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Seawater Greenhouse Equipped with a Novel Solar Humidification-Dehumidification Desalination Unit in MAKRAN Coast: Fabrication and Experimental Study

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Abstract: The purpose of this study is the fabrication and performance evaluation of a new type of solar humidification–dehumidification (HD) desalination unit to supply sufficient fresh water for a seawater greenhouse in the MAKRAN coast in southeast Iran. In the proposed design, a particular type of air-to-air condenser is used. The cold air coming out of the greenhouse ventilation system (fan and pad) in summer and the cold ambient air in winter is used to supply the required cooling of the system. In this way, when cold air passes over the pipes in air-to-air condensers, condensation of water vapor occurs in the moist air inside the pipes, and fresh water is produced. Greenhouse fans, which have an air flow rate of around 20,000 m^3/hr, are used to create this air flow. By fabricating two condensers, each using 42 rows of PVC pipes with a diameter of 75 mm, it is possible to produce 400 L of fresh water per day in a 400 m^2 greenhouse. The required heating is provided by the solar farm, which includes 96 square meters of flat plate collectors. The steps of unit fabrication are described in detail in this research. However, the effect of greenhouse air temperature and circulating seawater flow rate on freshwater production, energy consumption, and energy intensity are also investigated. By increasing the flow rate of circulating seawater and decreasing the greenhouse air temperature, the production rate of the system increases. When the hot seawater and greenhouse air temperature are 61.7 °C and 26 °C, respectively, the maximum instantaneous production is estimated to be 80 L/h. The energy intensity of the HD desalination unit is varied between 3192 and 4382 kJ/L, and the gain output ratio of the system is around 0.6. The proposed system can be easily paired with conventional greenhouses employing a fan and pad cooling system and produces around 1.25 (L/m^2·day) fresh water.

Keywords: seawater greenhouse; HD desalination; solar energy; air-to-air condenser

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1. Introduction

Desalination of seawater is one of the leading technologies of freshwater production worldwide, which has mainly taken place in coastal areas over the last few decades. Energy supply of desalination plants has always been an important issue in their development. The use of fossil energies is frequently criticized due to its harmful effects on the environment [1]. Solar energy is a green source of energy that can meet the energy needs of any system [2]. Seawater greenhouses have been proposed as one of the technologies that simultaneously use the greenhouse system, solar energy, and seawater for the sustainable supply of fresh water and greenhouse products. In general, the development of greenhouses has a significant role in reducing water consumption and mitigating the water shortage crisis. By transferring the cultivation of water-consuming plants such as vegetables and summer crops to greenhouses, the consumption of water resources is reduced by ten times. The low efficiency of freshwater production is the main drawback of this kind of greenhouse.

So far, solar water desalination units have been used in greenhouses in two ways. The first method is the direct distillation of seawater and the second is the process of air humidification and dehumidification (HD). Solar still has a relatively low productivity rate per unit area of the solar panel [3,4], so more studies have considered the HD method. To reduce the air temperature, especially in the summer, or to supply the CO_2 required by the greenhouse, it is necessary to discharge the greenhouse air to the outside at a specific rate in order to carry out the required ventilation of the greenhouse. Evaporative cooling systems are used to cool the incoming air. In this way, a type of packing is used in the air inlet to the greenhouse, and water flows over it in a closed cycle. The air becomes cold and moist by passing through the evaporative cooler. Considering that the water is flowing in a closed cycle, and assuming low heat losses in the water flow path, the process follows a path that is close to the adiabatic saturation line in the psychrometric chart. As the air passes through the greenhouse, heat exchange occurs between the plant, soil, and air, and the air is then directed out of the greenhouse with axial blowers.

The combination of air humidification and dehumidification processes to produce fresh water from seawater in coastal greenhouses was first proposed by [5]. In 1994, the first greenhouse with an area of 360 m^2 was built on the island of Tenerife, Spain. Cellulose packing was used in this design for the humidification process. The potential of water production is reported between 0.6 and 1.2 L/m^2 of the greenhouse area. The quality of water produced is excellent, and the mass of total dissolved solids (TDS) is reported to be less than 50 ppm. They considered the Middle East region suitable for the development of this system, and in the following years, they built two more examples in this region [6,7].

A project to implement the HD process in a greenhouse was carried out by Perret et al. [8]. At the end of the proposed greenhouse, two tubular condensers with brass tubes and copper fins with 0.9×0.9 m cross-section were used. Due to the reduction of the air flow cross-section in the condensers, the velocity of the air increased significantly. Additionally, due to the very low heating point of the water entering the humidifier, the temperature difference between the water and air entering the condenser was between 3 and 4 °C. For this reason, freshwater production was deficient. In their research, the condenser is introduced as the bottleneck of the combined system, which has a significant effect on the cost of freshwater production. By examining different dehumidification methods and providing the required cooling, Dawoud et al. [9] have introduced the condenser with water cooling as the best type of condenser. In addition, it was proposed to direct the air from the upper part of the greenhouse to the inlet of packing dehumidification that increases the evaporation in this packing and, as a result, intensifies the production of fresh water in the condensers.

Davies et al. [10] have proposed using a method of solar cooling, which utilizes absorbent materials to facilitate air cooling. Mahmoudi et al. [11] have investigated the potential of the greenhouse to generate electricity from wind and solar energy, confirming the possibility of the system's complete independence from fossil energy. Zaragoza et al. [12] presented a plan in which the main goal was to use solar energy to provide the thermal energy required by the greenhouse at night and produce fresh water during the day. During the day, the sun's energy is transferred to the water tank through the central tower, which consists of several heat exchangers, and during the night, it heats the greenhouse air by passing through the same exchanger again. Condensed vapor is then conducted to the tank during the day. Based on their presented results, this project was successful in absorbing and storing solar energy and supplying the heat needed by the greenhouse during the night. Nevertheless, the production of fresh water was minimal. Research has also been conducted on the controllability of the main parameters in stabilizing the air quality inside the greenhouse [13,14].

In 2008, Zurigat et al. [15] conducted a comprehensive study on seawater greenhouses. The main reason for the decrease in dehumidification efficiency was the low-temperature difference between the air and the coolant entering the condenser. They experimentally investigated using a condenser made of thin and flexible polyethylene sheets. Their experimental results showed a 16.5% increment in freshwater production compared to the polyethylene tube condenser used by Paton [16] in Oman. Therefore, the humidity and temperature of the air entering the condenser and the air flow are more significant in the HD desalination unit. Tahri et al. [17] have experimentally evaluated the performance of an HD unit in a seawater greenhouse in Oman. The seawater is conducted through a series of pipes that are located on the roof of the greenhouse and heated by solar energy. The production rate reached 65 L/h when the solar radiation was around 800 W/m^2. Mahmoudi et al. [18] have employed a new condensation system. A tank was used as a cooling source, and the air flow transferred its heat to the water in the tank in two ways. The first method is to place pipes inside the tank, so that air passes through the pipes that were installed inside the tank. This method creates a significant pressure drop in the air path. In the second method, the air passes over the pipes, and circulates naturally due to the heating of the water inside the pipes. In each of these methods, there is no need to pump water, but the electricity consumption of the air blower is increased.

Zamen et al. [19] have proposed a direct contact condenser instead of a fin tube condenser. The corrosion and leakage problems are eliminated in this method. Given that their proposed unit was installed in a place far from the sea, and the resulting lack of access to cool seawater, their experimental results were expected to be lower than the design values. However, even in the case of supplying cold water at 30 °C and hot water at 60 °C, the entire water requirement of the greenhouse can nonetheless be provided in this way. In 2018, Abdulrahim et al. [20] studied a model of seawater greenhouses that provided fresh water for irrigation through the HD desalination process. The overall efficacy of their method primarily depends on the effectiveness of its condenser. Four variables were considered, consisting of solar radiation, inlet air temperature, air velocity, and humidity. They provided a multiple linear regression model to predict the amount of dehumidification within a greenhouse.

Elsewhere, the application of an evaporative cooler to decrease the volume of seawater greenhouses was proposed by Akinaga et al. [21]. Instead of an electric fan, only the natural movement of air was considered for ventilation in their research. Taleb Zarei et al. [22] have employed machine learning (ML) methods to investigate the significant parameters of the solar seawater greenhouse on water production, such as the evaporator's size and the transparency of the roof. They concluded that for a greenhouse with a size of 125 × 200 × 4 m and a roof transparency of 0.6, the amount of freshwater produced is 161.6 m^3/day. Xu et al. [23] have fabricated a HD desalination unit using an air-cooling condenser. The air-cooling temperature varied between 16 and 27 °C in their experiment, and 129 kg/day of fresh water was produced when the hot water temperature was at 49.5 °C. Recently, a HD desalination unit was presented by El-Ashtoukhy et al. [24]. Their proposed system was able to produce 133.72 kg of fresh water per total volume of packed section at 60 °C.

This research investigates the fabrication steps involved in developing a seawater greenhouse pilot on the MAKRAN coast, using a novel air-to-air condenser. A HD desalination unit is proposed, using cold air from the greenhouse ventilation system (fan and pad). In brief, the following can be elaborated as technical innovations in the current research:

- Using a new air-to-air condenser instead of conventional condensers that have corrosion problems and higher operating costs;
- Evaluating the performance of an HD desalination unit in low temperatures;
- Providing the thermal energy needed for desalination of seawater using solar energy.

2. Technology Description

In previous studies, various methods have been proposed to produce fresh water in seawater greenhouses. Some of these methods can be classified as follows:

- HD desalination with indirect tubular condenser;
- HD desalination with direct contact condenser on packing;
- HD desalination with underground condenser;
- Compression refrigeration cycle for simultaneous production of cooling and water in greenhouse;
- Absorption refrigeration cycle for the simultaneous production of cooling and water production;
- HD desalination using cold air from the ventilation system (fan and pad) of the greenhouse.

In this research, we investigate an HD desalination unit that used output air from the ventilation system (fan and pad) of a seawater greenhouse. The proposed system, which is based on the process of air humidification and dehumidification, can operate at low temperatures. Therefore, the application of solar energy can provide the required heat well. In this plan, the solar radiation energy is first absorbed by flat plate solar collectors in a solar farm, then transferred to the seawater by a thermal coil placed in the seawater tank. Hot seawater with a temperature of about 60 °C is sprayed in the humidification tower. When air passes over the packing inside, the humidifier becomes warm and humid.

The most important part of this water desalination unit is using the greenhouse's cool air instead of conventional condensers, which are used to condense water vapor in the dehumidification section. The ambient air is cooled by passing it through the wet greenhouse pad, so that the air inside the greenhouse is cooled. To take advantage of the cooling energy of the greenhouse air in this system, a heat exchanger is installed next to the greenhouse. The cool air passes through the condenser tubes, in which hot and moist air flows with the help of installed fans. In the proposed plan, the air-to-air condenser is used as a dehumidifier. Moist air flows inside the pipes of this heat exchanger and cooled greenhouse air or ambient air flows over the tubes. On hot days, when the ambient air temperature is high and the greenhouse cooling system is turned on, the exhaust air of the greenhouse ventilation system (which has a temperature of between 25 and 30 °C) can be used to cool the condenser (Figure 1a). On cold days, when the ambient air temperature is suitable, there is no need to turn on the fan and pad system and the ambient air (whose temperature is around 25 °C) can be used to cool the condenser (Figure 1b). For this purpose, the connection between the greenhouse and the desalination condenser is disconnected, and the cool ambient air flows directly over the condenser tubes.

The hot air (50 °C) comes out from the top of the humidification tower and is transferred to the inlet collector of the condenser through the transfer channels. It is then uniformly spread between the condenser tubes by the inlet distributor. The cool greenhouse air that flows over the condenser tubes cools the hot and moist air that flows through the condenser tubes, and the water vapor in the moist air is condensed. After condensing the water vapor, the humid air enters the output collector and the suction blowers then transfer it to the humidifier tower. Due to the slope of the pipes, the condensed water flows towards the condenser outlet collectors and is transferred to the freshwater tank. The water collected in the freshwater tank is kept at a suitable temperature or is pumped directly to the place of consumption, i.e., inside the greenhouse.

Since many greenhouses have evaporative cooling systems (fans and pad), it is possible to implement the proposed system in these kinds of greenhouses. Additionally, by adding a desalination unit to the greenhouse, it becomes possible to develop greenhouses in areas that have saline water sources.

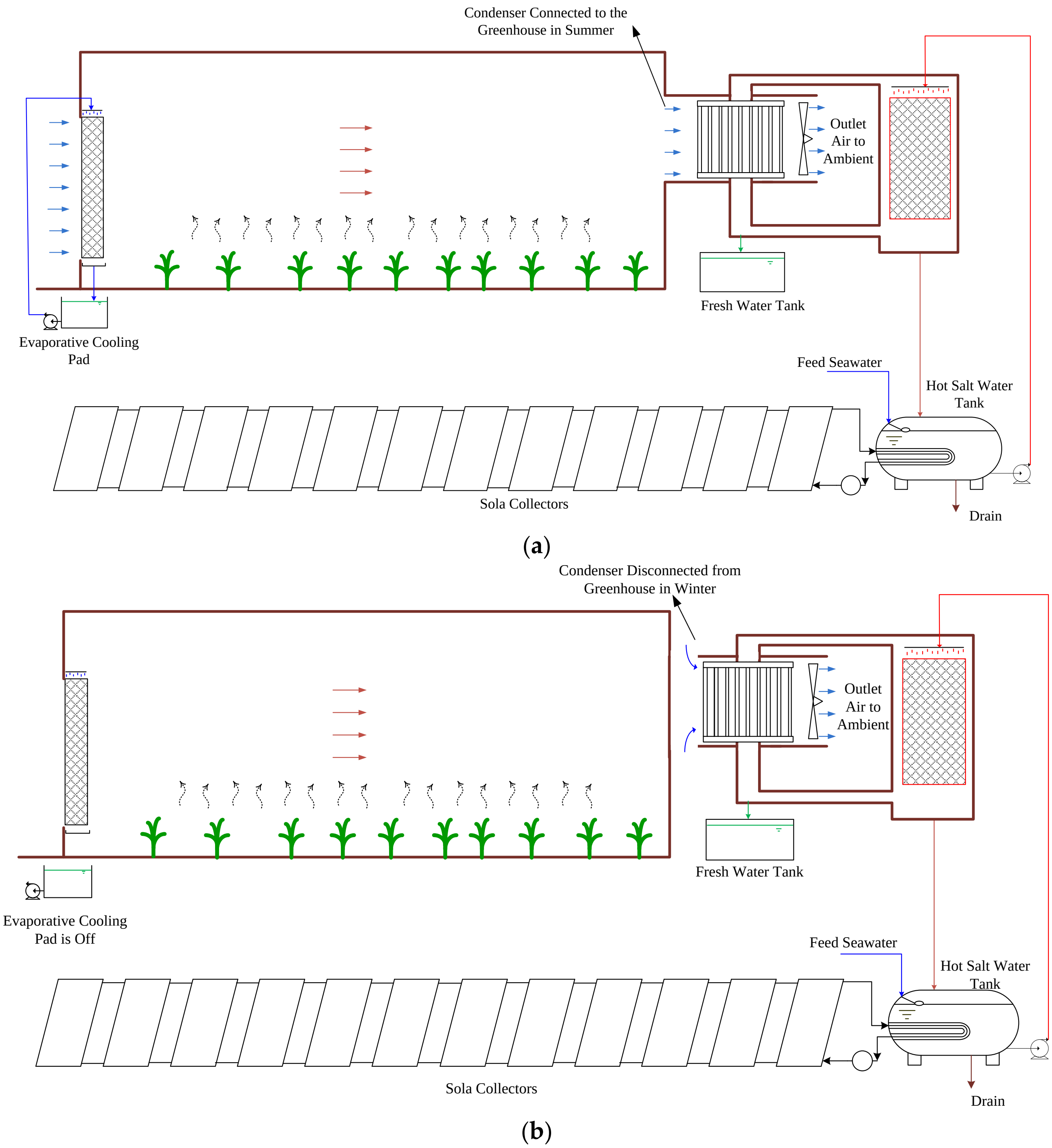


Figure 1. Proposed seawater greenhouse equipped with HD desalination unit on (**a**) hot days, and (**b**) cold days.

3. Fabrication and Installation of the HD Desalination Unit

3.1. Condensers

Using two condensers (east and west), each with 42 rows of PVC pipes with a diameter of 75 mm, it is possible to produce around 400 L of fresh water per day in winter, and more production can be achieved in the summer. Moreover, using two condensers reduces the total length they occupy in front of the greenhouse. The design parameters of the condensers are given in Table 1.

Table 1. Fixed parameters during the experimental tests on each condenser.

Parameter	Value
• Cross-section of the channel connected to the greenhouse (m)	• 1.4 × 1.4
• Cold air velocity over the pipes (m/s)	• 1.50
• Mass flow rate of cool air over pipes (kg/s)	• 3.45
• The number of rows of tubes in each condenser (-)	• 42
• Inner diameter of pipes (cm)	• 7.50
• Hot air velocity through the pipes (m/s)	• 1.22
• The total mass flow rate of hot air entering each condenser (kg/s)	• 0.20
• Air humidity inside the pipes (%)	• 100

The fabrication of the first condenser starts with the welding of corresponding iron profiles to build the structure. Next, the prongs designed to mount the 3-inch polyvinyl chloride (PVC) pipe in each row along the condenser length are welded to the structure. All surfaces are also coated with stainless paint. In the next step, the condenser tubes and their related elbows are prepared with high precision using a standard glue and mounted on the condenser in a suitable place. It is essential to connect the PVC pipe and elbows well so as to prevent leakage. Two 16-inch pipes, considered as the headers and the collectors, are then installed at the top and the bottom of each condenser. For this purpose, a few holes are made to connect the 3-inch pipes. The connection of the 3-inch pipes and the 16-inch PVC pipes above and below the condenser is completed with the help of a special glue. Finally, the condensers are covered with insulating foams, and blue-colored iron sheets are installed on top of them. Every step mentioned for the fabrication of the first condenser is repeated for the second one. Figure 2 shows the arrangement of tubes in condensers and two fabricated condensers.

(**a**)

Figure 2. *Cont.*

(b)

Figure 2. The arrangement of tubes in condensers (**a**) and two fabricated condensers (**b**).

3.2. Humidifier

The structure of the humidifier tower is made according to the design drawings with profiles and galvanized sheets. The outer surface of the humidification tower is also covered with colored iron sheets. For the humidification tower, 18 polypropylene packing blocks (30 × 30 × 100 cm) which can tolerate up to 80 °C are used. In addition, to choose the right type of nozzle for seawater spraying over the packing, various kinds were tested. Finally, the petal model nozzle was selected and used for this purpose. Six nozzles are utilized in the upper part of the humidification tower to cover the whole cross-section of the tower completely. In addition, to prevent liquid droplets escaping into the moist air output channel, a drift eliminator is used in the upper channel of the humidifying tower. The nozzle, the drift eliminator, and the packing used in the humidification tower are all shown in Figure 3.

(a) (b) (c)

Figure 3. (**a**) Drift eliminator, (**b**) packing and (**c**) nozzle that used in the humidification tower.

To circulate the air in the condenser and tower systems, two backward centrifugal type blowers of Bib-40/14n4t model are used. In addition, two suitable bases were designed and built to fix the blowers. Sixteen-inch pipes also restrain the connection between the saturated air exiting the tower and the header part above each condenser. Meanwhile, the blowers direct the air to the tower through the respective transfer channels.

3.3. Hot Seawater Tank

Due to the high temperature of seawater and its corrosiveness, it is not possible to use conventional iron sheets for its construction. Accordingly, the tank is made using galvanized sheets, which are shaped and welded together in different parts. To prevent corrosion of the tank, a special silicate-based epoxy color was used, which demonstrates resistance up to temperatures of 90 °C. A gate at the top of the tank that allows for access to its interior is also integrated into the construction process. Finally, all the external parts of the tank were covered with Pflex insulation.

To increase the temperature of seawater using hot water directed from the solar farm, an 85-foot copper coil with a length of 185 cm is used, along with copper pipes that have a thickness of 0.9 cm. The T-shaped parts inside the tank are designed and built to support the weight of the copper coil pipes. In addition, in the coil construction, the maximum possible distance between the pipes is ensured to prevent the rapid formation of sediment. The thermal coil and fabricated seawater tank are shown in Figure 4. A $1\frac{1}{2}$ inch hot water meter is also used to measure the hot water flow from the solar farm to the tank. To supply sufficient energy, an electrical heater is placed in the seawater tank.

Figure 4. The thermal coil and the fabricated seawater tank.

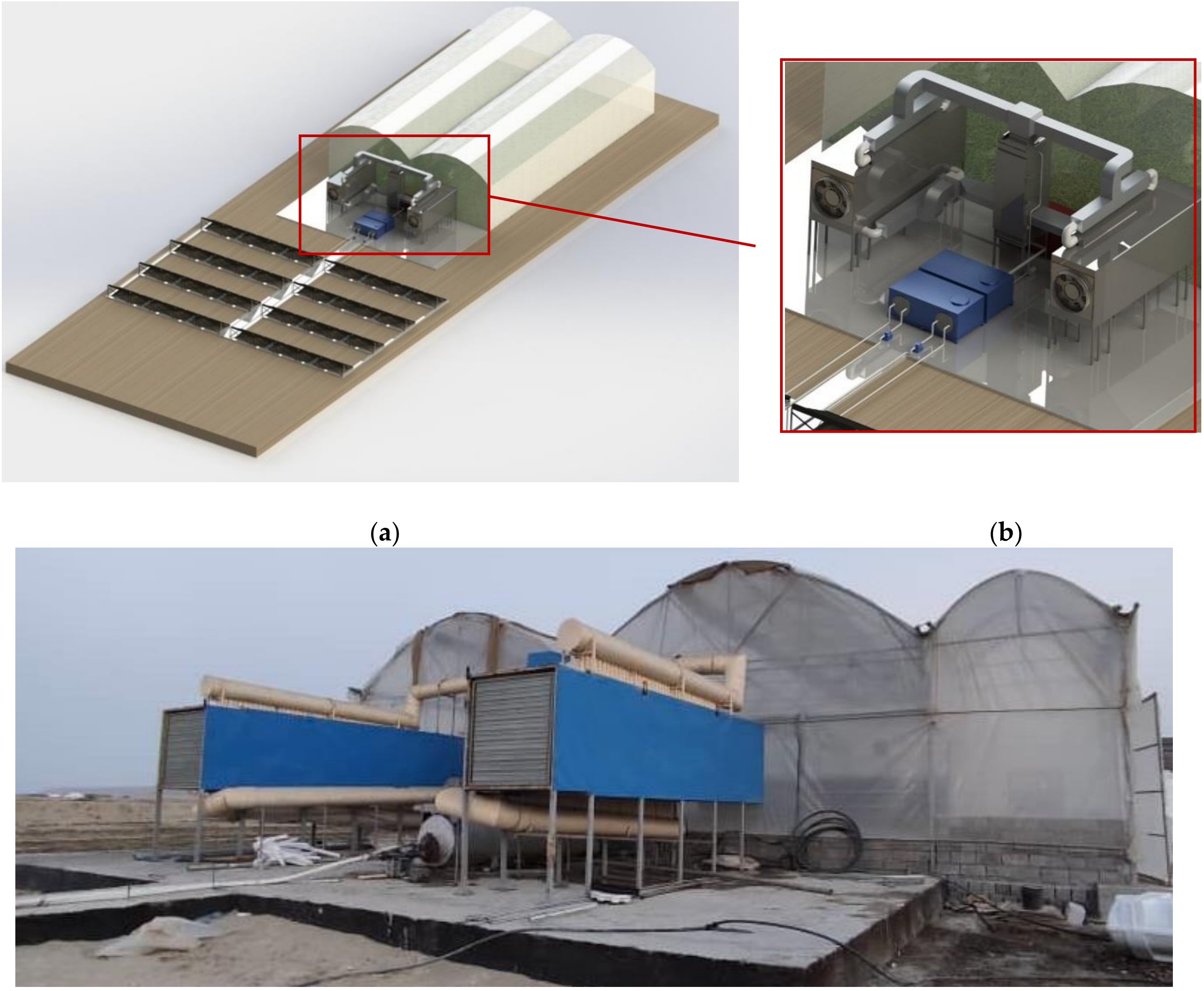
3.4. Solar Farm

To install the solar system, the necessary foundation is firstly implemented on the specified part in front of the greenhouse. This is in order to establish a solar farm in four rows and two columns, as shown in Figure 5. Forty-eight flat plate solar collectors with an active surface area of roughly 96 m^2 are used to provide the necessary heating for seawater. In addition, four expansion tanks of 80 L capacity are installed in a suitable place to capture the oscillation of heated water by the solar farm. The necessary piping is also performed to connect the ring of water circulation in the solar system and transfer it to the seawater tank. The seawater's temperature depends on the surface area and the type of solar collectors. More energy and higher temperatures can be achieved if vacuum tube collectors are used.

Figure 5. Solar farm in front of the seawater greenhouse.

At the end of the installation process, the air circulation system was installed between the condensers and the humidification tower. By installing four fans in the greenhouse, each with a power of 1.1 kW, the ventilation rate of the greenhouse improved significantly (Figure 6). Two of the existing fans are used directly in the HD desalination condensers to create cooling over the pipes, and the remaining two fans are directly connected to the environment just to improve the ventilation of the greenhouse. Installing the shade over the greenhouse has led to a decrease in the temperature of the greenhouse from 35 °C to 30 °C. A schematic and a photo of the seawater greenhouse equipped with HD desalination unit are shown in Figure 7.

Figure 6. The position of ventilation fans installed in the seawater greenhouse.



(a) (b) (c)

Figure 7. (**a**) Schematic of the seawater greenhouse equipped with HD desalination unit, (**b**) schematic of HD desalination unit and (**c**) the photo of installed unit in MAKRAN coast, Iran.

4. Measurements and Data Gathering

After installing the HD unit at the project site located in the MAKRAN coast, preliminary experiments were conducted to check the performance of the water desalination unit. In general, the experimental data that must be recorded during the unit's operation are classified into general categories, including the solar system, the humidification section, the eastern and western condenser, the greenhouse, and the environmental condition. The values of temperatures at different points, the flow rate of the air in the condensers, the flow rate of circulating seawater, and the production rate of fresh water, as well as the temperature and humidity of the greenhouse, are measured and recorded in each experiment. The locations of temperature and humidity sensors, and flow meters are shown in Figure 8. The K-type thermocouples (0.1 °C accuracy) and a hot wire anemometer (ST-3880) are used to measure temperature and air velocity in the system, respectively.

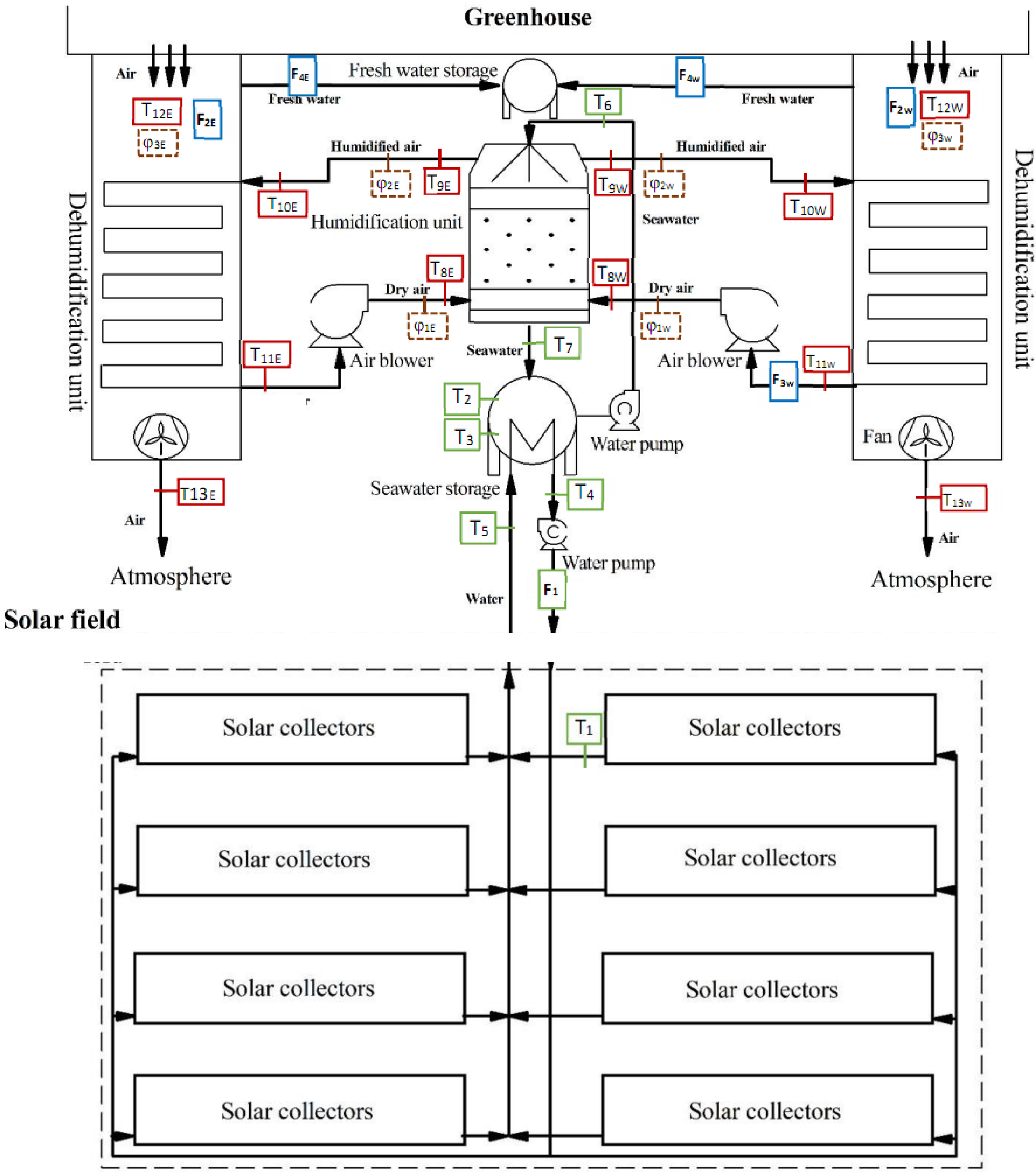


Figure 8. Position of measuring sensors.

The absolute humidity of moist air (ω) is predicted by Equation (1) as follows [25]:

$$\omega = 2.19 \times 10^{-6}T^3 - 1.85 \times 10^{-4}T^2 + 7.06 \times 10^{-3}T - 0.077 \quad (1)$$

where T is the temperature of moist air (°C). The evaporation rate of seawater ($\dot{m}_{evaporation}$) can be calculated based on Equation (2).

$$\dot{m}_{evaporation} = \dot{m}_G(\omega_{out} - \omega_{in}) \quad (2)$$

in which, $\dot{m}_G\left(\frac{kg}{s}\right)$ is the mass flow rate of air and ω_{out} and $\omega_{in}(kg_{vapour}/kg_{dry\ air})$ are the absolute humidity of air flow at the outlet and inlet section of the humidifier tower, respectively. The energy consumption (Q) of the HD unit can be expressed as Equation (3):

$$Q = \dot{m}_{seawater} C_p (T_{\omega_{in}} - T_{\omega_{out}}) \quad (3)$$

in which, $\dot{m}_{seawater}$ is the mass flow rate of circulating seawater in the system (kg/s) and $T_{\omega_{in}}$ and $T_{\omega_{out}}$ are the hot seawater temperature at the inlet and outlet section of the humidifier tower (°C), respectively. The gain output ratio (GOR) is expressed as follows:

$$GOR = \frac{\dot{m}_{distillate} \times h_{fg}}{Q} \quad (4)$$

where, h_{fg} and $\dot{m}_{distillate}$ are the latent heat of seawater and water production rate (kJ/kg and kg/s), respectively. Q is the energy consumed during this process (kW).

5. Results and Discussion

The air temperature profile in different parts of the seawater greenhouse equipped with the solar HD desalination unit is presented in Figure 9. In this figure, the seawater flow rate is 120 L/min, and the greenhouse air temperature is considered constant at around 26 °C. The greenhouse's fans can ventilate air at a high flow rate to supply the required cooling energy in condensers. When the seawater temperature increases, the temperature difference of greenhouse air at the inlet and outlet of the condensers varies between 1.5 and 5.4 °C. The moist air coming out of the condenser's tubes does not experience any significant temperature change before entering the humidifier tower. As the temperature of the seawater entering the humidifier increases from 41.7 to 61.7 °C, the temperature of the air leaving the humidifier tower increases from 40.6 to 59.5 °C. The air temperature flowing between the humidifier tower and the condensers decreases by around 7.7% because it passes through the intermediate connecting pipes. With the proper design of the humidification tower, the temperature difference between the air and water on top of the tower reached less than 5 °C.

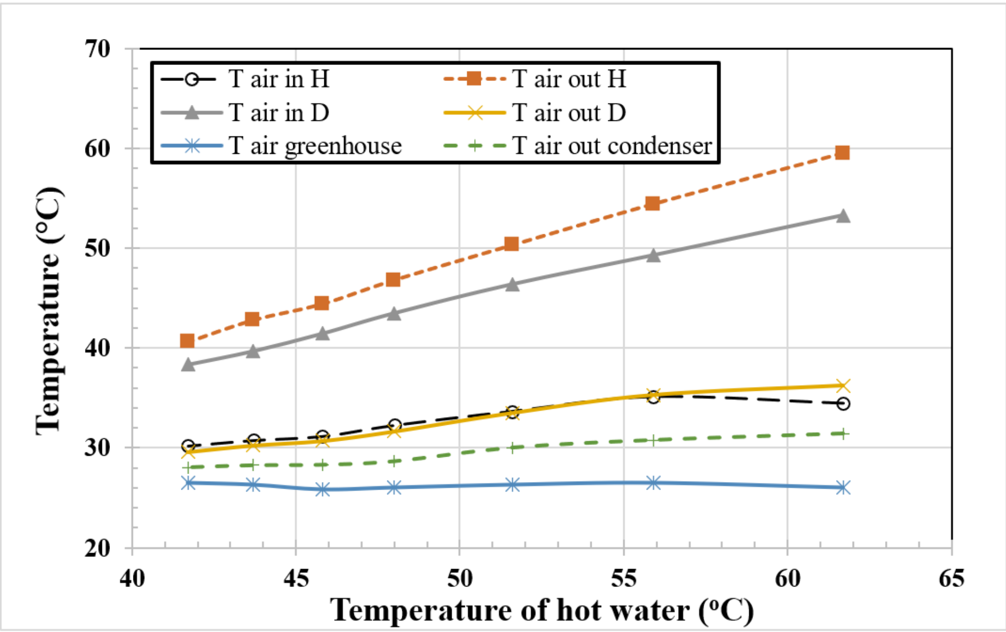


Figure 9. Air temperature profile in different parts of the system versus hot seawater temperature.

Several experiments have been conducted to evaluate the effect of circulating seawater flow rate and greenhouse air temperature in September.

5.1. Effect of Greenhouse Air Temperature

By adjusting the flow rate of circulating seawater to 120 L/min, the effect of the air temperature inside the greenhouse that flows over the condensers tubes is studied at two levels of 30 and 26 °C, as illustrated in Figure 10. As seen in this figure, the increment in the hot seawater temperature has a direct and considerable effect on the amount of freshwater production. In the initial moments, when the seawater temperature is at its maximum and the air temperature in the greenhouse is 30 °C, the instantaneous production rate reaches 1.3 L/min. Gradually, as the seawater's temperature entering the humidification tower decreases, the production rate decreases and reaches 0.55 L/min at the end of the experiment. As is clear from the Figure, the rate of instantaneous production when the greenhouse air temperature is 26 °C is higher compared to the rate of production at 30 °C. By reducing the greenhouse air temperature to 26 °C and increasing the seawater temperature from 41.7 to 61.7 °C, the instantaneous production rate reaches from 0.46 to 1.33 L/min. In general, as the air inside the greenhouse or the air passing through the condenser gets cooler, the amount of water vapor condensation from the moist air flowing in the inner tubes of the condenser is enhanced, and therefore more fresh water is generated.

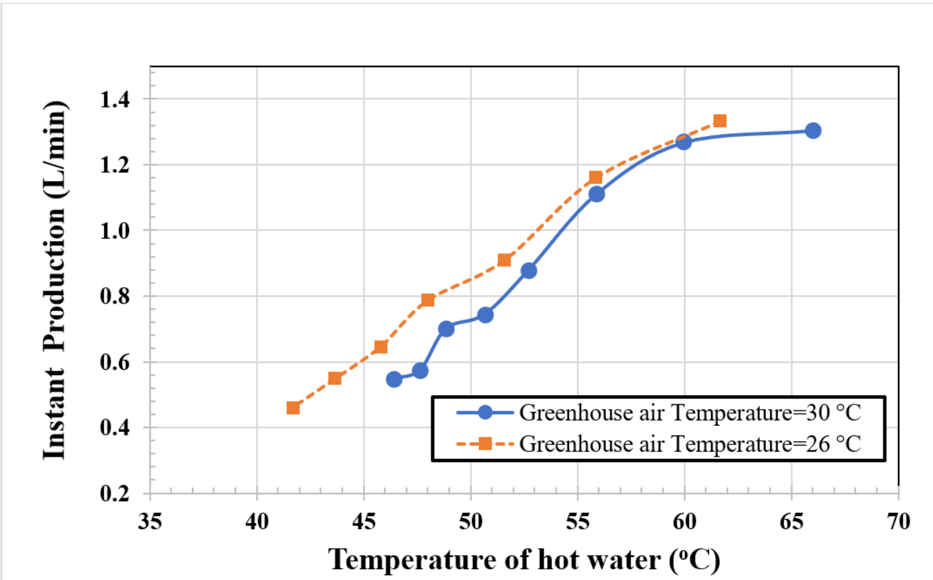


Figure 10. Instantaneous production of fresh water versus the temperature of the seawater at two different levels of the greenhouse air temperature.

The amount of energy that the seawater loses in the humidifier tower (namely, the required thermal power of the HD desalination unit versus hot seawater temperature in two different levels of greenhouse air temperature) is depicted in Figure 11. At the higher level of the greenhouse air temperature, more energy is required than at the lower level. When the greenhouse air temperature is 30 °C, the maximum required power is equal to 75.6 kW at 66 °C of seawater. The required power reduces to about 37.8 kW when the seawater temperature is 46.4 °C. At the lower level of greenhouse temperature (26 °C), by decreasing the seawater temperature from 61.7 °C to 43.7 °C, the power consumption drops from 84.8 to 36.1 kW.

The lower greenhouse air temperature increases the heat transfer rate and the humid air (inside tubes) coming out of the condenser becomes colder. As a result, the air will enter the humidifier with a lower temperature and the water will leave the humidifier tower with a lower temperature, which results in more energy consumption. In short, reducing the inlet temperature of the condenser increases water production and consumes more energy. Therefore, its effect on the intensity of energy consumption should also be investigated.

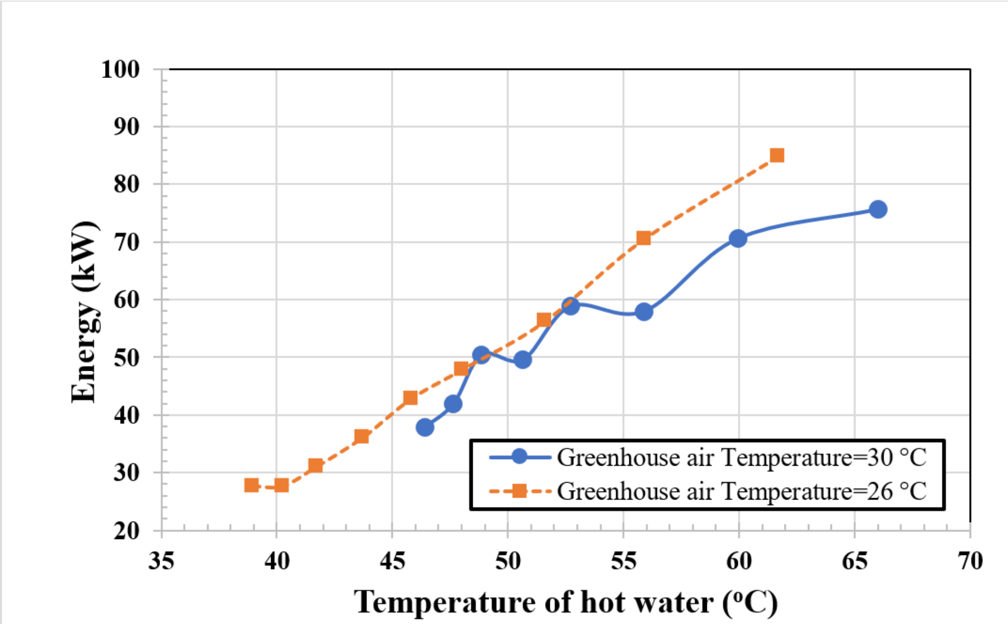


Figure 11. Energy consumption at two levels of greenhouse air temperature.

The energy intensity is defined as the energy consumption (kJ) per volume production of fresh water (L). The energy intensity at two levels of greenhouse air temperature versus hot seawater temperature is shown in Figure 12. When the greenhouse air temperature is 30 °C, the energy intensity varies between 3998 and 4382 kJ/L, while for a greenhouse air temperature of 26 °C, this variation is between 3696 and 3894 kJ/L. With a 4 °C decrement in the greenhouse air temperature, the average value of energy intensity decreases by around 8.3%. Despite the energy consumption increasing at a lower greenhouse temperature, the rate of water production is higher, leading to a decrease in the energy intensity of the system.

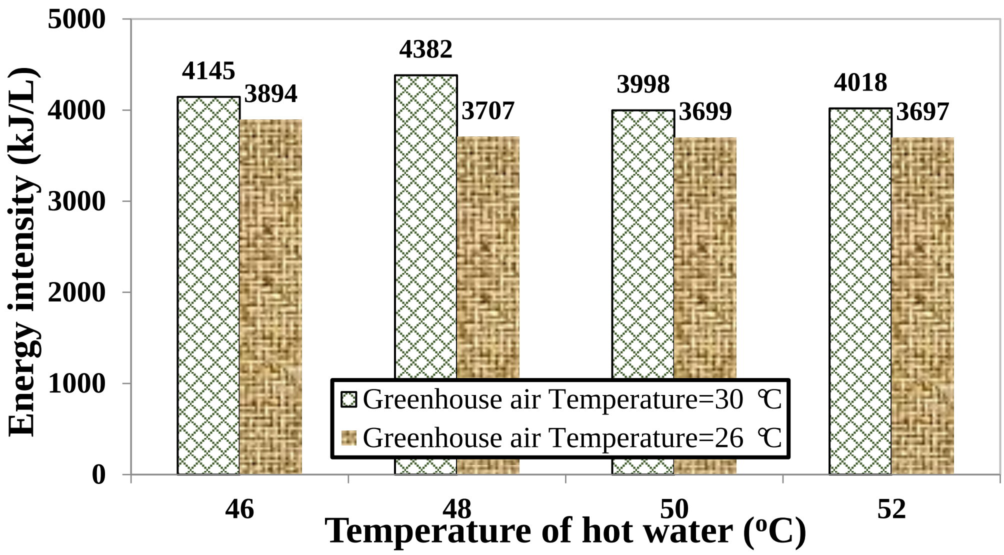


Figure 12. Energy intensity versus seawater and greenhouse air temperature.

5.2. Effect of Hot Seawater Circulation Rate

To evaluate the effect of circulating seawater flow rate on the performance of the solar HD desalination unit, experiments were conducted at two flow rate levels of 120 and 60 L/min. In both experiments, the greenhouse air temperature is constant and equals 30 °C. As shown in Figure 13, increasing the seawater flow rate improves the instantaneous production rate of fresh water. For example, when the seawater temperature is adjusted around 60 °C and the seawater flow rate increases from 60 to 120 L/min, freshwater production reaches from 0.94 to 1.27 L/min, which marks a 25.8% improvement in the production rate of fresh water. When the seawater flow rate is adjusted to 60 L/min, with the seawater temperature increasing from 45.0 to 63.3 °C, the production rate rises from 0.35 to 1.03 L/min. By increasing the water flow rate, the heat and mass transfer coefficients on the packing intensify, which leads to more evaporation. Therefore, the water production will be greater with a higher circulation rate. This increment equates to about 25% with the doubling of water flow. Therefore, we should consider the increase in energy consumption due to higher water pumping.

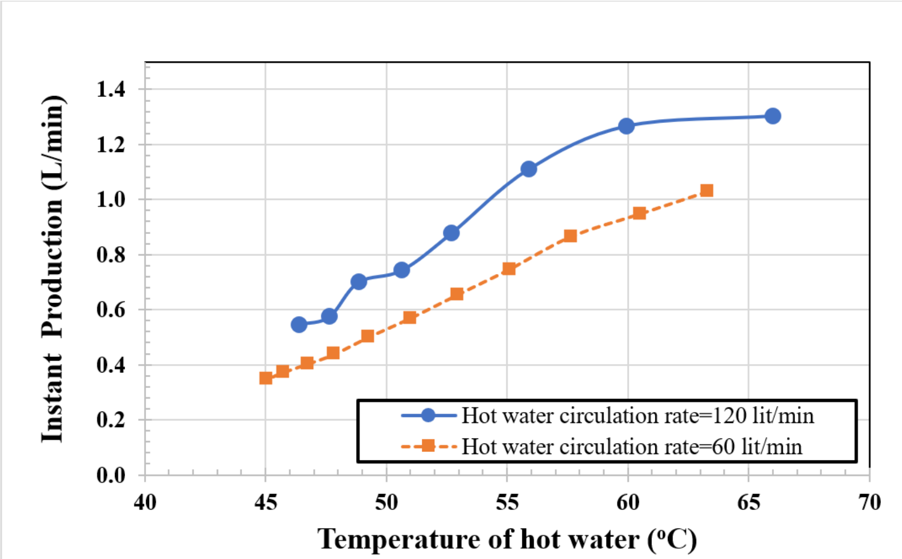


Figure 13. Instantaneous production of fresh water versus the temperature of the seawater at two different levels of hot seawater circulation rate.

The system power consumption for two levels of seawater flow rate is illustrated in Figure 14. When the flow rate of circulating seawater is 120 L/min, with a 42% increment of the hot seawater temperature (from 46.4 to 66 °C), the power consumption is doubled. For the lower level of seawater flow rate, with the increase in seawater temperature from 46.7 to 63.3 °C, the energy consumption increases from 27.3 to 56.7 kW. As mentioned previously, increasing the circulation rate increases the rate of evaporation, and therefore, the energy consumption of the system has also increased. So, for the final evaluation of the effect of water flow rate, energy intensity should be considered.

The energy intensity at two levels of the circulating seawater flow rate versus the temperature of the hot seawater entering the humidification tower is shown in Figure 15. As the temperature of seawater increases, the intensity of energy consumption decreases. The minimum value of energy intensity is around 3200 kJ/L, observed at the temperature of 60.5 °C and a flow rate of 60 L/min of seawater. It can also be seen that the energy intensity increases at a higher water flow rate. This shows that the rate of increase in energy consumption is higher than the rate of increase in water production and therefore, from the point of view of energy consumption, increasing the flow rate is not suitable.

The optimal temperature of greenhouses is around 25 °C. As depicted in Figure 16, the GOR of the system is around 0.6 at the optimal operational temperature of the greenhouse. As the heat taken from moist air is fed into the environment in the condensers, the efficiency of this method is lower than most HD desalination systems with heat recovery.

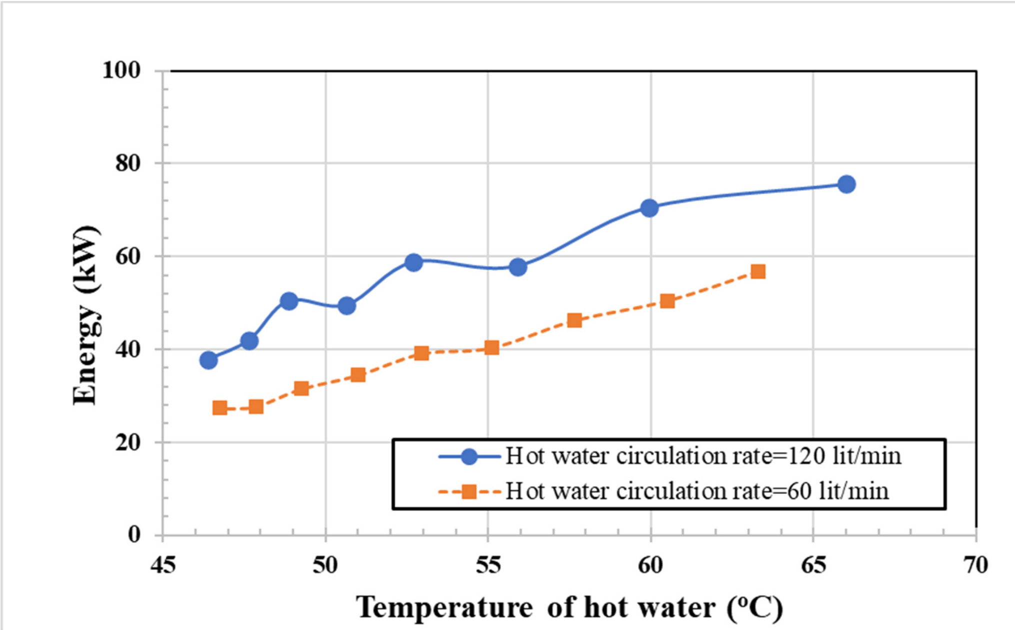


Figure 14. Energy consumption of system versus hot seawater temperature at two levels of seawater flow rate.

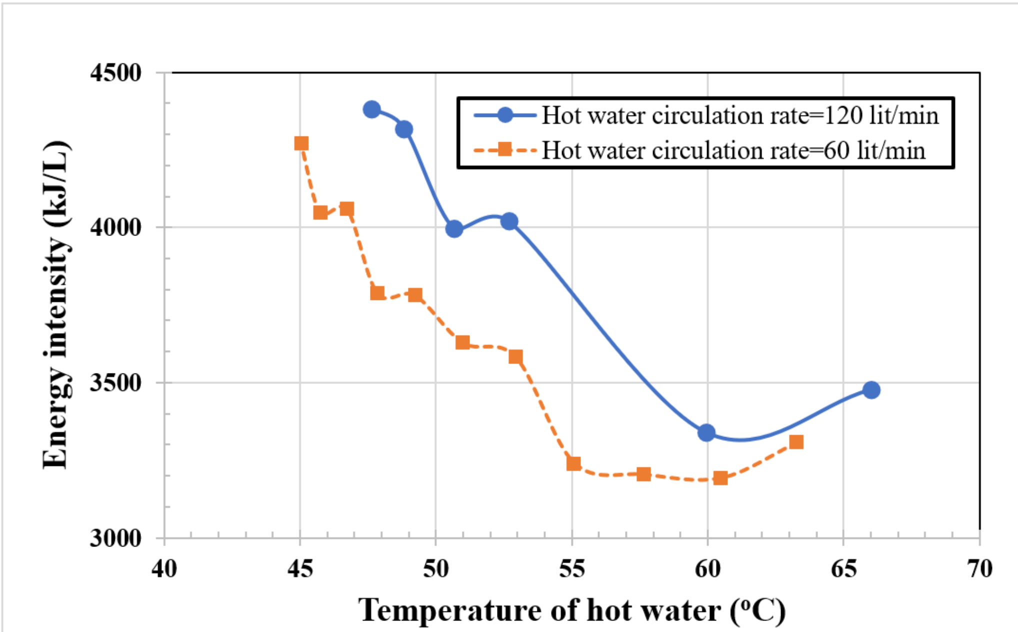


Figure 15. Energy intensity versus hot seawater temperature at two levels of seawater flow rate.

As mentioned in the introduction, the application of greenhouse cold air to produce fresh water has been investigated in limited research studies, mostly conducted on a laboratory scale. However, in this research, a real-scale HD desalination system has been built for a seawater greenhouse, and it is not possible to accurately compare the results of other research with the current study. Figure 17 is presented to check the ability of the proposed system to produce water with theoretical values. In this figure, the evaporation rate in the humidifier that can be calculated from Equation (2) is compared with actual freshwater production. Around 11.8% difference is observed between the expected and the actual production of fresh water, which is due to the possibility of water and air leakage in the system.

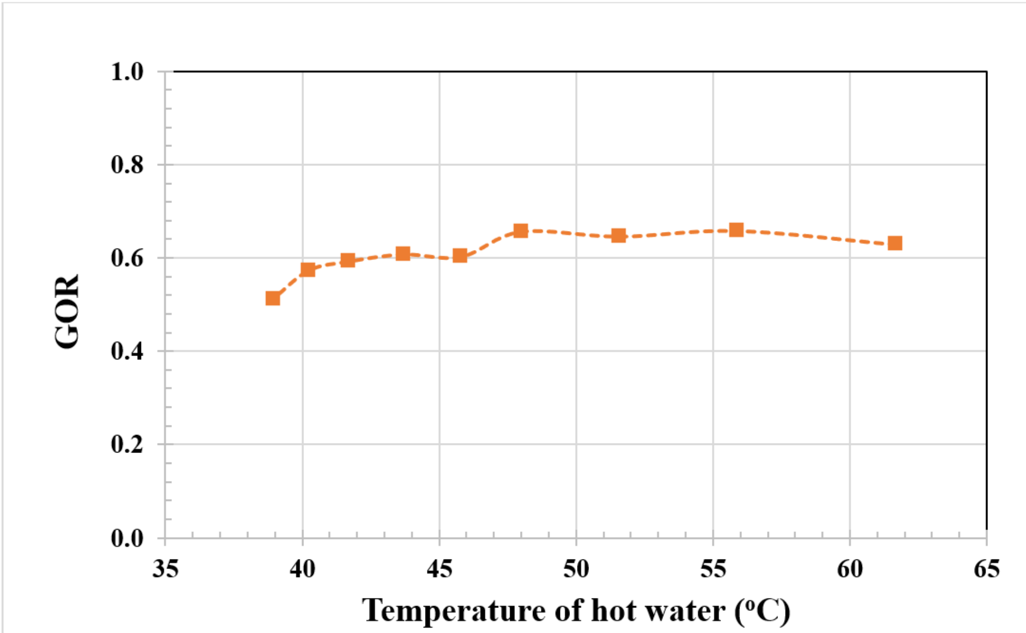


Figure 16. GOR of the solar HD desalination unit versus hot seawater temperature.

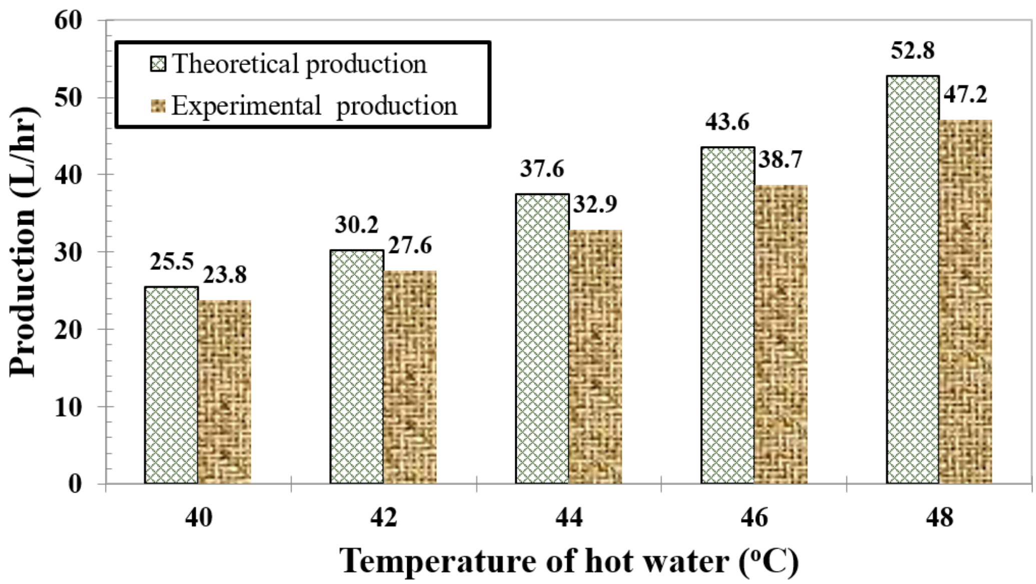


Figure 17. Comparison between expected and experimental freshwater production.

The advantage of this system is its performance at low temperatures. In the proposed HD desalination system, the temperature difference between the highest point of the cycle (the hot seawater entering the humidifier) and the lowest temperature (the air entering the condenser from the greenhouse) is varied between 15 and 35 °C. As described in the results of these tests, the system is able to produce between 20 and 80 L/h fresh water when the seawater temperature varies between 40 and 65 °C. If the desalination unit works eight hours per day and 50 L/h is considered as the average of freshwater production, it is possible to reach a production rate of 400 L/day. According to the dimensions of the studied greenhouse (400 m^2), the production of one liter per day per square meter of the greenhouse area can be achieved.

6. Conclusions

This study presents the practical results of a solar HD desalination unit for a seawater greenhouse with a new air-to-air condenser system. A 400 m^2 greenhouse was built on the coast of MAKRAN in the southeast of Iran. The HD desalination unit consists of a humidification tower and two air-to-air condensers. A solar farm with 96 m^2 of flat plate collector was designed and installed to supply the required thermal energy to the system. Several experiments were conducted to check the effect of temperature and flow rate of hot seawater, and the temperature of the greenhouse's air entering from the greenhouse into the condensers. We found that the most crucial parameter in the performance of the system is the temperature of the seawater entering the humidification. This temperature varied between 40 and 65 °C in different tests. By reducing the greenhouse air temperature from 30 to 26 °C, freshwater production can be increased by up to 16.3%. In addition, doubling the flow rate of hot seawater leads to a rise of about 26% and more than 40% in freshwater production and energy consumption, which increases the energy intensity of the system.

The energy intensity of the HD desalination unit is more than 3200 kJ/kg and the average GOR was recorded to be around 0.6. The lower GOR in this system is due to the lack of heat recovery in the dehumidification process (condenser). It is worth mentioning here that the temperature difference between the highest point of the cycle (the hot seawater entering the humidifier) and the lowest temperature (the air entering the condenser from the greenhouse) is varied between 15 and 35 °C. In this low-temperature difference, the system was able to produce between 20 and 80 L/hr. This is a significant feature of the system, which able to produce water at low temperatures and very low-temperature differences. The sedimentation and corrosion problems in the conventional condensers used in seawater greenhouses have also been resolved by the application of the proposed system. Based on the obtained results, this solar HD water desalination plant has a production rate of about 1 L/day per square meter of the greenhouse surface area at a working temperature of 60 °C, which is significant when compared to other seawater greenhouses.

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