or -powered MD desalination systems have been reported by researchers. Kim et al. [1] presented a model-based solar-assisted DCMD desalination system with a heat recovery scheme and temperature modulating scheme. A shell-and-tube-type hollow fiber membrane module was employed using polyvinylidene fluoride (PVDF), and the results showed that overall the permeate production capacity is 31 m^3/day. Guillen-Burrieza et al. [22] presented an experimental analysis of a solar desalination system incorporating the AGMD process using a flat sheet type PTFE membrane module. Chen and Ho [23] presented experimental and theoretical studies of immediately assisted solar DCMD in saline water desalination using lab-scale experimental equipment. Banat et al. [28] presented a performance evaluation in an experimental study of the solar-driven MD desalination plant in Aqaba, Jordan.

All of aforementioned theoretical and experimental studies have been carried out to investigate short- or long-term operation near the equator in areas such as Jeddah in Saudi Arabia or Aqaba in Jordan, which experience negligible changes in monthly average meteorological data. However, the construction of solar-thermal systems outside of equatorial areas should be considered. In these areas the variance in monthly average meteorological data must be accounted for based on the lines of longitudinal and latitude because the variation of the earth-sun distance does lead to large variations in aspects such as radiation, ambient temperature, and seawater temperature over the span of a year.

In addition, a number of modules in a multi-stage concept should be dynamically adjusted to increase the thermal efficiency and water production according to monthly changes in meteorological data by implementing the suggested dynamic operating system. A dynamic operating system is a modulating system that adjusts the number of membranes used based on the inlet feed temperature of the successive module. The available inlet feed temperature at each month has been changed based on monthly changes in meteorological data; the available difference in partial water vapor pressure as a driving force should also be changed each month. As shown in Fig. 1, a higher thermal efficiency and partial water vapor pressure difference can be achieved at the higher temperature difference region between the feed and permeate sides in the MD process. This means that it would be better to not operate the MD process at the low inlet feed temperature of the successive module by using a dynamic operating system to improve the water production and thermal efficiency.

The SMDCMD system featured in this study which includes an energy recovery scheme and a dynamic operating system has been suggested to increase monthly average daily water production and thermal efficiency. The monthly average daily water production and thermal efficiency have been compared both with and without the dynamic operating system each month at a collector area of 550 m^2 and a tank volume of 28.8 m^3. A theoretical study has been performed in order to investigate the spatial and temporal variations in the feed and permeate temperatures and permeate flux. In addition, we examined the monthly average daily water production with respect to collector area in the range of 350 m^2 − 550 m^2 and seawater storage tank volume in a range of 16 m^3 − 28.8 m^3, and the solar fraction with respect to desired feed temperature between 50 °C and 80 °C in October and December, producing the maximum and minimum water productions, respectively. The monthly averages of hourly diffuse, beam radiations, and ambient temperature data are estimated using monthly average meteorological data, and the monthly average daily seawater temperature is used as the supply temperature of the seawater and bulk permeate. The monthly average meteorological data and seawater temperature are taken from Busan, Republic of Korea.

2. System description

2.1 Solar-powered multi-stage DCMD system

A schematic diagram of the SMDCMD desalination system is shown in Fig. 2. The SMDCMD system consists of the solar-thermal and multi-stage DCMD systems. The solar-thermal system is composed of two circuits: the primary solar circuit for the collection of solar energy and the secondary circuit that supplies hot seawater to the DCMD modules through the four seawater storage tanks. In the present work, the solar collector area is in the range of 350 m^2 − 550 m^2 and the seawater storage tank volume is in a range of 16 m^3 − 28.8 m^3. The flow rate of heat transfer fluid (HTF) through the solar collector is based on ASHRAE standards. The heat transfer fluid, Syltherm 800 (silicone-based fluid, Dow corning Co.), is employed at the primary solar circuit due to its low fouling potential (1.5×10^{-5} m^2°C/W), low freeze point (400 °C), high-temperature stability (−400 °C), long life (10 years or more), corrosive resistant, low odor, and low acute oral toxicity. The plate heat exchanger (HX1) is used to heat up the feed seawater from the HX2 that recovers heat from the brine. The multi-stage DCMD system consists of a total of eight module stages. It is assumed that the bulk permeate (pure water) cools down to the monthly average daily seawater temperature via the HX3. The operation procedure of the SMDCMD system is as follows: During the mid-day hours, the makeup seawater is continuously heated by the solar-thermal system and supplied to the seawater storage tanks (top left of Fig. 2). When the top temperature of seawater storage tank-4 meets the operative feed temperature (set-point 1), the feed seawater drawn from the storage tank-4 is delivered to the multi-stage DCMD system by controlling valve operation (CV) in the control system (top right of Fig. 2). The multi-stage DCMD process with a dynamic operating system then operates to produce the fresh water and the number of modules used is dynamically controlled based on the inlet feed temperature of each successive module (bottom of Fig. 2). If the outlet feed temperature of each successive module is lower than set-point 2, the subsequent-stage module is not operated and the brine flows to the HX2 to recover its remaining heat to the makeup seawater.

Fig. 3 demonstrates the effects of temperature difference on permeate flux and thermal efficiency of a single module (50 cm × 60 cm × 0.3 cm) with respect to temperature difference between the inlet feed and permeate temperatures at the inlet and permeate flow rates of 20 l/min and an inlet permeate temperature of 20 °C. The thermal efficiency is defined as the ratio of the vaporization heat associated with the transmembrane flux to heat transferred through the membrane. As shown in Fig. 3(a), typically the higher temperature difference between the feed and permeate sides can lead to a higher permeate flux and conductive heat loss, thus the thermal efficiency asymptotically increases with the increased temperature difference, as shown in Fig. 3(b), which is attributed to the relatively larger vapor latent heat compared to the heat conduction. In this study, the minimum permeate flux and thermal efficiency required in the SMDCMD are set to be 10 kg/m^{2}h and 54%, respectively; thus the temperatures of set-point 1 and 2 are determined to be 45 °C and 40 °C, respectively.

2.2 DCMD process using a composite membrane

A schematic diagram of the DCMD module using a commercial hydrophobic microporous PTFE/PP composite membrane is depicted in Fig. 4 [2]. The flat sheet type DCMD module consists of a flat sheet membrane and the two rectangular channels (feed and permeate sides). As shown in Fig. 4, the water vapor is generated at the liquid/vapor interface on the feed side of the membrane by the partial vapor pressure difference between the feed and permeate sides, and the generated water vapor moves through the hydrophobic membrane pores via diffusion. The detailed physical properties of the composite membrane are shown in Table 1. The polypropylene mesh spacer is used at both sides of the composite membrane as a support and turbulence promoter. Detailed spacer specifications are shown in Table 2.

3. Theoretical approaches

3.1. Solar thermal system

The rigorous mathematical models for the meteorological data such as ambient temperatures and beam and diffuse irradiances, the evacuated-tube collector, the plate heat exchanger, and the seawater storage tanks in the solar thermal system were previously developed and well described elsewhere [1]. With correlated empirical theories based on monthly averages of daily global radiation (MJ/m^2/day), which consists of beam and diffuse components, using the NASA SSE model [29], the monthly average of hourly global radiation incident upon a tilted surface is calculated to estimate the local solar insolation input. Fig. 5 presents the monthly averages of hourly ambient temperatures and global irradiances on a tilted surface (Busan, Republic of Korea) obtained from the previously developed model [1]. The maximum monthly average of hourly ambient temperatures and global irradiance are approximately 28.7 °C in August and 756 W/m^2 in April, respectively. For the system simulation, the plant parameters and input data of the solar-powered multi-stage DCMD system are given in

Table 3. The monthly average daily seawater temperatures in Busan, Republic of Korea, are also presented in Table 4 [30]. For simplicity, the supply temperatures of the raw seawater and bulk permeate to the multi-stage DCMD system are assumed to be same as the monthly average daily seawater temperature.

In order to evaluate the monthly average daily thermal performance of the SMDCMD system, the monthly average daily solar fraction, *SF*, which is the ratio of the energy demand met by solar energy (q_s) to the total energy demand required to attain the desired feed temperature (q_{tot}) each month, is given as follows [1]:

$$SF = \frac{Q_s}{Q_{tot}} = \frac{\sum_{1}^{\text{days of month}} \int_0^{t=24h} q_s dt}{\sum_{1}^{\text{days of month}} \int_0^{t=24h} q_{tot} dt} \tag{1}$$

where q_s and q_{tot} are determined as

$$q_s = \dot{m}_t c_p \left(T_{f,in,s} - T_m \right) \tag{2}$$

$$q_{tot} = \dot{m}_t c_p \left(T_{D,f,in} - T_m \right) \tag{3}$$

where T_m is the makeup seawater temperature via the HX2, $T_{f,in,s}$ is the actual feed temperature supplied to the multi-stage DCMD system which is same as to the storage tank-4 temperature ($T_{st,4,1}$), and $T_{D,f,in}$ is the desired feed temperature of the multi-stage DCMD system ranging from 50 °C to 80 °C.

3.2 Unsteady-state multi-stage DCMD process using a composite membrane

The steady-state theoretical models including heat and mass transfers for the DCMD process using composite membranes are already described elsewhere [2]. In this study, in order to investigate the transient performance of the SMDCMD system, the previously-developed theoretical models have been revised from a steady state to an unsteady state. Thus, the energy balance equations for the feed and permeate sides are revised as in the following equations:

$$\frac{d \rho_f v_f c_{p,f} T_f}{dz} = -\frac{Q_f}{\varepsilon_{sp} h_c} - \rho_f c_{p,f} \frac{dT_f}{dt} \tag{4}$$

$$\frac{d \rho_p v_p c_{p,p} T_p}{dz} = -\frac{Q_p}{\varepsilon_{sp} h_c} - \rho_p c_{p,p} \frac{dT_p}{dt} \tag{5}$$

where h_c is the channel height and ε_{sp} is the spacer porosity.

The equation for the thermal efficiency of each module is defined as [2]

$$\eta(z) = \frac{\varepsilon\, J(z) \Delta H\big|_{al} + (1-\varepsilon)\, J(z) \Delta H\big|_{al-sl}}{Q_m} \tag{6}$$

$$\eta_i = \frac{1}{L} \int_0^L \eta(z) dz \tag{7}$$

where $\eta(z)$ is the local performance ratio, defined as the ratio of the vaporization heat associated with the permeate flux to the heat transferred through the membrane, and is given by [2]. In order to investigate the monthly average daily thermal efficiency for a dynamic operating system, the following Eqs. (8)−(9) are defined because the SMDCMD system has different available number of modules and operating times during the operation throughout the day.

$$\eta_{TM} = \frac{\sum_{1}^{N_{TM}} \eta_i}{N_{TM}} \tag{8}$$

$$\eta_m = \frac{\sum_{1}^{N_{OH}} \eta_{TM}\,\Delta t}{N_{OH}\,\Delta t} \tag{9}$$

where η_i is the thermal efficiency at each module, η_{TM} is the average thermal efficiency of the total modules operated at each time, η_m is the monthly average daily thermal efficiency, N_{TM} is the total number of operating modules at each time, and N_{OH} is the operating hours.

3.3. Solution procedure

A diagram of the solution procedure for the SMDCMD system with a heat recovery and dynamic operating system is depicted in Fig. 6. Detailed solution procedures of solar-thermal systems and the DCMD process using composite membranes are described in [1,2].

4. Results and discussion

4.1 The effect of dynamic operating system on the system performance

Fig. 7 presents the effects of the dynamic operating system on the daily average water production and thermal efficiency each month at the 550 m^2 collector area and a seawater storage tank volume of 28.8 m^3. The highest and lowest water productions are 1.16 m^3/day in October and 0.37 m^3/day in December, respectively, without the implementation of a dynamic operating system; while the highest and lowest water productions with a dynamic operating system are 1.17 m^3/day in October and 0.4 m^3/day in December, respectively. It is shown that the water productions increase slightly with the use of a dynamic operating system, indicating that a suitable number of modules based on the inlet feed temperature can lead to incremental increases in the water production over that of a system without a dynamic operating system, which keeps the eight modules. The highest and lowest thermal efficiencies are 54% in October and 31.1% in December, respectively, without a dynamic operating system and 58.6% in October and 45.4% in December, respectively, with a dynamic operating system. These results indicate that a suitable number of modules is beneficial to water production and thermal efficiency. In view of the results obtained, the dynamic operating system can increase overall system performance.

4.2. Spatial variation

Fig. 8(a) presents the feed temperature along the DCMD module length for a continuous 24 h/day operation on the 17th of October with the use of a dynamic operating system. In this study, the length of one module is 0.6 m and 3.6 m of module length represents six series modules. In October, the maximum number of modules used is six, given the use of a dynamic operating system for a continuous 24 h/day. Meanwhile, five series modules only are used at 12:00; this means that the solar energy harvested during the midday hours in October does not enough to operate six modules for a continuous 24 h/day. In other words, the inlet feed temperature decreases during the time between 18:00 and 12:00, because the solar energy cannot be harvested from sunset

(18:00) to sunrise (07:00) and thus the SMDCMD system only uses the solar energy stored in the storage tanks after sunset. The inlet feed temperature still decreases after sunrise to noon, because the harvested solar energy is lower than the energy consumed for water production. On the other hand, the inlet feed temperature increases between 12:00 and 18:00 as the harvested solar energy is much greater than the consumed energy.

As shown in Fig. 8(a), the feed temperature decreases along the DCMD module length due to the water vaporization on the membrane surface of the feed side and conductive heat loss between the feed and permeate sides. The permeate temperature profile is shown in Fig. 8(b) along the DCMD module length for operation over a continuous 24 h/day on the 17th of October with a dynamic operating system. In this system, the monthly average daily seawater temperature for Busan, Republic of Korea are employed as the supply temperatures of the raw seawater as a makeup water and cooling medium, thus the bulk permeate temperature supplied to the multi-stage DCMD system is considered the same as the monthly average daily seawater temperature. The permeate temperature of each module in a counter-current configuration increases along the DCMD module length due to the heat transfer by latent heat and conduction through the membrane. Fig. 8(c) presents the permeate flux along the module length in October. Typically, the permeate flux relates significantly to the temperature difference between the feed and permeate sides; thus the permeate flux decreases along the module length, as a consequence of a significant decrease in the partial vapor pressure difference.

Fig. 9(a) presents a profile of feed temperature along the module length for a continuous 24 h/day operation on the 17th of December at the 550 m^2 collector area and a tank volume of 28.8 m^3 with a dynamic operating system. The maximum number of module stages used is three, which is because the solar energy available for harvest in December is one third of that in October due to changes in meteorological conditions. Typically, the primary factor in the capacity of solar energy has been the longitudinal and latitude of the region. The decrement of feed temperature along the module length is slightly lower than that of October, indicating that the heat loss by conduction and latent heat is typically lower with a decrease in temperature difference between feed and permeate temperatures. Fig. 9(b) presents the permeate temperature profile along the module length in December. The increment of permeate temperature along the module length is also lower than that of October due to low conduction and condensation heat transfer. The permeate flux is also less than one half of that of October, as shown in Fig. 9(c).

4.3. Temporal variation

Fig. 10 presents the profiles of the inlet feed temperature and permeate flux at each module for 72 h of continuous operation, respectively, in October at the 550 m^2 collector area and a tank volume of 28.8 m^3 with a dynamic operating system. The inlet feed temperature and permeate flux exhibit the same tendency, because the temperature difference between the feed and permeate sides is a driving force of the MD process. The inlet feed temperature increases from 12:00 to 17:45, indicating that the harvested solar energy is sufficient for the storage of energy in the storage tanks as well as the operation of the MD process. After sunset, only the storage energy in the seawater tanks can be used, therefore the inlet feed temperature decreases gradually during the late-afternoon and night-time hours. Meanwhile, the inlet feed temperature decreases greatly between 07:00 and 12:00, because the energy stored during the midday hours does not meet the load requirement in early morning, which is far greater than solar energy incident on the collector in the morning. Thus, the five modules only can be used from 10:00 to 13:00, as shown in Fig. 10.

Fig. 11 shows the profiles of the inlet feed temperature and the permeate flux at each module for a continuous 72 h of operation in December at the 550 m^2 collector area and a tank volume of 28.8 m^3 with a dynamic operating system. As shown in Fig. 11, significantly less solar energy is harvested in December, indicating that the system performance will change based on monthly meteorological data.

4.4. Effect of A_c and V_{st} on η_m

The effects of the collector area (A_c) and storage tank volume (V_{st}) on daily averages of thermal efficiency (η_m) have been theoretically examined with respect to collector area in the range of 350 m^2 to 550 m^2 and tank volume in the range of 16 m^3 to 28.8 m^3 in October and December.

Tables 5 and 6 present the effects of the collector area and seawater storage tank volume on thermal efficiency in October and December. It is shown that the thermal efficiency increases with an increase in the collector area at a constant seawater storage tank volume by attaining a higher temperature difference between the feed and permeate sides, however, at a lower collector area the slightly better thermal efficiency is observed. For instance, the reason can be found in Fig. 12 for collector areas of 475 m^2 and 500 m^2 at a storage tank volume of 19 m^3 in October (Table 5). When the outlet feed temperature of the sixth-stage module with a collector area of 500 m^2 is slightly greater than set-point 2 during the times from 14:30 to 15:30 and again from 16:45 to 00:35, the subsequent-stage module, i.e., seventh-stage module, is operated at the low inlet feed temperature, thus having a lower average thermal efficiency. The thermal efficiencies denoted as N/A in Table 5 indicate the system configurations where the seawater storage temperature does exceed the water boiling temperature.

4.5. Effect of A_c and V_{st} on J_m and SF

The effect of collector area and storage tank volume on the daily water production (J_m) and solar fraction (SF) has been theoretically examined with respect to collector area ranging from 350 m^2 to 550 m^2 and seawater storage tank volume ranging from 16 m^3 to 28.8 m^3 in October and December in Busan, Republic of Korea.

Fig. 13 presents the effect of the collector area and storage tank volume on the monthly average daily water production in October and December. As can be observed in Fig. 13(a) and (b), the collector area is found to be a significant factor influencing the water production. This is because, as stated earlier, the higher inlet feed temperature from the high collector area leads to a higher transmembrane temperature difference, which results in an increased driving force, yielding a higher permeate flux. On the other hand, the water production increases slightly with a decrease in the storage tank volume at fixed collector area, but shows a behavior almost independent of the storage tank volume. It is because a higher storage tank volume requires more energy to heat the seawater to the required inlet feed temperature, as well as an increase in heat losses from the storage tanks at a given load requirement.

Fig. 14 shows the effect of the desired feed temperature ($T_{D,f,in}$) from 50 °C to 80 °C on the solar fraction with respect to collector area ranging from 350 m^2 to 550 m^2 and seawater storage tank volume ranging from 16 m^3 to 28.8 m^3 in October. The results reveal that with an increase in the desired feed temperature, the minimum solar fraction decreases greatly in a linear manner, i.e., from 94% to 64%, and the maximum solar fraction decreases slightly, i.e., from 99% to 87%. This is because with an increase in the desired feed temperature the thermal demand of the load increases greatly, as compared to the rate of the removed energy from the storage tank to supply the feed seawater. At lower desired feed temperatures below 80 °C, the solar fraction is dependent on both collector area and storage tank volume, while its value at a higher desired feed temperature is dependent only on solar collector area, which is because regardless of storage tank volume the collected solar energy is insufficient to meet high demand requirements. It is shown that there exist N/A system configurations at a higher collector area and lower storage tank volume.

With the same conditions as in Fig. 14, the effect of the desired feed temperature on the solar fraction with respect to collector area and seawater storage tank volume in December is shown in Fig. 15. It is noted that the qualitative trend shown in Fig. 14 is also upheld by the system in December. The solar fraction exhibits a behavior almost independent of the storage tank volume at the desired feed temperatures above 60 °C, as well as at lower collector areas below approximately 450 m^2 for the desired feed temperature of 50 °C. In particular, with increasing desired feed temperature the maximum and minimum solar fractions decrease significantly in a linear fashion from 97% to 61% and from 84% to 47%, respectively.

Therefore, the aforementioned results indicate a very important point in the design of the SMDCMD system: for instance, at the given desired feed temperature condition of 80 °C, the installation of the higher seawater storage tank volume does not necessarily improve the system performance as well as it is not feasible from economic point of view.

5. Conclusions

In this paper, a solar-powered multi-stage direct contact membrane distillation (SMDCMD) system with a heat recovery scheme and dynamic operating system has been suggested to increase water production and thermal efficiency. To examine the effects of a dynamic operating system on water production and thermal efficiency, a theoretical investigation of the SMDCMD system with an energy recovery scheme and dynamic operating system has been conducted. In addition, the system performance is evaluated with respect to collector area in the range of 350 m^2 − 550 m^2 and seawater storage tank volume in range of 16 m^3 − 28.8 m^3 in terms of the water production, thermal efficiency, and solar fraction. The meteorological data of Busan, Republic of Korea, which exhibits monthly changes in meteorological data, is employed to investigate the effects of monthly meteorological changes on the system performance. By implementing a dynamic operating system, the daily water production increased from 1.16 m^3/day to 1.17 m^3/day and the daily thermal efficiency from 54% to 58.6% in October at a collector area of 550 m^2 and a seawater storage tank volume of 28.8 m^3. Meanwhile, in December the daily water production increased from 0.37 m^3/day to 0.4 m^3/day, the daily thermal efficiency also increased from 31% to 45%. The solar fraction during the month of October decreased from 99% to 64% with an increase in the desired feed temperature from 50 °C to 80 °C with respect to collector area ranging from 350 m^2 to 550 m^2 and seawater storage tank volume ranging from 16 m^3 to 28.8 m^3. The solar fraction during the month of December decreased from 97% to 47% with increasing desired feed temperature from 50 °C to 80 °C. It is also observed that the installation of the higher seawater storage tank volume does not necessarily improve the system performance as well as economic feasibility.

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Nomenclature

A_c	Total collector area [m^2]
A_a	Aperture area per collector [m^2]
c_1	Global heat loss coefficient [W/m^{2}K]
c_2	Temperature dependence of global heat loss coefficient [W/m^{2}K^2]
c_3	Effective thermal efficiency [kJ/m^{2}K]
c_p	Specific heat capacity [kJ/kgK]
D	Chevron angle [°]
h_s	Spacer thickness [m]
J_m	Daily water production [m^3/day]
L_h	Effective plate height [m]
L_w	Effective plate width [m]
L_{loc}	Longitude [°East]
$N_{DM,max}$	Number of DCMD modules [-]
N_c	Number of collectors [-]
N_{TM}	Total number of operating modules [-]
N_{OH}	Operating hours [-]
P	Pressure [Pa]
p	Plate pitch [m]
Q	Heat flux [W/m^2]
R_f	Fouling factor [m^{2}K /W]
SF	Solar fraction
T	Temperature [K]
t	Plate thickness [m]
v	Velocity [m/s]
V	Volume flow rate [l/min]
V_{st}	Seawater storage tank volume [m^3]
U	Heat loss coefficient [W/m^{2}K]

Greek letters

β	Tilt angle [°]
γ	Azimuth angle [°]
η	Local performance ratio or collector efficiency
η_i	Thermal efficiency at each module

η_{TM}	Average thermal efficiency of the total operated modules at each time
η_m	Monthly average daily thermal efficiency
η_0	Optical efficiency [%]
$\eta_{m,\mathrm{avg}}$	Monthly average daily thermal efficiency
η_{stage}	Monthly average daily thermal efficiency in each module stage
θ_z	Zenith angle [°]
ρ	Density [kg/m^3]
ϕ	Latitude [°North]

Subscripts

a	Ambient
al	Active layer
b	Bulk
D	Desired
f	Feed
m	Mean or membrane
p	Permeate
s	Salt
sl	Support layer
v	Vapor
w	Water

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Table captions

Table 1 Characteristics of the PTFE/PP composite membrane [2].

Table 2 Specifications of the spacer [2].

Table 3 Parameters and input data for the solar-powered multi-stage DCMD desalination system.

Table 4 Monthly average daily seawater temperatures in Busan, Republic of Korea.

Table 5 Monthly average daily thermal efficiency (%) of the SMDCMD system with respect to collector area (A_c) and tank volume (V_{st}) in October.

Table 6 Monthly average daily thermal efficiency (%) of the SMDCMD system with respect to collector area (A_c) and tank volume (V_{st}) in December.

Figure captions

Fig. 1. Seasonal effect of (a) water vapor pressure (kPa) versus temperature (K) and (b) thermal efficiency (%) versus temperature difference (K).

Fig. 2. Schematic diagram of the SMDCMD desalination system

Fig. 3. The effect of temperature difference on (a) permeate flux and (b) thermal efficiency using a single module (50 cm × 60 cm × 0.3 cm) with respect to temperature difference between the inlet feed and permeate temperatures at the inlet and permeate flow rates of 20 l/min and an inlet permeate temperature of 20 °C.

Fig. 4. Schematic diagram of the DCMD module using a composite membrane [2].

Fig. 5. Monthly average of hourly (a) ambient temperature and (b) global irradiance on a tilted surface in Busan, Republic of Korea.

Fig. 6. Diagram of the solution procedure for the SMDCMD system.

Fig. 7. Simulation results of the monthly average daily (a) water production and (b) thermal efficiency at the 550 m^2 collector area and a tank volume of 28.8 m^3 (Busan, Republic of Korea).

Fig. 8. (a) Feed temperature, (b) permeate temperature, and (c) permeate flux profiles along the DCMD module length for a continuous 24 h/day operation on 17th October at the 550 m^2 collector area and a tank volume of 28.8 m^3 with a dynamic operating system.

Fig. 9. (a) Feed temperature, (b) permeate temperature, and (c) permeate flux profiles along the DCMD module length for a continuous 24 h/day operation on the 17th of December at the 550 m^2 collector area and a tank volume of 28.8 m^3 with a dynamic operating system.

Fig. 10. Profiles of (a) inlet feed temperature and (b) mean permeate flux at each module for 72 h of continuous operation in October at the 550 m^2 collector area and a tank volume of 28.8 m^3 with a dynamic operating system.

Fig. 11. Profiles of the (a) inlet feed temperature and (b) mean permeate flux at each module for a continuous 72 h of operation in December at the 550 m^2 collector area and a tank volume of 28.8 m^3 with a dynamic operating system.

Fig. 12. Monthly average daily thermal efficiency of the total modules operated at each time (η_{TM}) and total number of operating modules at each time (N_{TM}) for a continuous 24 h/day operation at the 475 m^2 and 500 m^2 collector areas and a tank volume of 19 m^3 in October.

Fig. 13. Effect of the collector area, $350 \text{ m}^2 \leq A_c \leq 550 \text{ m}^2$, and seawater storage tank volume, $16 \text{ m}^3 \leq V_{st} \leq 28.8 \text{ m}^2$, on the monthly average daily water production, J_m (m^3/day), in (a) October and (b) December.

Fig. 14. Effect of the collector area, $350 \text{ m}^2 \leq A_c \leq 550 \text{ m}^2$, and seawater storage tank volume, $16 \text{ m}^3 \leq V_{st} \leq 28.8 \text{ m}^2$, on the solar fraction, SF, with respect to (a) $T_{D,f,in}$ = 50 °C, (b) $T_{D,f,in}$ = 60 °C, (c) $T_{D,f,in}$ = 70 °C, and (d) $T_{D,f,in}$ = 80 °C in October ($T_{D,f,in}$: desired feed temperature).

Fig. 15. Effect of the collector area, $350 \text{ m}^2 \leq A_c \leq 550 \text{ m}^2$, and seawater storage tank volume, $16 \text{ m}^3 \leq V_{st} \leq 28.8 \text{ m}^2$, on the solar fraction, SF, with respect to (a) $T_{D,f,in}$ = 50 °C, (b) $T_{D,f,in}$ = 60 °C, (c) $T_{D,f,in}$ = 70 °C, and (d) $T_{D,f,in}$ = 80 °C in December ($T_{D,f,in}$: desired feed temperature).