PERFORMANCE ASSESSMENT OF SOLAR-POWERED MEMBRANE DESALINATION SYSTEM: A THEORETICAL MODELING APPROACH UNDER DIFFERENT OPERATING CONDITIONS

S. A. El-Agouz[1,2,a)], *Ali M. Aboghazala*[1,b], *AymanRefatAbd Elbar*[1,c], *M. Y. Zakaria*[3,d],
KhaledKhodary Esmaeil[1,e]*and Mohamed E. Zayed*[1,f]

1 Department of Mechanical Power Engineering, Faculty of Engineering, Tanta University, Tanta 31521, Egypt.
2 Faculty of Industry and Energy Technology, Delta Technological University, Quesna, Egypt.
3 Military Technical College, El-Qobba Bridge, El Weili, Cairo, Egypt.
a) Corresponding author: el-sayed.abdelazim@f-eng.tanta.edu.eg
b) ali_aboghazala@f-eng.tanta.edu.eg
c) Ayman.Refaat@f-eng.tanta.edu.eg
d) zakaria@vt.edu.eg
e) khaled.shneshan@f-eng.tanta.edu.eg
f) mohamed_zayed@f-eng.tanta.edu.eg

ABSTRACT

Membrane distillation (MD) is a promising technology for seawater distillation, integrating the advantages of both membrane segregation and thermal distillation. The interest in utilizing solar thermal heating techniques for feed water heating in MD systems is increasing worldwide for sustainable freshwater production and lowering energy consumption. In this study, a detailed numerical modeling is conducted to simulate the thermal performance of a solar direct contact membrane distillation system powered by a vacuumed tube solar collector in the hot weather conditions of Tanta, Egypt (30.47° N and 31° E). The effects of the use of additional electric heaters for the proposed solar MD system for stabilizing and improving the feed inlet temperature of the saline water are studied as well. The three investigated schemes were solar direct contact membrane distillation (DCMD) system without electric heaters (CASE 1), solar DCMD system with internal electric heaters (CASE 2), and solar DCMD system with direct electric heater (CASE 3). The results indicated that the utilization of either internal electric heaters inside the collector tank or direct electric heater directly placed in the feed saline water loop before the membrane module remarkably enhanced the inlet feed temperature feeding the membrane for the solar DCMD system at an optimal limit of 80−73 ^{o}C and thus improved the freshwater productivity of the proposed solar DCMD system. The daily freshwater yield is reached to be 5.50, 25.15, and 27.35 kg/day, respectively, for the CASE 1, CASE 2, and CASE 3, at a feed water flow rate of 0.20 kg/s, respectively. Conclusively, it can be inferred that CASE 3 is the best design configuration from both freshwater production and energy consumption saving considerations among the three investigated solar-based DCMD configurations

Keywords: Solar-powered Membrane Desalination, Theoretical Modeling, Freshwater Production Improvement, Comparative study

1 INTRODUCTION

The increased need for freshwater is one of the most significant challenges confronting developing countries (El-Agouz et al., 2022a, Zayed et al., 2021). Solar desalination is regarded as one of the best methods utilized to produce freshwater from seawater or brackish water (Aboelmaaref et al., 2020, Zayed et al., 2019). Water desalination technologies are categorized into two essential processes, viz. either membrane separation or thermal-based technologies (Hammad et al., 2022). Recently, distillation by RO predominates the global distillation market in terms of the world's installed freshwater production. Nevertheless, one of the considerable challenges in its effective operation is the membranes fouling and relevant technicality utilized to prevent scaling because of the exiting of significantly dissoluble salts (Lim et al., 2021, Elzahaby et al., 2016). Hence, this necessitates further research on energy-efficient and eco-friendly methods for distillate production. Thus, the combination of membrane separation with thermal distillation has recently been regarded as a promising technique that possesses the advantages of both methods as membrane distillation (MD).

MD is a thermally powered membrane separation mechanism, which depends on the transport of vapor through a microporous anti-wetting membrane, represents as a hindrance for the liquid stage at which the membrane pores only allow the distilled vapor flow into the cold side (Lutze and Gorak, 2013). It is a thermal process in which the permeate solution (cold side) and feed solution (hot side) take the driving power via the difference of vapor pressure created by the temperature gradient over the membrane surface. Heat and mass transfer phenomena simultaneously occur from the hot side to the cold side (Susanto, 2011). In a typical MD system, both thermal and electrical energies are required. To provide a hot stream (i.e. feed), the saline solution or water/wastewater should be heated (40-80 ^{o}C) and for re-circulation of hot and cold streams (El-Agouz et al., 2022b). Therefore, the energy source should be used to provide the electricity to operate an MD process. One of the advantages of the MD process is that it could be coupled with a source to improve overall efficiency. Solar collectors such as solar flat plate collectors (SFPCs), solar vacuum tube collectors (SVTCs), solar concentrating collectors, and solar ponds are used to provide thermal energy to MD processes.

A theoretical study on spiral-wound air gap membrane distillation (AGMD) coupled with internal heat recovery was initially performed by (Koschikowski et al., 2003). The entire membrane surface area used was 8.0 m^2 and the SFPC area was 5.9 m^2. In the winter, the daily freshwater productivity was 11 kg/m^2 of SFPC, whereas, in the summer, it was 22 kg/m^2 of SFPC. A prototype one-loop compact DCMD system driven by SFPCs was modeled by (Duong et al., 2017). The outcome was expressed as 19.7 kg/day per m^2 of membrane or 6.3 kg/day per m^2 of both membrane and SFPC. Under real-world weather circumstances, a 7.2 m2 spiral wound DCMD system integrated with 22.6 m^2 SFPC can be provided daily total water about 140 kg, equating to daily productivity of 19.7 kg per m^2 of membrane or 6.3 kg per m^2 of SFPC (Wang et al., 2009)investigated a solar-heated hollow fiber VMD system for drinkable water production in the meteorological conditions of Hangzhou, southern China. The findings of the system revealed that the system's pure water flux reached 32.19 kg/m^2.h (per 1 m^2 of membrane area and 8 m^2 SFPC), with a specific permeate flux of higher than 1.95 kg/m2 of SFPC day. (Ma et al., 2018)mathematically examined a modest VMD system incorporated with a solar flat-plate collector. Relying on a 0.35 m^2 membrane/collector area, a daily freshwater yield of 2.8 kg and a GOR of 0.71 were estimated. Moreover, different investigations have used solar vacuum tube collectors) SVTCs to drive membrane distillation systems. (Kim et al., 2013)investigated the performance of a 50 modules solar-assisted hollow-fiber, DCMD plant with a heat recovery arrangement for 24 h/day continuous operations. SVTCs with a surface area of 3360 m^2 and 160 m^3 sea-water storage tanks were used to operate the plant to produce 31 m3/day of distillate. Results showed that the module fiber length is the most important design factor affecting the distillate flux. Furthermore, the specific thermal energy consumption (STEC) of the system with heat recovery was 436 kWh/m^3 of permeate. Sandid et al (Sandid et al., 2021)experimentally studied a multi-channel AGMD (with an overall area of 14.4 m^2) driven by both SETC plus SFPC. The pure water flow of the AGMD with evacuated tube collectors was 18.81% – 30.44% greater than the flat plate solar collector, with a cost of 22.48% less. The proposed AGMD system's specific heat energy consumption varied from 158.83 kWh/m$_3$ to 346.55 kWh/m^3. At 52 °C, the highest gain output ratio was 4.4, and the thermal efficiency of the AGMD system was 72%. Solar collectors and photovoltaic (PV) modules could both produce thermal and electrical power to the grid, making it totally self-contained.

In the present study, it was planned to introduce a theoretical study of a new solar direct contact membrane distillation (DCMD) system in three different arrangements under actual hot weather conditions in Tanta, Egypt (30.47° N and 31° E). A mathematical model implemented in MATLAB software was developed to simulate the proposed solar DCMD system operation to analyze its performance, under three different arrangements. The effects of the use of additional electric heaters for the proposed solar DCMD system for stabilizing and improving the feed inlet temperature of the saline water were studied as well. The three investigated schemes were solar direct contact membrane distillation system without electric heaters (CASE 1), solar DCMD system with internal electric heaters inside the collector tank (CASE 2), and solar DCMD system with a direct electric heater directly installed at the feed saline water stream loop before the membrane module (CASE 3).

2 SYSTEM DESCRIPTION

MD is a thermal process in which the permeate solution (cold side) and feed solution (hot side) take the driving power via the difference of vapor pressure created by the temperature gradient over the membrane surface. Heat and mass transfer phenomena simultaneously occur from the hot side to the cold side. First, the evaporation of feed solution at the boundary of the surface of the membrane causes the mass transfer to be started between liquid and vapor. Then, the propagation of the vapor atoms through the membrane can be stimulated by the pressure gradient of the vapor after the happening of condensation at the cold side. A schematic for the solar-powered DCMD pilot system flow diagram is shown in Fig. 1. The figure shows that the proposed solar DCMD consists of three main loops. Loop (i) is the solar energy-collecting loop, to satisfy the unit's thermal energy demand. Loop (ii) is the desalination loop with Spiral wound Membrane module DCMD module for freshwater production. Loop (iii) is a controlled 250 L capacity thermal sink, from which the cooling water was circulated through the DCMD module. The performance of the proposed solar desalination system is evaluated under three different operating configurations at three sunny consecutive days, from 9:00 a.m. to 3:00 p.m at the hot weather conditions of Tanta, Egypt (30.47° N and 31° E) to compare the distillate product improvement and thermal behavior of the studied solar DCMD system under the different applied modifications. In the first case, the solar direct contact membrane distillation system (SDCMDS) is driven by a 1.80 m2 evacuated tube collector (ETC), which the ECT is only supplied the MD system with the required heat for preheating the saline water that fed to the membrane without any electric heating boosters. This configuration is called a solar direct contact membrane distillation system without electric heaters (CASE 1). In the second case, the solar direct contact membrane distillation system (SDCMDS) is driven by the ETC and extra two internal tubular electric heaters (Unit Power 6.0 kW; 230 Voltage) are utilized and placed within the tank of ETC for boosting the preheating of the total volume of saline inside the collector tank. This configuration is called a solar direct contact membrane distillation system with internal electric heaters (CASE 2). While in the third case, the internal electric heaters are replaced by a 6.0 kW direct compact electric heater installed at the feed saline water stream loop which is directly placed before the membrane module to directly enhance the stabilizing and preheating of the specified amount of saline water flow rate feeding the membrane. The third configuration is called a solar direct contact membrane distillation system with a direct electric heater (CASE 3). The main technical specifications of the proposed solar-powered DCMD system are demonstrated in Table 1.

Table 1.Main technical specifications of the proposed solar-powered DCMD system

Tubular DCMD Membrane module type		**Evacuated tube solar collector system**	
Model type	SE 090 TP 1M FF DIN V1 00	Number of tubes	25
Area of membrane	1.0 m^2	Tube Length	1800 mm
Nominal module diameter	9.00 cm	Outer tube diameter	58 mm
Number of membranes	46.0	Inner tube diameter	47 mm
Tube length	1.27 m	Glass material	Borosilicate Glass
Membrane outer diameter	8.5 mm	Absorptive Coating	ALN/ALN-SS/CU
Membrane inner diameter	5.5 mm	Vacuum	5xl0^{-3} Pa
Max. operating temperature	60 ^{o}C	**Internal electric heaters**	
Membrane material	Polypropylene	Two electrical tubular heaters (Unit Power 6.0 kW; 230 V) - Stainless Steel Tube (Outer diameter 8 mm & Length 1000 mm)	
Outer shell material	Polypropylene	**Compact Direct Electric Heater**	
Potting material	Polyurethane	6 kW electric heating system, the electric thankless water heater supplies instant & endless hot water of 46.6 ^{o}C.	

2.1 Thermal Performance Modeling

A numerical study was conducted to simulate the proposed solar DCMD integrated with an evacuated tube solar collector. MATLAB software was used to build the model and to perform related calculations. Performance of MD can be assessed by gained output ratio (GOR), which is the ratio between the latent heat required for evaporation process and supplied energy (Eq. 1)., the higher the GOR means better performance of the system;

$$GOR = \frac{\dot{m}_d * h_v}{\dot{m}_f * C_{pf} * (T_{fi} - T_{fo})} \quad (1)$$

Thermal efficiency is the ratio between heat gain for saltwater vaporization through the membrane and the overall heat transferred via the membrane [25]. It can be computed as:

$$\eta_t = \frac{J H_v A_m}{Q_{total}} \quad (2)$$

Where J is the permeate flux (kg/m^2 s), A_m is the membrane effective area (m^2), H_v is the enthalpy of vaporization of water (kJ/kg), and Q_{total} is the total heat flux through the membrane (kW) that can be calculated by using Eq. (3):

$$Q_{total} = \dot{m}_f * C_{pf} * (T_{fi} - T_{fo}) \quad (3)$$

Where, $\dot{m}_f$, is the feed mass flow rate (kg/s), C_{pf} is the feed water specific heat (kJ/kg °C), and $T_{fi}$and T_{fo} are the inlet and outlet feedwater temperatures, respectively (°C). Another important parameter in the

MD systems is the STEC which is defined as the energy required for producing one m^3 of desalinated water:

$$STEC = \frac{\rho^* Q_{total}}{JA_m} / 3600 \quad (4)$$

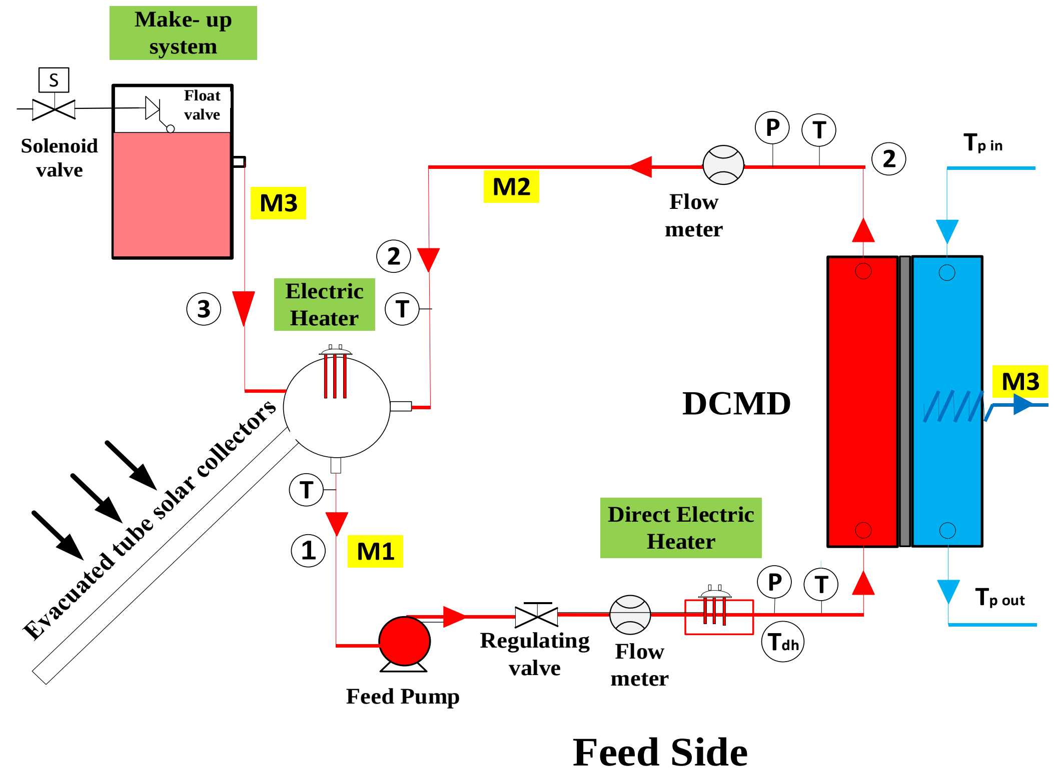


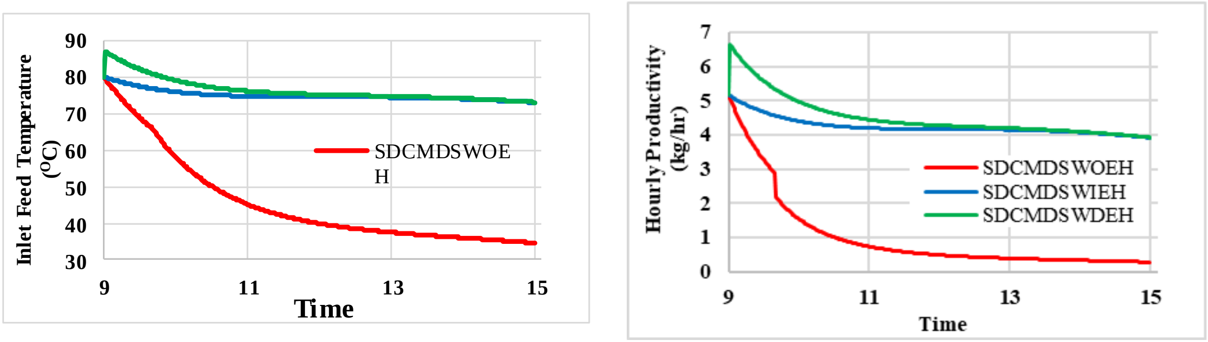
Figure 1. Schematic description of the proposed solar-based DCMD system

3 RESULTS AND DISCUSSIONS

The performance of the proposed solar MD system was evaluated under three different configurations on three sunny consecutive days, from 9:00 a.m. to 3:00 p.m. at the hot weather conditions of Tanta, Egypt (30.47° N and 31° E). Figure 2 (a) presents the variation of inlet feed temperature feeding the membrane with time under three different system configurations (CASE 1, CASE 2, and CASE 3) at a feed flow rate of 0.20 kg/s. The inlet feed temperature feeding the membrane was kept at 80 ^{o}C at the beginning of the experiments for all different system configurations. For the conventional SDCMDS, the feed inlet temperature decreases with time as shown in Fig. 2, because the energy lost from water in the system is larger than the energy gained by solar radiation to the solar collector. The inlet feed temperature feeding the membrane for the SDCMDWOEH is varied between 80 oC and 35oC throughout the day. For the other two configurations, the effects of using internal electric heaters or using direct electric heaters within SDCMDS are considerably effective to overcome the intermittence nature of solar radiation and minimize the energy lost from water. At these times, the role of internal electric heaters or direct electric heaters remarkably enhanced the inlet feed temperature feeding the membrane for the SDCMD and became more stable at 80 oC throughout the day. This improvement is led to relatively high stabilize mass flux through the membrane and a consequent increase in the overall efficiency of the system. The variations of hourly freshwater productivity with time under three different system configurations (CASE 1, CASE 2, and CASE 3) are displayed in Fig. 2 (b). It is observed that the hourly productivity has the same trend. The hourly water productivity for the traditional CASE 1 is decreased with decreasing feed water temperature as shown in Fig. 2(b) for the same mentioned above. As feedwater temperature decreases, the vapor pressure of feed water decreases and the vapor pressure difference across the membrane is also decreased. This results in a decrease in the permeate water productivity. Another key conclusion which can be drawn from Fig.2 (a) is the effectiveness of using internal electric heaters or using direct electric heaters within SDCMDS in the feed stream of the system which worked as a feed heat controller for the membrane and stabilized the feed inlet temperature at the optimal limit of 80-73 oC and thus improved the freshwater productivity in both systems. The application of using internal electric heaters inside the ETC and usage of direct electric heaters in the feed stream significantly increased the average hourly freshwater productivity by 351% and 323%, respectively, compared to that of traditional SDCMDS at feed mass flow rate of 0.20 kg/s.

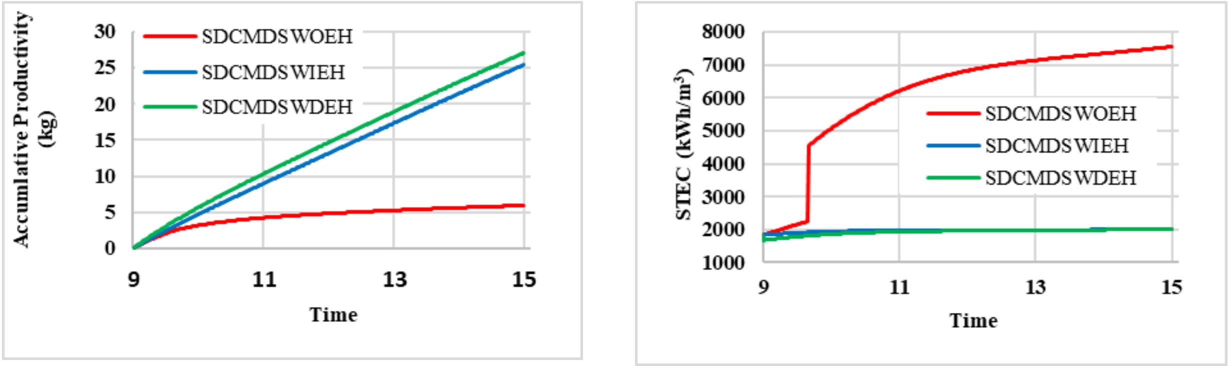
The diurnal changes in accumulative productivity for the three investigated SDCMDS configurations clearly shown in Fig. 3 (a). The obtained accumulative collected yield is reached to be 5.50, 25.15, and 27.35 kg/day, respectively, for the CASE 1, SDCMDS with internal electric heaters, and SDCMDS with direct electric heaters at constant water saline water flow rate of 0.20 kg/s fed to the membrane. Hence, it can be concluded that the proposed SDCMDS obtained an improvement in the daily distillate by 357.3% and 397.3 % over the traditional CASE 1 when using 6.0 kW internal electric heaters and 6.0 kW direct electric heater, respectively. As mentioned before, these great ameliorations are mainly due to the influence of usage of the internal and direct electric heaters.

Fig. 3 (b) depicts the variation of hourly STEC with time under the three different system configurations (CASE 1 CASE 2, and CASE 3). The STEC of both CASE 2 & CASE 3 is significantly lower than that in SDCMDWOEH throughout the day. This is mainly attributed to the higher temperature of synthetic seawater and higher freshwater productivity of the system in both CASE 2 & CASE 3 compared to that in CASE 1. The STEC of the CASE 1 had the lowest value in the morning, starting from 1833 kWh/m3 at 9:00 AM due to the maximum freshwater productivity at this time because of the maximal inlet feed water temperature. Then, the STEC undergoes ascending trend and reaches its maximum at 3:00 PM (i.e., 7550 kWh/m3). This can be attributed to the sharp decrease in inlet feed water temperature by the passage of time and consequent decrease in freshwater production rate. In contrast, the STEC for both CASE 2 & CASE 3 remains unchanged slightly due to the uniform inlet saline water temperature feeding the membrane over the day and consequent constant rate in distilled freshwater production. The average STEC of the conventional CASE 1, CASE 2 & CASE 3 are 1645.5, 1969, and 1930 kWh/m3, respectively. The GOR of the desalination module and thermal efficiency of the system is one of the most important performance parameters for a desalination system. Fig. 4 (a) depicts the variation of hourly GOR with time under the three different system configurations (CASE 1, CASE 2, and CASE 3). The hourly average GOR in all cases had an increasing trend in the morning and reached the maximum values at the beginning of operation corresponding to the highest setpoint feed inlet temperature. Then, it is started to remarkably decrease for the CASE 1 and marginally decrease for both CASE 2 and CASE 3 which was mainly attributed to the feed inlet temperature reduction and its consequent effect on the hourly productivity for each system operative configuration. The GOR in CASE 1 was in the range of 0.360–0.088 while this parameter fluctuated between 0.364 and 0.328 in CASE 2, as well as between 0.40 and 0.34 in CASE 3. The hourly overall efficiency of the system in different cases is presented in Fig. 4 (b). The feed inlet temperature decreased as time passed which resulted in low hourly overall efficiencies obtained by the CASE 1. The hourly averaged efficiencies over the day for CASE 1 CASE 2, and CASE 3 are found to be 22.35%, 31.07%, and 33.10%, respectively at 0.20 kg/s feed flow rate, respectively.



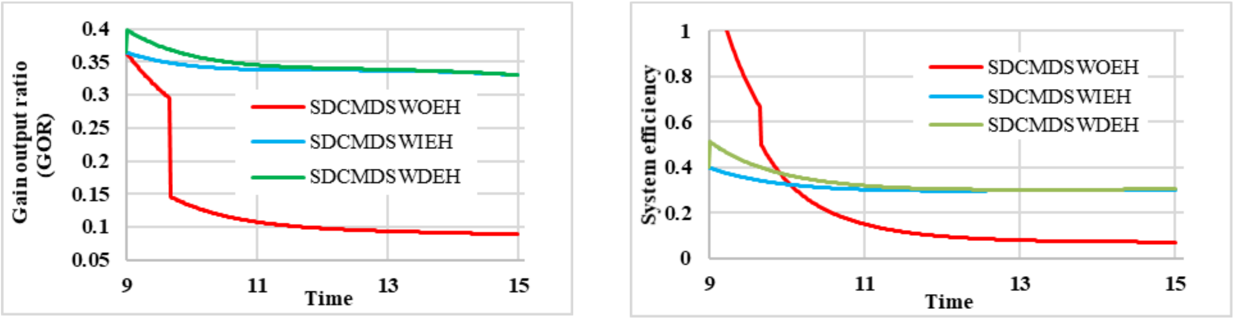
(a) **(b)**

Figure 2. Variation of (a) Inlet feed temperature feeding the membrane; (b) Hourly freshwater productivity under three different system configurations (CASE 1, CASE 2, and CASE 3).



(a) **(b)**

Figure 3. Variation of (a) Hourly freshwater productivity; (b) Specific thermal energy consumption under three different system configurations (CASE 1, CASE 2 , and CASE 3).



(a) **(b)**

Figure 4.Variation of (a) Hourly gain output ratio; (b) Hourly system overall thermal efficiency.

CONCLUSIONS

The following outcomes can be deduced as follows:

1. The obtained accumulative freshwater production was reached to be 5.50, 25.15, and 27.35 kg/day, respectively, for solar direct contact membrane distillation (DCMD) system without electric heaters (CASE 1), solar DCMD system with internal electric heaters (CASE 2), and solar DCMD system with direct electric heater (CASE 3) at constant water saline water flow rate of 0.20 kg/s, respectively.
2. The gain output ratio was estimated to be in the range of 0.360–0.088, 0.364−328, and 0.40−0.34 for CASE 1, CASE 2, and CASE 3 , respectively.
3. The average specific thermal energy consumption of the CASE 1, CASE 2 & CASE 3 were 1645.5, 1969, and 1930 kWh/m3, respectively.
4. The daily averaged system efficiencies of CASE 1, CASE 2, and CASE 3 were found to be 22.35%, 31.07%, and 33.10%, respectively at 0.20 kg/s inlet water feed flow rate, respectively.

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