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Improving the Distillate Production of a Solar-Driven Membrane Distillation Unit by Combining with a Heat Pump

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A solar-driven membrane distillation system has been built and tested. The system uses PV panel for electricity and solar-thermal collector to generate heat for the operation of the membrane distillation unit to produce water. Hence, this sytem can be considered as a stand-alone system. In order to increase the performance of the MD unit in producing water, a heat pump was coupled with the MD unit. Two of one-day operation based tests were conducted using heat pump (i.e. WHP = With Heat Pump) and without using heat pump ((i.e. WoHP = Without Heat Pump). These two test were conducted to investigate the effect of the heat pump on the system. The test results show that the T.Feed of the WHP test sharply increased (in a very steep slope) from 18°C to about 45°C initially and stable at 49°C. In contrary, the T.Feed of the WoHP test only increase a little of about 6°C only. At higher T.Feed, the feed water will evaporate earlier and faster than at the lower one, which resulted in more production of distillate. While, T.Cond.IN for the WHP test were much lower than that of WoHP test. The temperature difference was approximately 5°C throughout the hours of test. The heat pump successfully increased the temperature of the feed water by pre-heating it and in the same time decreased the temperature of the condenser, especially T.Cond.IN. These two conditions (i.e. higher T.Feed and lower T.Cond.IN) have led to a higher distillate production rate. The results also show that the average distillate output rate of the WHP test was about 11.62 L/h, which is almost twice that of the WoHP test (i.e. 5.98 L/h). Additionally, the total distillate production of the WHP test was about 70.1 which is almost twice that of the WoHP test (i.e. 34.72 L).

1. Introduction

Freshwater is one of the most important needs for the survival of human life and its demand is always increasing in all sectors worldwide (Wei et al. 2021; Ali et al. 2019; Hájek and Jegla 2012). The availability of freshwater has become a major issue in countries where the freshwater resources are limited, such as the Middle East and North Africa (MENA) region. In this region, freshwater is very scarce while the survival of civilization in this region greatly depends on the supply of freshwater. For such countries, desalination process of seawater or brackish water is considered as the best solution to solve this freshwater scarcity problem (Taha Sayed et al. 2022; Awaad et al. 2020). Many different desalination technologies are currently used to supply freshwater such as multi-effect distillation (MED), multi-stage flash (MSF) desalination, reverse osmosis (RO), vapor compression (VC), etc (Feria-Díaz et al. 2021; Hájek and Jegla 2012). Seawater desalination is considered as an energy intensive process in term of energy requirement. The problem is that most of these conventional desalination plants are using fossil fuels to fulfil their energy needs (Liu, Hu, and Chen 2014; Elminshawy, Siddiqui, and Sultan 2015). The data showed that approximately 22 million m^3/day of freshwater was produced by installed desalination plants across the world and this production needed approximately 203 million tons of oil yearly (Liu, Hu, and Chen 2014; Kalogirou 2005). The consumption of fossil fuels in large scale has caused the depletion of the fossil fuel resources, which eventually will be completely exhausted and lead to an energy crisis in the world. Fortunately, there has been an increasing trend in using renewable energy sources in all sectors including desalination process. The use of renewable energy sources led to clean energy implementation and reduce carbon foot print (Cipolletta et al. 2021).

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The utilization of solar energy to drive the desalination process (i.e. solar-driven desalination) has attracted great interest among researchers since solar energy is free and abundantly available, simple process and needs low maintenance, can save oil for other applications, reduces global warming effect [7]. While, the most important reason is that the development of solar-driven desalination technologies can solve the water and energy problem simultaneously [8, 9]. One of desalination technologies that is suitable to be coupled with solar energy is membrane distillation (MD). Therefore, many researchers have studied about solar driven membrane distillation technologies (Li et al. 2019; Zhao et al. 2020; Moore et al. 2018; Suwaileh et al. 2019; Shalaby et al. 2022; Elminshawy et al. 2020).

In the current work, a portable and stand-alone solar-driven desalination system via membrane distillation process has been built. Since the system is portable and stand-alone, hence it is very useful to be installed in remote areas such as island without access to electricity and water. Such of case has been a concern in other literature as well (Castro and Ocon 2021). As previously mentioned, the membrane distillation (MD) process is a combination of thermal and membrane separation based desalination process. One of the classical problems in the thermal based process is the low efficiency of energy. A device called heat pump is one of the solution to improve the energy efficiency of a thermal process. There are several types of heat pump available, some of them need external mechanical work, while the others need external thermal energy. Most of commercial heat pumps based on mechanical vapour compression cycle (Chua, Chou, and Yang 2010). In the current work, a mechanical-electrical device called heat pump was integrated within the system. The objective of this heat pump are to pre-heat the feed water and to cool the cooling water prior entering the MD unit.To the best of our knowledge, research studies about a solar-driven desalination system that was portable, stand alone, using Membrane Distillation MD process, and coupled with a heat pump are quite limited. Therefore, it is very interesting to study the influence of heat pump on the performance of such system.

2. Solar-Driven Desalination System

The solar-driven desalination system consists of three main sub-systems which are integrated, namely: solar-thermal, solar-photovoltaic (PV), and membrane distillation process (MD) unit. Each of the sub-systems are integrated to support the operation of the system for producing potable water by only utilizing solar energy. Figure 1 shows the appearances of the system and heat pump..

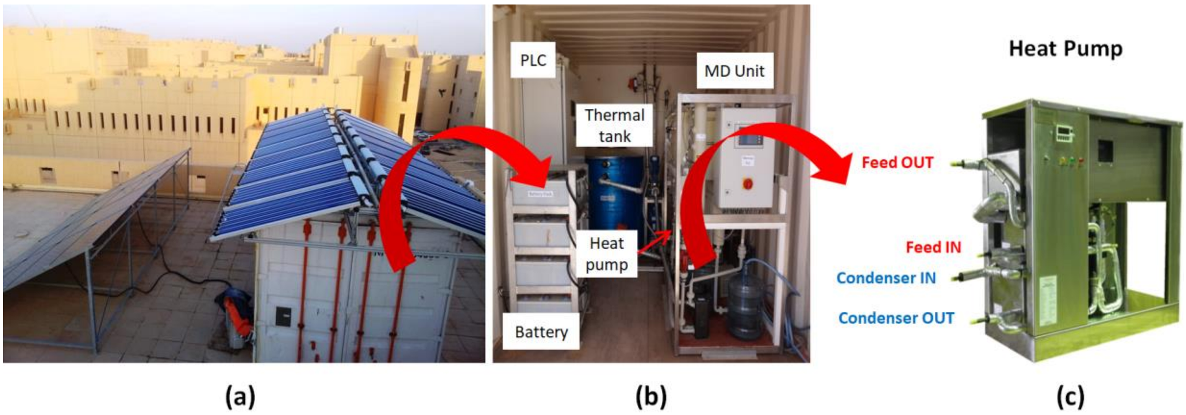

Figure 1: Photographs of (a) A stand-alone solar-driven desalination system; (b) Membrane distillation module and other auxiliaries inside the container; (c) Heat pump unit which combined to the membrane distillation modul unit.

The solar irradiation from the sun is utilized by converting it into two different of forms of energy, i.e. thermal energy and electrical energy, which are needed by the system. The solar-thermal system is responsible for harvesting or converting solar irradiation into heat, storing the heat, and supplying the heat required by the MD unit to produce potable water. The solar irradiation absorbed/harvested is used for heating up the heat-transfer fluid (i.e. freshwater) which circulated by the thermal pump through the evacuated tubes thermal collector, collected in the thermal tank, and re-circulated again. The operating temperature range of the thermal storage tank is approximately 55-95°C. Once, the temperature is reached, the heat stored in the thermal tank is transferred to the MD unit by circulating the hot freshwater inside the tank through a heat exchanger using the MD pump. The solar-PV sub-system is responsible for providing the electricity throughout all the parts of the solar-driven desalination system. This sub-system used a PV array which consisted of 16 HIT (Heterojunction with intrinsic Thin-layer) type PV modules made by SANYO, which were installed in a fixed position. The PV module has a dimension of 158 cm x 79.8 cm. It has a total power output of approximately 3.36 kW. In other hand, the membrane distillation unit is the main sub-system which responsbible for producing potable water. This unit comprised of three major parts, which are evaporator, evaporating-condensing multi-stages, and condenser (see Figure 2). In the evaporating-condensing multi-stages part, a type polytetrafluoroethylene (PTFE) based membrane was used. The membrane sheet has a dimension of 33.5 cm x 47.5 cm with pore size of approximately 0.2 □m.

To enhance the productivity of the MD unit, a heat pump was installed and integrated with the MD unit (see Figure 2 as red-highlighted). The objectives of the heat pump are to pre-heat the feed water e.g. seawater (before entering the evaporator) and to cool the cooling water i.e. freshwater (before entering the condenser) (see Figure 2). Hence, the temperature difference between the evaporator and the condenser will be higher than without the heat pump. As the consequence, the water production via membrane distillation process will also become higher. The heat pump used in this work has a direct suspension water cooled refrigeration system. Figure 1c shows the photograph of the heat pump with four pipes connected to feed water and condenser.

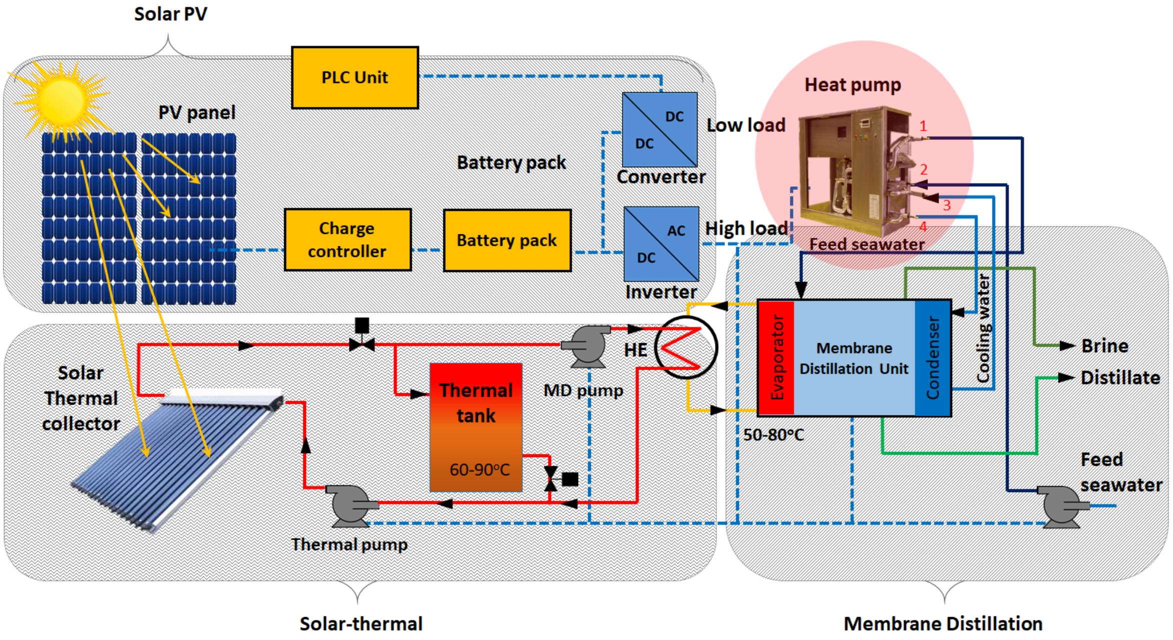

Figure 2: Schematic illustration of the solar-driven desalination system via membrane distillation process

3. Results and discussion

The performance of the desalination system and the effect of the heat pump have been studied by conducting two different tests. In one test, the solar-driven desalination system was operated for one day (i.e. seven hours) by employing a heat pump and another test did not use a heat pump. These two test were carried out to study the effect of the heat pump on fhe system. These two tests later on were called as “With Heat Pump = WHP” and “Without Heat Pump = WOHP” tests. There are several parameter during the test of the system, as shown in Table 1.

Table 1: Description of several parameters during the test of the desalination system

No	Parameter	Description
1	T.Feed	Temperature of feed water (e.g. seawater, brackish water) that enter the evaporator part of the MD
2	T.Cond.IN	Temperature of inlet condenser
3	T.Cond.OUT	Temperature of outlet condenser
4	T.Tank	Temperature of thermal tank or heat storage

3.1 The effect of heat pump on the temperatures of feed water and cooling water

Figure 3 shows the profiles of T.Feed, T.Cond.IN, T.Cond.OUT for both WHP (With Heat Pump) and WoHP (Without Heat Pump)tests. As seen in Figure 3, a significant difference in the T.Feed between both of the tests (i.e. with and without heat pump) was noticed. The T.Feed of the WHP test sharply increased (in a very steep slope) from 18°C to about 45°C initially and stable at 49°C. In contrary, the T.Feed of the WoHP test only increase a little of about 6°C only. In other hand, for the temperature profiles of the condenser, i.e. T.Cond.IN and T.Cond.OUT showed a contrast result compared with the T.Feed. As seen in Figure 3, the T.Cond.IN for the WHP test were much lower than that of WoHP test. The temperature difference was approximately 5°C throughout the hours of test. Whereas, the temperature profiles of T.Cond.OUT for both of the test were not much different. Additionally, as expected, the temperature profile of T.Cond.IN for both tests were lower than the T.Cond.OUT. These results show that heat pump played an important role in increasing the desalination system performance. The heat pump successfully increased the temperature of the feed water by pre-heating it and in the same time decreased the temperature of the condenser, especially T.Cond.IN. At higher T.Feed, the feed water started to evaporate earlier and faster than at the lower one, which resulted in more production of distillate. Furthermore, with lower T.Cond.IN, the temperature gradient of evporator-condenser became higher, and thus increasing the membrane distillation process driving force, which resulted in higher distillate production rate.

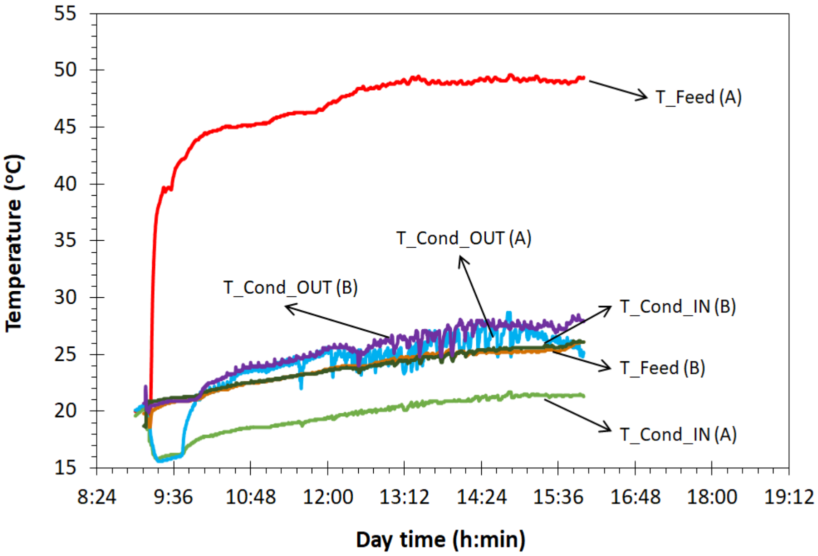

Figure 3: Temperature profiles of T.Feed, T.Cond.INcondenser IN, and condenser OUT for the test that used a heat pump (A) and the test that did not use a heat pump (B)

3.2 The effect of the heat pump on the water production

Figure 4 shows the profiles of global irradiation, temperature inside the thermal tank (T.Tank), distillate production rate, and distillate accumulation for both the tests (i.e. WHP and WoHP). As seen in Figure 4, the global irradiation profile for the test with a heat pump had a similar trend with the test without a heat pump. This result was expected since the tests were conducted on consecutive days. Additionally, the similar result was also noticed for the T.Tank. This result was also expected since the T.Tank was considerably depends on the global irradiation level. Since, the global irradiation level or both of the tests were similar, the T.Tank for both the tests were also similar. In other hand, significant differences were noticed in the profiles of distillate output rate and distillate accumulation. The profile of distillate output rate of WHP was higher than that of the WoHP. Whereas, the distillation accumulation profile for the WHP test increased with the slope steeper than that of the WoHP. Table 2 shows the comparison of the test results of the desalination system with and without the heat pump (i.e. WHP and WoHP). As seen in the table, the average global irradiation levels for the test with and without the heat pump were similar, i.e. 605.5 W/m^2 and 610.1 W/m^2. Additionally, the table also shows that the average distillate output rate of the WHP test was about 11.62 L/h, which is almost twice that of the WoHP test (i.e. 5.98 L/h). Additionally, the total distillate production of the WHP test was about 70.1 which is almost twice that of the WoHP test (i.e. 34.72 L). In term of distillate quality, the conductivity level for both of the tests were almost similar, i.e. 4.7 and 5/3 μS/cm for WHP and WoHP tests, respectively. Additionally, there was a unique finding as shown in Figure 4. As seen in the figure, there was a difference in a time lag between the test with and without the heat pump. The time lag was attributed to the time needed for the MD unit to start produce the distillate. This time lag occurred possibly due to the volumetric heat capacity (VHC) of the heating fluid (i.e. freshwater), and thus it took time for the solar-thermal system to harvest and store the thermal energy for increasing the temperature of the thermal tank. Once, the temperature of the thermal tank reached its operating temperature (i.e. 60-90°C), the thermal energy/heat was transferred from the tank to the evaporator part of the MD unit to evaporate the feed water. Only then, the production process of distillate will start. As seen in Figure 4 as well as Table 2, the difference of time lag between the test with and without the heat pump was about 30 minutes, which implies that the distillate production process of the WHP test started much earlier (i.e. 30 minutes) than that of the WoHP test. It was because the feed water in the WHP test was already warm/hot enough (see Figure 3) to be evaporated, and thus evaporate earlier than the WoHP test.

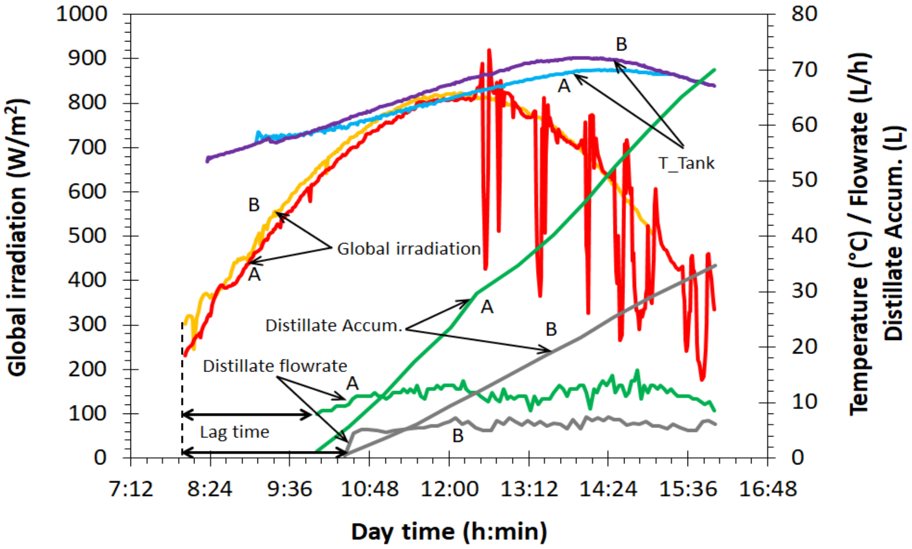

Figure 4: Profiles of global irradiation, thermal tank temperature, distillate production flowrate, and distillate accumulation of the test that used a heat pump (A) and the test that did not use a heat pump (B).

Table 2: The effect of the heat pump on the water production of the MD unit

Test	Heat pump	Average Global irradiation (W/m^2)	T.Feed (range) (°C)	Distillate output		
				Average rate (L/h)	Total (L)	Conductivity (µS/cm)
A	YES	605.5	17-49	11.62	70.1	4.7
B	NO	610.1	20-26	5.98	34.72	5.3

4. Conclusions

In this work, a stand-alone solar-driven membrane distillation process has been built and successfully tested. Two pilot-plant tests called WHP = “With Heat Pump” and WoHP = “Without Heat Pump” were conducted to study the influence of heat pump on the desalination system performance, e.g. distillate/water output rate, total distillate produced, etc. For one test, the system was operated for one day (i.e. seven hours) by employing a heat pump and another test did not use a heat pump. The test results showed that there was a significant difference in the T.Feed between both of the tests. The T.Feed of WHP test sharply increased from 17°C to 44°C and then steady at about 49°C for the rest of test. In contrary, the T.Feed profile of the WoHP test only increase a little of about 6°C only. Additionally, the T.Cond.IN for the WHP test were much lower than that of the WoHP test. The temperature difference was approximately 5°C throughout the hours of test. At higher T.Feed, the feed water will evaporate earlier and faster than the lower T.Feed, which resulted in more production of distillate. Furthermore, with lower T.Cond.IN, the temperature gradient between evaporator and condenser became higher. This condition will increase the membrane distillation process driving force, which resulted in higher distillate output. As reported, the average distillate output rate of the WHP test was about 11.62 L/h, which is almost twice that of the WoHP test (i.e. 5.98 L/h). Additionally, the total distillate production of the WHP test was about 70.1 which is almost twice that of the WoHP test (i.e. 34.72 L).

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