Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2020.26550

208 (2020) 1–8
December

Saltwater desalination by direct solar energy in Madinah, Saudi Arabia

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Received 22 March 2020; Accepted 7 September 2020

A B S T R A C T

The process of desalination is considered to be an expensive yet powerful solution for providing fresh water. This work aimed to introduce and examine a new and low cost process for seawater desalination using the direct heating power of the sun via a glass dome. The main disadvantage of this process is the potential for low productivity under sub-optimal winter weather conditions. Thus, this research aimed to study all the affected parameters, paying particular attention to the feasibility of this process and recommended design features under the sub-optimal winter weather conditions of Saudi Arabia. An optimal design was subsequently constructed for a practical treatment unit yielding adequate amounts of freshwater. Numerous trials were adopted to design and implement the desalination unit. Results showed that a high productivity rate for desalination unit in Madinah weather was seen between the hours of 11:30 a.m. and 3:30 p.m. and the peak productivity was between 2:30 p.m. and 3:30 p.m. Results also showed that using improvement facilities such as the heating collector and lenses increased the unit productivity and efficiency. The final design of the desalination unit suggests adopting a hybrid system in winter conditions including direct solar heating in addition to other technologies such as concentrated solar thermal and photovoltaic technology to compensate for the low heating efficiency of the sun.

Keywords: Freshwater; Solar desalination evaporation process; Glass dome

1. Introduction

The lack of availability of fresh and clean drinking water is an alarming problem in many parts of the world. Countries with arid climates, such as the Kingdom of Saudi Arabia (KSA), are especially prone to severe problems of fresh water availability. KSA has a shortage of fresh water supply further exacerbated by increasing demand due to ongoing urbanization. Currently, the only available and limited source of fresh water in KSA is groundwater. Therefore, they rely mainly on the seawater desalination for fresh water, which is usually a very expensive process in terms of money and finite energy resources. Currently, more than 15,000 desalination plants exist everywhere in coastal regions over the world. Combined, they deliver around 14 million m^3 of fresh water per day [1]. KSA found some of the largest desalination plants in the world such as Shoaiba and Al-Jubail plants, producing over 880 and 800 million L/d, respectively [2]. This high production is needed due to the high demand for household applications in KSA, which increases annually. Recently, freshwater consumption per day in KSA has been estimated at more than 8 million m^3 [3].

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There are three commonly used methods for seawater desalination: thermal, pressure, and electrical methods [4]. These desalination processes consume a large amount of energy in the form of heat or electricity generated from nonrenewable sources such as oil or natural gas. The process of solar desalination has emerged as a promising renewable energy powered technology for yielding fresh water [5]. Recent developments have demonstrated that solar-powered desalination processes are better than the other alternatives such as reverse osmosis and freezing processes for providing fresh water, especially in remote rural areas [6]. This is due to the fact that solar energy is sustainable and environmentally friendly. The main challenge of this process is the potential for low productivity. Thus, the main obstacle for this process to become more widely used is to ensure that we can increase the heating impact of the sun thereby increasing the evaporation process and consequently the freshwater production. Many techniques have been adopted to accelerate and increase the efficiency of this process. These include using additional effects such as multistage evacuated stills, adding absorption materials, and changing the design [7].

There are two main types of solar powered desalination: direct and indirect systems. In direct systems, the heating and desalination processes take place naturally inside one kit. The simplest form of direct solar-powered desalination is a solar still distillation, which represents a natural hydrologic cycle on a smaller scale. The basic design of a solar still is similar to that of a greenhouse. In this desalination process, greenhouse application is adopted as saltwater goes in the center reservoir. As the sun heats it up, water begins to evaporate. Vapors then settle on the glass dome in the closing system, which in turn transform into drops of water, which slowly runs down to water collectors located underneath the sides of the dome [8,9]. This process normally produces about 3–4 L/d for each one square meter of ground fresh water [7].

In indirect systems, the solar desalination plant is split into two divisions: a solar collector and a desalination unit. The solar collector can be a flat plate, evacuated tube, or solar concentrator. In these systems, the desalination unit can also be hybridized with other systems such as using solar photovoltaic (PV) devices to generate electricity. Solar PV systems directly convert sunlight into electricity by using solar cells made of semiconductor materials to supply energy to a desalination plant. Besides the PV modules, other electrical equipments are needed for the electricity supply. These include a charge inverter, controller, and batteries [10]. Solar desalination by humidification and dehumidification process is a promising technique for generating fresh water. In this desalination process, the evaporation of water and the condensation of steam occur from humid air. The natural convection between the condenser and the evaporator is driven by the humid circuit [11]. Recently, a new seawater desalination process based on interfacial solar heating was adopted. This solar process can produce clean water and electricity simultaneously, through storing and recycling the steam enthalpy resulting from the interfacial solar steam process [12].

In addition, the most important factor that influences level of production of the solar still is the amount of solar radiation on the glass cover, called irradiance. Not all the solar energy that contacts the glass will be harnessed for evaporation of the water in the basin because it gets reflected and absorbed by anything it passes through. The solar irradiance is the main parameter influencing the heating energy of the sun. Solar radiation affects the surface of the earth in two ways, either by direct solar irradiation or by diffuse solar irradiation. The total radiation received from the sun is the sum of both types of radiations. Direct radiation is effected by the orientation of the receiving surface, while diffuse radiation is not affected at all. Depending on these two types, total solar radiation, or heating energy of sun will exhibit variations on both daily and yearly bases. The atmospheric conditions of any given area including factors such as dust storms or clouds also affect the heating energy of the sun at the ground level [13]. Thus, it is important to study the sun radiations in the area intended for using solar energy in desalination.

Therefore, this research work aimed to study experimentally and theoretically all effected parameters with particular emphasis on sub-optimal winter conditions characterized by low temperatures, in Madinah, KSA. This is done in order to determine the feasibility of applying this process and to determine the best design for a practical treatment unit yielding adequate amounts of fresh water at a low cost. In this study, many parameters were investigated to finalize the unit design and increase solar heating such as finding the best glass side slop; adding lenses to concentrate solar heating; using heat collector before feeding saltwater to warm it; and using electrical heater underneath saltwater basin to compensate for the low temperature in the winter.

2. Methods and materials

2.1. Study area and data collection

This research work examined the feasibility of applying direct solar energy for desalination of saltwater in the Kingdom of Saudi Arabia (KSA). The study focused on the local conditions of Madinah region, the western part of the KSA. Data about sun radiations in Madinah region were collected. Monthly variations of direct and diffuse radiations for this region from 2015 to 2018 were collected from King Abdullah City for Atomic and Renewable Energy (K.A. CARE, Riyadh) [14]. The data were analyzed to examine the feasibility of using solar energy in Madinah for the desalination process.

2.2. Prototyping and experiments details

A prototype was designed for a small-scale desalination unit working by the power of direct solar energy. The main body of the prototype comprises of two tanks: one for feeding saltwater into the unit, and one for collecting fresh water. It also comprises of a steel basin for a saltwater with a net area of 46 cm × 46 cm (2,116 cm^2) and a height of 10 cm, which is coated by black paint and enclosed by a glass pyramid. The concentrated seawater brine is drained from a hole in the bottom of the seawater basin and collected in another open basin and then dried by sun. Fig. 1 presents a schematic for the designed desalination unit. Many parameters were investigated to finalize the unit design and increase solar heating such as finding the best glass side slop; adding

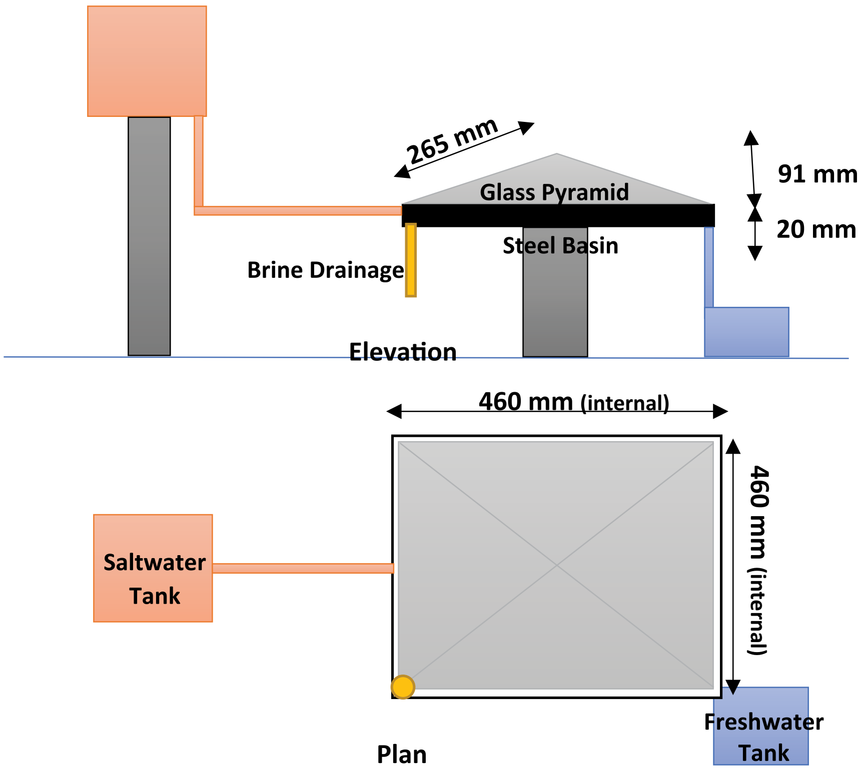

Fig. 1. Schematic for a desalination unit working by direct solar energy.

lenses to concentrate solar heating; using heat collector before feeding saltwater to warm it; and using electrical heater underneath saltwater basin to compensate for the low temperatures in the winter months. Details of these factors and their results will be discussed in the following sections. Each parameter was examined in a separate experiment to evaluate its individual impact and it was repeated three separate times in order to average the results and reduce the uncertainty in the obtained readings. Each experiment ran for around 12 h during the daytime. The atmosphere temperature and freshwater quantity were recorded every hour. The experiments were carried out during the harshest weather conditions of Madinah in the months of December and January, in which the temperatures reach their lowest levels. Typical temperatures are below 20°C with a wind speed of approximately 15 km/h.

2.3. Fundamental equations for solar energy

In this study, many theoretical models were adopted to examine the obtained solar heating and to assess the performance of a solar desalinating system.

The heat released in the lens due to the thermal energy exploited from the solar irradiation, can be calculated as follows:

$$\text{Heat released in lens } = (\text{SI})(\text{AC}) \tag{1}$$

where SI is solar irradiation on the lens, which equals DNI, that is, the direct normal irradiance, times by lens area, AC is absorption coefficient.

The direct normal irradiance in Madinah is calculated to have an average of 5.83 kW/m²/d [15]. A vital parameter for the precision of the results is the data accuracy regarding sun irradiation. The solar irradiation is measured on the ground by using a pyrheliometer device. However, this equipment is costly [16] and might not always be available. As solar thermal technologies utilize DNI, it could be calculated through the values of global horizontal irradiance (GHI) and diffuse horizontal irradiance (DHI) as follows:

$$\text{GHI} = \text{DNI} \cos\theta + \text{DHI} \tag{2}$$

where θ is the zenith angle [17].

The water desalination process is a costly and energy-intensive process. The minimum energy required to separate the water from seawater through the difference in Gibbs energy can be determined as follows [18]:

$$W_{\min} = \frac{m_{\text{br}} g_{\text{br}} + m_w g_w + m_{\text{sw}} g_{\text{sw}}}{m_w} \tag{3}$$

where $W_{\min}$ is the minimum required energy, m is the mass, br is the rejected brine, w is the produced fresh water, sw is the feed seawater, g is the specific Gibbs energy. In thermodynamics, the Gibbs free energy reflects the maximum reversible work that can be performed by a system at a given temperature and pressure. It is determined as follows [18]:

$$g = h - \text{TS} \tag{4}$$

where h is the enthalpy, T is temperature in K, and S is the entropy.

To evaluate the performance of a solar thermal desalinating system, the specific water productivity (SWP) is used [18]. It determines the water produced per solar radiation area per time as follows:

$$\text{SWP} = \frac{E}{L}\alpha\eta_t\text{GOR} \quad (5)$$

where E is the solar irradiance (kWm^{-2}), L is the latent heat of evaporation (kWh L^{-1}), α is the solar absorptivity of the system (dimensionless), η_t is the thermal efficiency (dimensionless), and GOR is gain output ratio. It is the kilogram of distilled water produced per kilogram of vapor produced. GOR is an important metric in water desalination, which measures how much thermal energy is consumed in a desalination process [19,20]. The thermal energy required to generate one kilogram of vapor is constant, Thus, GOR is considered as a measure of energy efficiency of thermal distillation. For a well-designed thermal distillation system, the GOR should be notably greater than one.

3. Results and discussion

3.1. Results of data collection about sun radiation impacts in Madinah

The process of solar irradiation in terms of utilization as energy source can be broken down into three main components: direct normal irradiance (DNI), diffused horizontal irradiance (DHI), and global horizontal irradiance (GHI), which is the summation of the first two types. While solar photovoltaic technology (PV) utilizes different components of solar irradiance to generate electricity through sun light, solar thermal technologies can only benefit from DNI using the perpendicular solar irradiation striking the receiving parts of the system. This limitation emphasizes the importance of studying the weather characteristics of the intended location to apply solar thermal technologies. The analysis outputs can only be as accurate as the weather data. High level of DNI is required to utilize thermal energy from simple direct heating applications to desalination process, and all the way up in heat requirement to electricity generation [21]. Literature indicates that the DNI level considered sufficient for electricity generation is around 1,800 kWh/m^2 annually, which reflects a daily average of approximately 5 kWh/m^2 [22,23]. Fig. 2 shows satellite demonstration of DNI in a color-coded map of KSA. It is demonstrated in Fig. 2 that Madinah region falls into a DNI range that is of feasible level for electricity generation and desalination by direct solar heating. This abundance of DNI was reflected in the strategic energy plans of KSA including a large share that is intended to be harnessed through concentrated solar thermal (CST) plants in Madinah and other potential regions.

In order to obtain more accurate data of the location of consideration for the solar thermal desalination prototype developed in this research, data were obtained from the Saudi Renewable Resource Atlas leveraging data collected

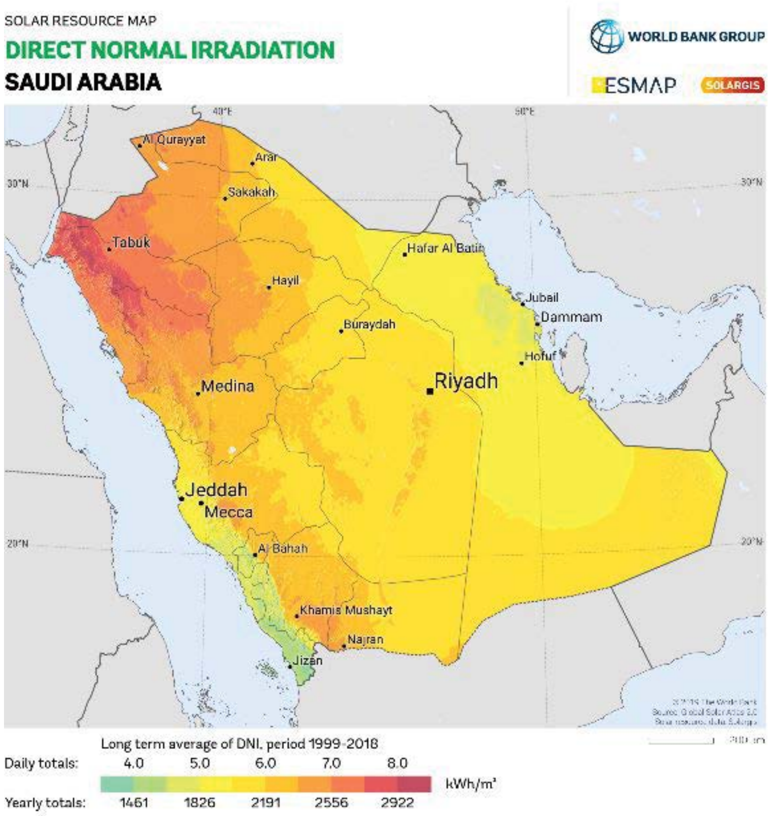

Fig. 2. Direct normal irradiance (DNI) map in KSA [24].

under the Renewable Resource Monitoring and Mapping program (RRMM) [25]. Fig. 3 shows long-term data of DNI and its correlation to air temperature in Madinah. The figure illustrates the positive correlation of air temperature and DNI level over the course of 3 y with a monthly reading with 0.5°C degree uncertainty of air temperature. The average DNI is above 5 kWh/m^2 threshold sufficient for electricity generation, and accordingly, it is suitable also for the desalination process, as was reported elsewhere [26]. The maximum monthly DNI reaches over 10 kWh/m^2.

3.2. Results of prototype experiments

3.2.1. Control experiment

In this experiment, the test ran only by using greenhouse application, that is, only the impact of direct solar heating without adding any improvement facilities. The prototype illustrated in Fig. 1, comprised of a basin sheltered by a glass pyramid and two tanks for feeding saltwater and collecting fresh water. Three levels of saltwater were examined to determine the best amount of saltwater for the evaporation process. The prototype basin was filled with three different levels of saltwater: 1, 2, and 3 cm height making 2.2, 4.4, and 6.6 L of saltwater, respectively. Results showed that the lowest level of saltwater is the best among other cases in the evaporation process and increased the yielding of the fresh water. The total water yielded by the end of the day were 320, 306, 298 mL for 1, 2, and 3 cm height, respectively. Fig. 4 presents the results of the case of 1 cm height of saltwater for each hour. Results showed that the high productivity rate was between 11:30 a.m. and 3:30 p.m. and the peak productivity was between 2:30 p.m. and 3:30 p.m.

3.2.2. Impacts of using heating collectors

In this section, a heating collector was added to the prototype before the feeding pipe of the saltwater, as shown in Fig. 5. The collector consisted of a set of horizontal pipes coated by black paint, which can store the same quantity of saltwater needed inside the prototype basin, that is, 2,200 mL or 1 cm height of saltwater. The heating collector was adopted to warm the saltwater before entering the basin and to aid the evaporation area in order to accelerate the process. Results showed an increase from 320 mL of fresh water collected in the control experiment to 349 mL collected using the heating collector, representing an increase of 9%.

3.2.3. Impacts of using lenses

In this section, four lenses were added above the glass pyramid to increase the concentration of sun heat as shown in Fig. 6. The lenses were chosen to give their focus points inside the basin of saltwater. The experiment was run two separate times: once without the heating collector and the other with the collector. Results revealed a significant improvement in freshwater yield when the heating collector was used with the lenses. The amount of fresh water yielded was 15% and 12% more than the control experiments when used with and without the heating collector, respectively.

3.2.4. Impacts of using hybrid system including direct/indirect sun heating

To compensate for the lowest temperatures of the winter and increase the desalination unit efficiency and feasibility, a suggestion of using an electrical heater underneath the saltwater basin was adopted. The heater was proposed in order to get electricity through a solar PV system; however, in this experiment, the heater was supplied from the public grid with a low consumption rate of 400 W/h. Results herein also revealed a significant increase in saltwater heating and the productivity of fresh water. The rate of freshwater production was increased by 47% (relative to control) in the case of using only the heater collector, and by 69% (relative to control) by using both the heating collector and lenses.

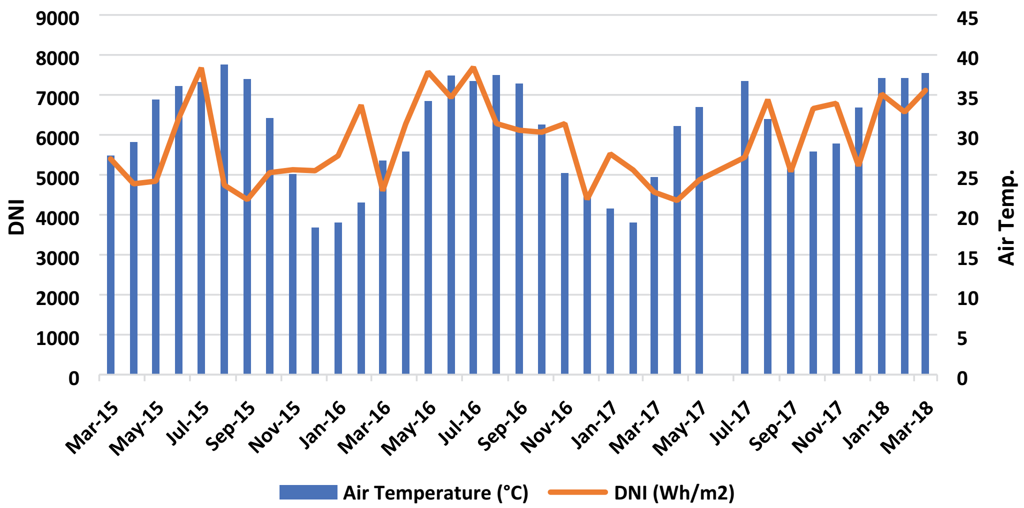

Fig. 3. DNI and air temperature in Madinah (2015–2018) [21].

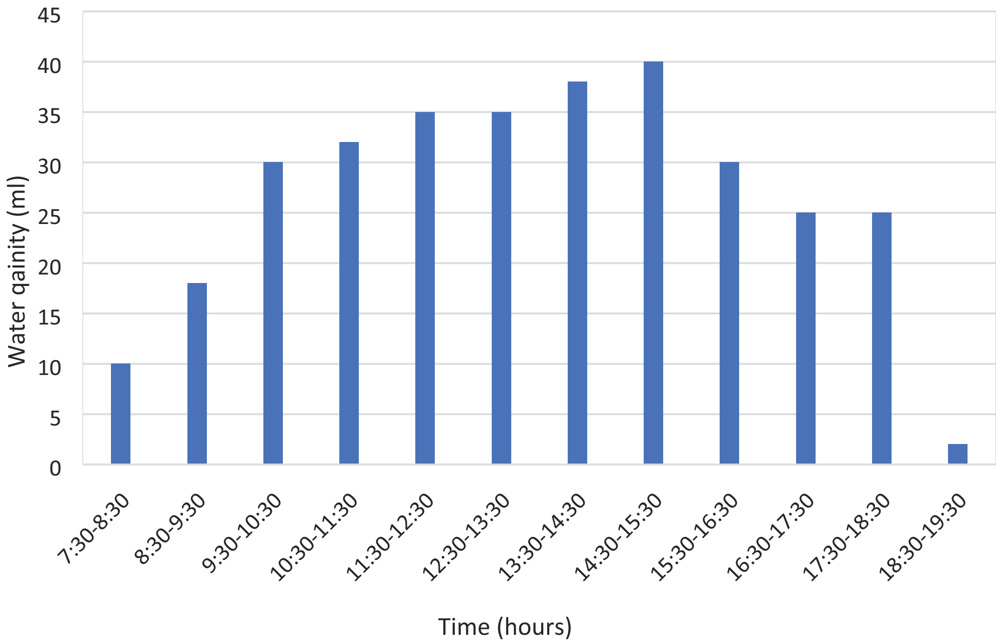

Fig. 4. Fresh water quantity generated by the control experiment (only the impact of direct solar heating).

Fig. 5. A picture for setting heating collector in the prototype.

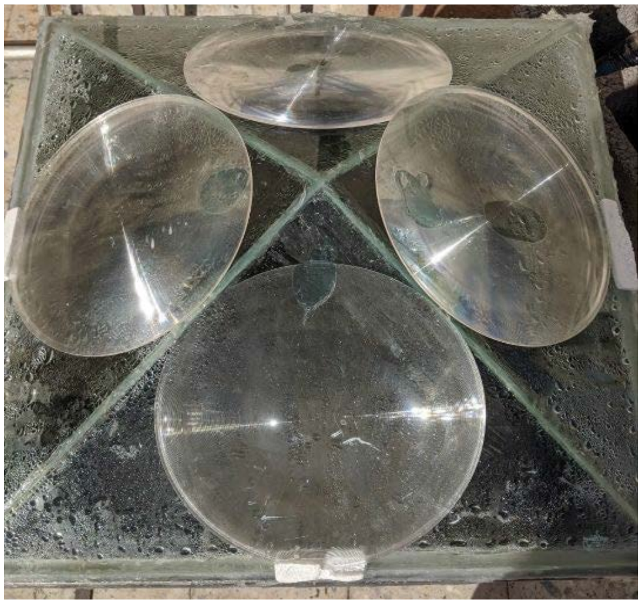

Fig. 6. A picture for setting four lenses above the pyramid glass of the prototype.

3.3. General discussion and unit final design

Fig. 7 presents a summary of the results of all studied parameters and added improvement facilities. As discussed previously, results showed that using these improvement facilities increased the unit productivity and efficiency. The quantity of yielded water from this unit reached 540 mL generated from unit surface area of 0.22 m^2, thus the water amount per square meter is expected to be around 2.45 L/d. This rate is very close to the average rate reported in the literature as 3 L/d [7]. Furthermore, it is worth mentioning that this water amount was collected in the wintertime, thus a significant increase in freshwater productivity is expected in other times especially during the summer season with the adopted facilities.

As discussed earlier in the section of data collection analysis, Madinah region is suitable for all solar energy applications including solar PV technology and solar thermal technologies. Therefore, using a hybrid system of direct and indirect solar energy for desalination would be more valuable and feasible. In this study, the final design of the

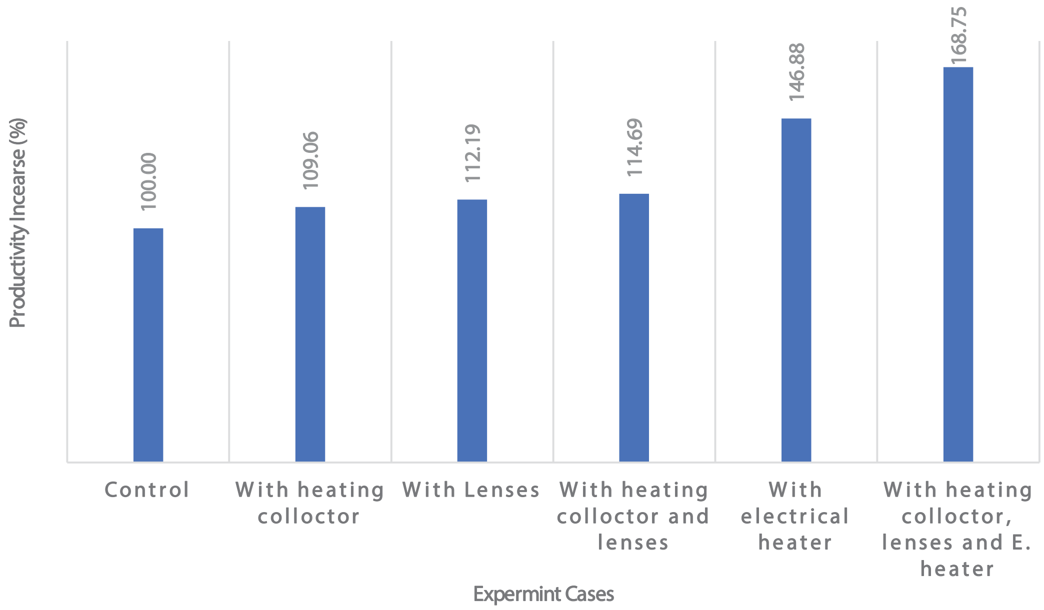

Fig. 7. Freshwater productivity increase for different adopted improvement facilities.

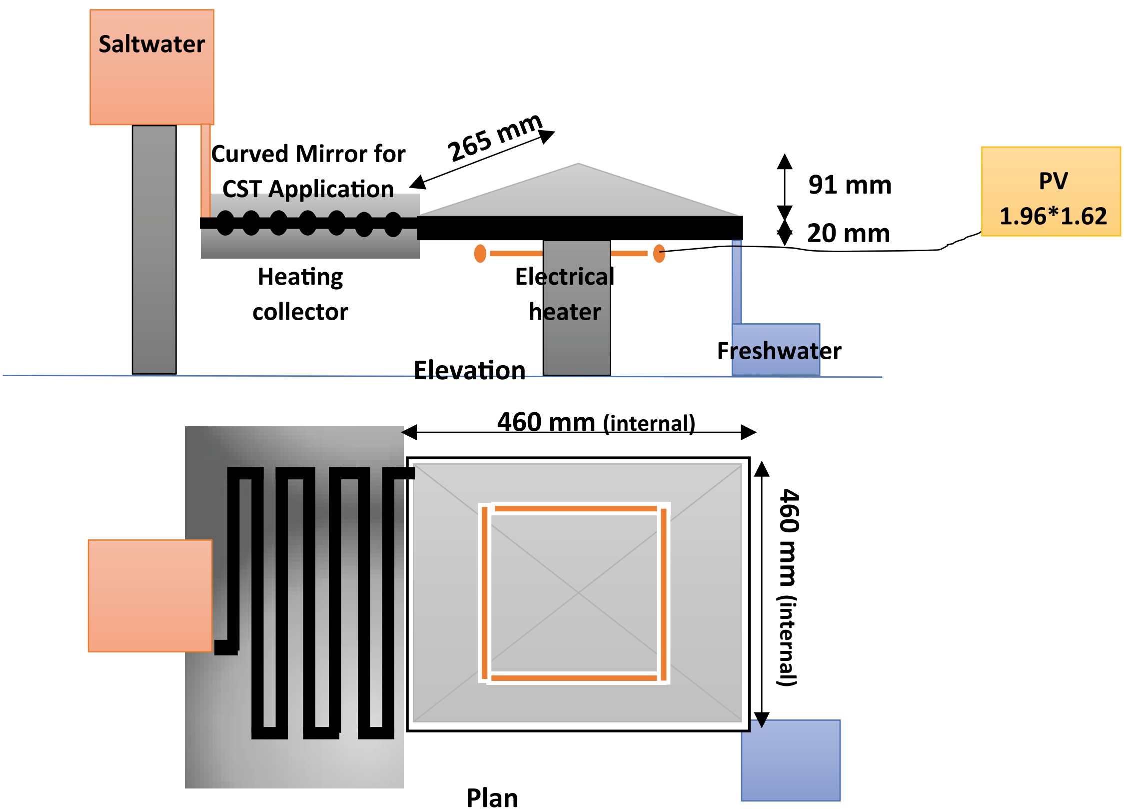

Fig. 8. Final design of the desalination unit with a hybrid system with both direct and indirect solar energy applications.

desalination unit suggests adopting direct solar heating in addition to CST and PV technologies as shown in Fig. 8. In other words, beside benefits from greenhouse application for direct sun heating energy, the unit includes applying CST application in format of using curved mirror around heating collector pipe system and generating electricity via using PV for supplying the electrical heater underneath the steel basin. The PV unit's area of 3.2 m^2 will be enough to supply electricity to the heater. The total cost of establishing such desalination unit is estimated at 3,000 SR (i.e., 800 USD) for each one square meter.

4. Conclusion

- The Madinah region, in comparison to many other regions in KSA, is a suitable region for all solar energy applications including solar Photovoltaic (PV) technology and solar thermal technologies.
- Results showed that the high productivity rate for desalination unit was between the hours of 11:30 a.m. and 3:30 p.m. and the peak productivity was between 2:30 and 3:30 p.m.
- Results also showed that using the improvement facilities such as the heating collector and lenses increased the unit productivity.
- The water amount yielded by the proposed system per square meter is expected to be around 2.45 L in winter. In the summer season, this amount is estimated to increase fourfold.
- The final design of the desalination unit suggests adopting a hybrid system including direct solar heating in addition to CST and PV technologies.
- The total cost of establishing such desalination unit is estimated at 3,000 SR (i.e., 800 USD) for each one square meter.

Acknowledgment

The authors would like to thank Mr. Mustafa Akad, Fars Dolli, Abdullah Alalway and Omer Bastawy, for their efforts in manufacturing the prototype adopted in this study. Authors also thank Ms. Alyssa Castracane for her help in editing the manuscript.

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