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Experimental Investigation of Solar Distillation System Integrated with Photoelectric Diffusion-Absorption Refrigerator (DAR)

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Abstract. The limited productivity of conventional solar distillation system is one of the most prominent obstacles that engage researchers to seek for solving using various technologies. Though many technologies suggested to enhance the rate of freshwater production, most of them are expensive and require special equipment for implementation. Therefore, the current work aims to increase solar distillery production and reduce the production cost using new technology. The current study is a hybrid system consisting of the conventional solar still CSS and photoelectric diffusion-absorption refrigerator (DAR), which consumes relatively low power energy 79 W. This is to increase the basin water temperature and the surface area of condensation which improving daytime production and continuity during the night. From the analysis of experimental results, it is observed that the daytime production of conventional solar still integrated with a diffusion-absorption refrigerator (CSSIDAR) model improved by 251% compared to a conventional solar still CSS model and improved by 470% during the nighttime. The estimated cost to produce 1 liter of freshwater from CSS and CSSIDAR found to be 0.051 $ and 0.046 $, respectively.

Keywords: Solar Distillation System, DAR, Photoelectric.

INTRODUCTION

The water scarcity is considered as the main problem in the world which worsen with time, due to the fluctuations in weather conditions all over the world. In civilized areas freshwater is available, but there is real suffering to get freshwater in rural and remote areas. Pollution rates of drinking water increased due to industrial development, getting drinking water using the solar distillation system is an acceptable, available and inexpensive method especially in remote and rural areas with abundant solar energy [1]. A solar water distillery is simply equipment that produces freshwater from saline or polluted water. It consumes free energy from the sun without fuel consumption, which leads to reduce global warming and greenhouse gas emissions problems [2]. The solar water distiller working principle is simple and like the mechanism of rain in nature. The solar radiation heats and evaporates basin water within solar still to separate dirt, salt and impurities and anything else, when water vapour temperature reduced, the latter returns to the liquid phase [3].

The limited production is considered the main problem of the conventional solar still, therefore, there are many attempts and studies to improve the production of solar distillers. Thermal energy storage materials have been used within basin solar still to store the thermal energy during sunrise hours and release during the shadow and evening hours to increase night production [4]. It is observed that the used storage materials have led to reduce freshwater

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productivity during daytime by 7.4% and increase the output during night time. The highest daily production found to be 7.54 kg / m^2 with storage materials, while productivity found to be 4.51 kg /m^2 without storage materials in the basin solar still. Enhancing the heat transfer from the basin liner to the saltwater by increasing the surface area of the basin has been suggested as another useful modification. Placing fins within single basin solar still to increase the surface area has been investigated. The authors found that the daily productivity increased by about 36.7% and 26.3% for square and circular finned solar still respectively [5]. Another study investigated the utilization of thermoelectric cooling duct integrated with solar still to cool the solar still cover. The authors investigated also the addition of copper oxide nanofluid in the modified solar still basin instead of saltwater. The results showed that the use of thermoelectric cooling duct with adding 0.08% friction volume of the Cu_2O nanoparticles in the modified solar still basine maximize the value of productivity enhancement by about 81%. The optimal cost of freshwater productivity per liter found to be 0.0218 \$/L/m^2 for modified solar still [6].

Cooling the solar still cover by passing water over the cover has been investigated also. The water flow rate, water film cooling thickness, water film cooling temperature, and wind speed have been studied to show their effect. The results concluded that the water film could improve freshwater productivity by about 8.2%, which depends on the water-cooling film. Enhancing the productivity of solar still by using a rotating drum or shaft within the solar still has been investigated also [7]. This was conducted by increasing the evaporation surface area by installing a rotating-hollow drum within solar still. The new improved distillate products were evaluated in terms of economic and operational probability. The presented new design results in a 200 to 300% increase in freshwater output [8]. Another study investigated enhancing distillery using a rotating-hollow cylinder inside solar still and performed an analytical study to evaluate performance. A theoretical analysis included governing equations, which have been resolved numerically and validated by experimental data. The hollow cylinder rotational speed was between 0.25 to 4 rpm. The study concluded that the cylinder speed inversely proportional to the freshwater distillate and the modified solar still with the hollow cylinder can cost less compared with other types of distiller's technology [9],[10]. Integrating heat pump with solar still to increases the basin water temperature has been investigated also. Placing the condenser in the solar still basin water and the evaporator below the cover of solar still has been conducted to increase the surface area of condensation [11]. The results showed that the optimum daily freshwater productivity found to be 13.5 kg/m^2, and the rate of distillation in the evaporator is higher by 75% compared with condenses from glass cover [11]. Combined solar still with heat pump investigated experimentally including three cases; solar still fixed to the south direction, tracking it the solar radiation intensity and place it inside without sun or outside with sun. The results showed that the sun contributes to 0.666 because of the heat pump when combined with solar still can continue the production day and night. The basin water temperature found to be 60 ^oC with sun and 46 ^oC without sun, also found that the moisture was higher with the sun [12].

From the review of previous studies, many attempts and techniques were used to improve the rate of freshwater production, but most of them are expensive and require special equipment for implementation. Furthermore, it requires an expensive energy source to continue their work despite the improvement of their production rate. For example, the combined heat pump with a solar distillation system that aims to increases the basin water temperature and increases the condensation surface area requires a power source to operate the compressor with no less than 500 watts. Therefore, the current work aims to obtain augmentation of the production of freshwater by using a solar water distillation. This work is a ground-breaking attempt to introduce a diffusion-absorption refrigerator system (DAR) integrated with a solar still unit. The DAR condenser was immersed in the basin to increase the basin water temperature, which leads to an increase in the temperature difference within the solar still and increase the surface area for condensation. Therefore, the evaporator was added at the top of the distillery under Plexiglas cover in a small thermally insulated box to prevent sun rays.

DISTILLATION SYSTEM DESCRIPTION

The experimental system mainly consists of two types of solar still. The first type is conventional single slope solar still (CSS), the second type is conventional solar still integrated with diffusion-absorption refrigerator (CSSIDAR). Conventional single slope solar still consists of a metal basin that accommodates saltwater, a transparent cover Plexiglas and thermal insulation from the back and bottom sides of the solar still. The Diffusion-absorption refrigerator consists of an evaporator located under the upper area of Plexiglas cover, a condenser immersed in the basin water of solar still, generator and absorber. The condenser contributes to raising the basin water temperature; thus, it evaporates, during the day, especially during periods of low radiation by the refrigerant (NH_3) that flows through the absorption refrigerator. On the other hand, the evaporator contributes to condense a large part of water vapour. Accordingly, the basin water is heated by the solar radiation transmitted through the transparent Plexiglas cover and the condenser. Therefore, some saltwater will evaporate and condense under the Plexiglas and the evaporator.

The CSS Model

Figure 1 shows a schematic diagram of the experimental setup of a CSS with dimensions of 100 * 50 * 61.8 * 26.6 cm (length, width, big side height, and small side height respectively), consists of wooden frame of dimensions 100 * 50 * 10 * 1.8 cm (length, width, height, and thickness respectively). A plexiglass cover (0.3cm) of deamination100 * 50 * 50 * 14.8 (length, width, big side height, and small side height respectively) fixed on the wooden frame with single inclined to the horizontal (35 degrees). To provide a transparent cover from all sides except the bottom and back, the frame was opened to install the cover on both the wooden frame and MDF wooden board (100 * 60 * 0.18 cm length, width, and thickness respectively) in the backside of solar still. The water basin with a dimension of 94 * 46 * 10 * 0.08 cm (length, width, height, and thickness respectively) has been coated with black color to absorb the maximum amount of solar radiation. The basin was installed on the base of the solar still with dimensions of 100 * 50 * 0.18 cm (length, width, and thickness respectively). Solar still was closed by installing the top cover of the solar still. The inner surface of still covered by Aluminum foil with 0.03cm thickness. Plexiglass is fixed on the wooden frame by using an Aluminum channel to collect condensed water droplets through the plexiglass. The condensed water passed through the Aluminum channel to a gradient plastic pipe installed at the bottom of solar still. All parts are fixed by silicone glue to prevent air leakage. A water tank is connected to the solar still via pipes to feed the solar still with seawater. The level of salt-water inside has been controlled by using a mechanical floater, to clean basin liner, a hole was made at the bottom of the water basin and a globe valve was installed to drain brackish water.

The CSSIDAR Model

The CSSIDAR model shown in fig 2 consists of a conventional solar still as mentioned above integrated with a diffusion-absorption refrigeration DAR to increase the freshwater productivity as well as the continuation of production at night times. Figure 3. illustrates a schematic diagram of a threefold-Fluid Platen-Munters system. Starting with point 5 represent a strong solution at absorber exit, a thermal heat added in the generator by an electrical heater (79 Watt), as a result, vapour of ammonia is generated. Due to the buoyancy force, the ammonia vapor generated inside the bubble pump moves upward, as the ammonia vapour moves up, carries a weak solution at the top level of the bubble pump. At the top level of the bubble pump, the ammonia vapour separated from a weak solution. At point 1 the refrigerant ammonia vapour inter into the condenser (high pressure and temperature) and condensate by rejecting the heat to the ambient air. At point 2, the condensate liquid enters the evaporator, where its partial pressure decreases to the pressure and temperature of the evaporator due to the hydrogen gas present in the evaporator. Because of the low pressure, ammonia evaporates by taking heat energy from the cooled space. Ammonia vapour diffuses through hydrogen gas to form a colder mixture which flows down into the absorber at point 3 due to the buoyancy force. Within the absorber, a weak solution absorbs the ammonia vapour, which is coming from the bubble pump point 6, also the absorption rejected the heat energy to the surrounding. As a result, the hydrogen gas temperature increases and flows back into the evaporator at point 4 due to the force of buoyancy. Thus, fluids circulation throughout the unit continues because of buoyancy and gravity. The strong solution (water + ammonia) in the absorber flows returning to the generator at point 5. A photocell panel 100 Watts has been used to supply AC heater in generator with electrical power 220 V through the converter during the daytime and connected to a storage battery to operate during night times [13],[14].

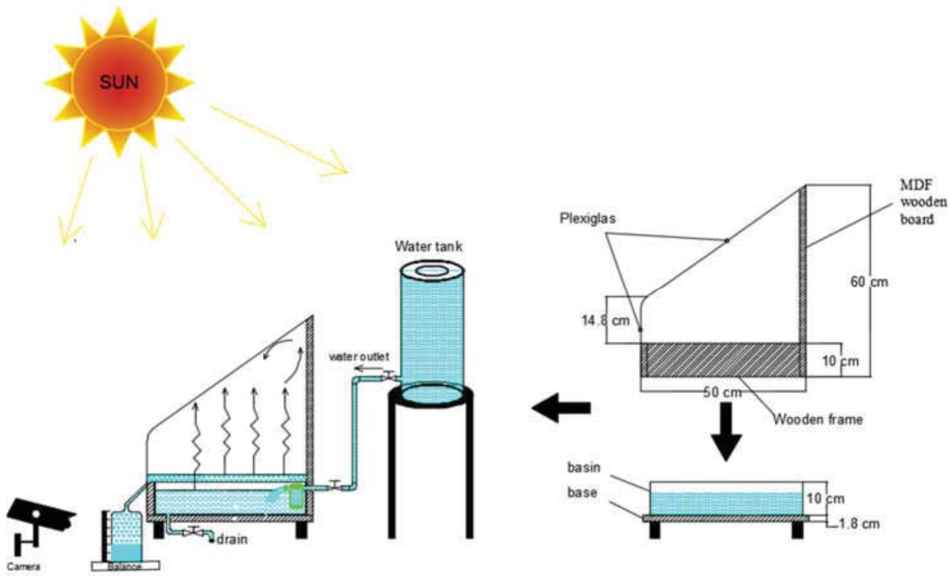

FIGURE 1. Schematic diagram of the conventional solar still (CSS)

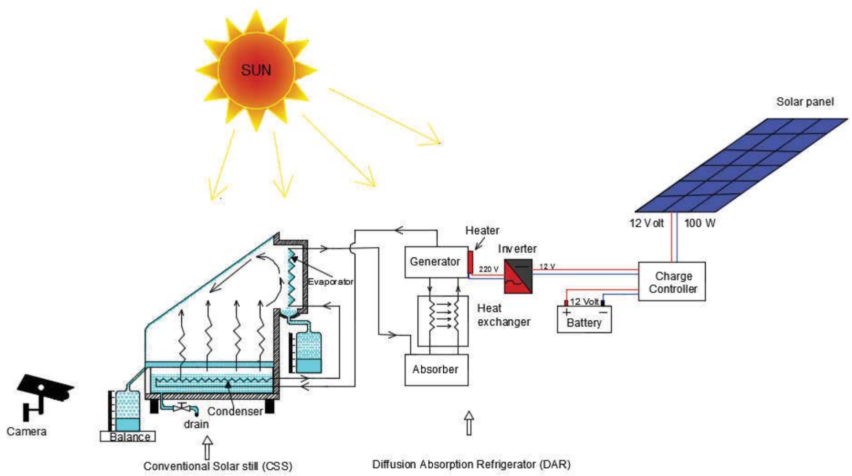

FIGURE 2. Schematic diagram of the modified solar still (CSSIDAR)

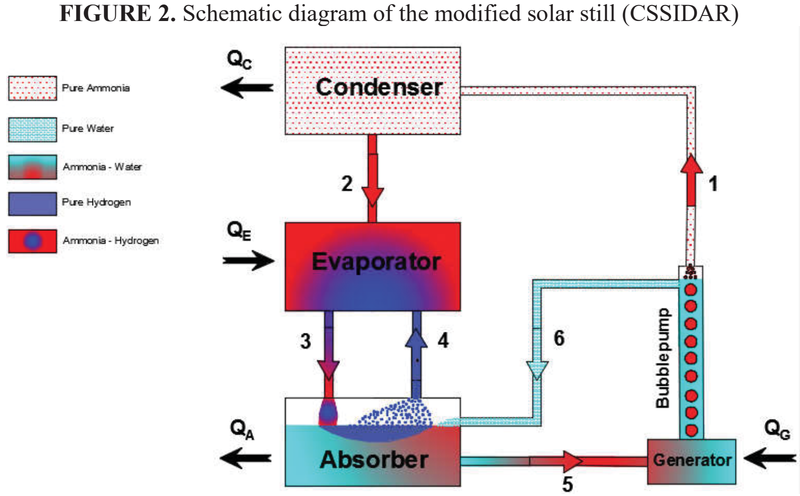

FIGURE 3. Schematic diagram of the DAR system

Parameter Identification and Measurement

The condensation process inside the solar still depends mainly on the temperature difference between the basin water and Plexiglas cover at a lower temperature (free convection) which is caused by buoyancy forces due to the differences in vapour density. When the basin water heated, the density changes in the boundary layer and led to the evaporation of some water molecules in the boundary layer of basin water. The generated vapour rises and replaces with a cooler vapour which will also heat up and rise. These phenomena continue to be called natural or free convection. The vapour reaches the cooler surface will lose part of its energy and condense. The condensation rate increases with the increasing temperature difference between the two surfaces. Therefore, in the current study, two factors have been investigated, first the increase in the basin water temperature, and the second is the increase in the condensation surface area at the top part of the solar still. The initial basin water temperature important parameter that directly affects the performance and productivity of solar still [15]. During the experiments, it was observed that the basin water temperature in the morning was low and around 18 ℃. Therefore, to solve this problem, DAR condenser was immersed in the basin to increase the basin water temperature. To increase the temperature difference within the solar still, an evaporator was added at the top of the distillery under Plexiglas cover in a small thermally insulated box to prevent sun rays.

To know the effect of different parameters on the solar stills system performance, different devices have been used to measure these parameters, as shown in table 1. SD data logger 4 channel has been used with K-type 0.3 mm thermocouples, which calibrated between 0 and 100 °C, to measure the temperatures at different places of the distillation system. The measured points include water basin temperature, basin liner temperature, water vapor temperature within the solar still, Plexiglas temperature and evaporator temperatures of DAR system. Anemometer device has been used to measure the ambient wind speed and solar power meter device used to measure solar radiation intensity in W/m^2. Humidity and temperature meter device have been used to measure the temperature and relative humidity for the ambient air.

TABLE 1. The various experimental measuring devices with their accuracy.

Measuring Device	Accuracy
SD data logger 4 channel (model 88598)	$\pm$ 0.3% rdg + 1℃
Digital laser infrared thermometer temperature (model TEGMART TE-TEM-LS-PRB).	$\pm$ 1.5%
Humidity and temperature meter (model GM1362)	Humidity 3% Temperature 0.5%
Solar power meter device (model TENMARS TM-207)	$\pm 10\ W/m^2$
Anemometer device (model ut363)	$\pm$5% rdg + 0.5℃

Experimental Procedures

The experimental test carried out at the Ural Federal University during August 2019 according to Ekaterinburg/ Russia city climate (Latitude 56.84 °N, Longitude 60.58 °E). The system distillery directed to the south direction. All tests started at 08:00 am to 08:00 am for the next day (24 hours) for different days. Data has been recorded hourly, which includes temperatures of Plexiglas cover, basin liner, basin water and evaporator, the intensity of solar radiation, wind speed, temperature and relative humidity of ambient air. The study has been conducted over one month with variable environmental conditions, as well as the time of sunrise and sunset ranging from 05:20 am to 08:40 pm. The current study included two stages. In the first stage, the freshwater productivity from conventional distillers has been investigated. The second stage has included the effect of integrating CSS with DAR unit to the distillate system on productivity. The tests were conducted for 10 days, however, 21 Aug. and 22 Aug. 2019 have been chosen as perfect days.

RESULTS AND DISCUSSION

The most important factors in solar still productivity are the intensity of solar radiation and ambient temperature. In the Yekaterinburg city, rarely the weather is clear and without clouds. In the perfect day 21.08.2019 the effect of solar radiation started after 8:00 am and the maximum intensity of the solar radiation is approximately at 14:00 pm, 980 W/m^2 which decreases gradually until the end of the sunrise at 20:00 pm to reach 21 W/m^2 as shown in figure 4. After 08:00 pm, the radiation intensity was almost zero until the next morning 22.08.2019, to reach approximately

28 W/m^2 at 08:00 am. Also, from fig 4, it is observed that the ambient temperature is directly proportional to solar radiation. The maximum ambient temperature recorded at 14:00 pm 22.9 °C, which gradually decreases as the intensity of solar radiation decreases to record 16.7 °C at 20:00 pm, and continued to decline slightly overnight, reaching 15 °C at 08:00 am morning of 22.08.2019.

To estimate the productivity of the two solar still models (CSS and CSSIDAR), temperatures were recorded at different locations in the two models for 24 hours. Figure 5 shows that the temperatures at different locations in the two models are a function of time during the test. In the morning all temperatures are close to 18 °C, the basin water temperature at 18 °C considered low and takes time to increase due to the solar radiation intensity effect. Furthermore, it is observed that after one hour, (09:00 am) the basin water temperature in the CSS was 28.2°C while in the CSSIDAR 36.4 °C, which indicates an improvement in the basin water temperature of 29% and this is very important to accelerate the evaporation process. For the CSSIDAR model, the basin water temperature was higher than that of the basin liner until 12:00 noon, which was 43.2 °C for basin liner and 43.1°C for basin water. On the other hand, in the CSS model, the water was the highest until 11:00 am where the basin liner temperature was 39.1°C and the water temperature 36.6 °C. In both models, the basin liner temperature was higher than the rest temperatures during the day and night, and very close to the water temperature, due to the high absorbency of the black painted basin plate.

The maximum temperature recorded 50.9 °C at 14:00 for CSSIDAR and 49.8 °C at 15:00 for CSS. Furthermore, it was observed that the Plexiglas temperature is lower than the basin water temperature for both models due to the heat capacity of the Plexiglass which is lower than the basin water. Therefore, the glass is heated firstly in the early morning hours, after that, its temperature decreases and becomes below the basin water temperature during the day and at night. The maximum value of the Plexiglas temperature reached 43.7 °C at 15:00 pm for CSSIDAR and 43.1 °C for CSS at 15:00 pm. It was also observed that the Plexiglas temperature in the CSSIDAR model was higher than that of the CSS model, to reach about 0.5 to 3.2 °C during the day 08:00 am - 20:00 pm and 2.8 to 12.9 °C during the night, due to the higher evaporation rate in the CSSIDAR model due to the effect of continuous heat supplied to the basin water from the condenser of DAR.

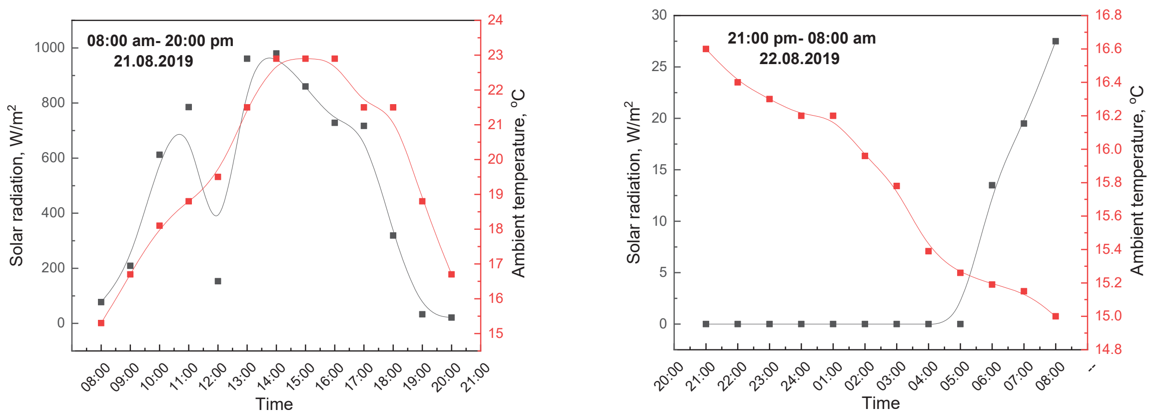

FIGURE 4. The solar radiation intensity and ambient temperatures per each hour for a perfect day 21.08-22.08 2019.

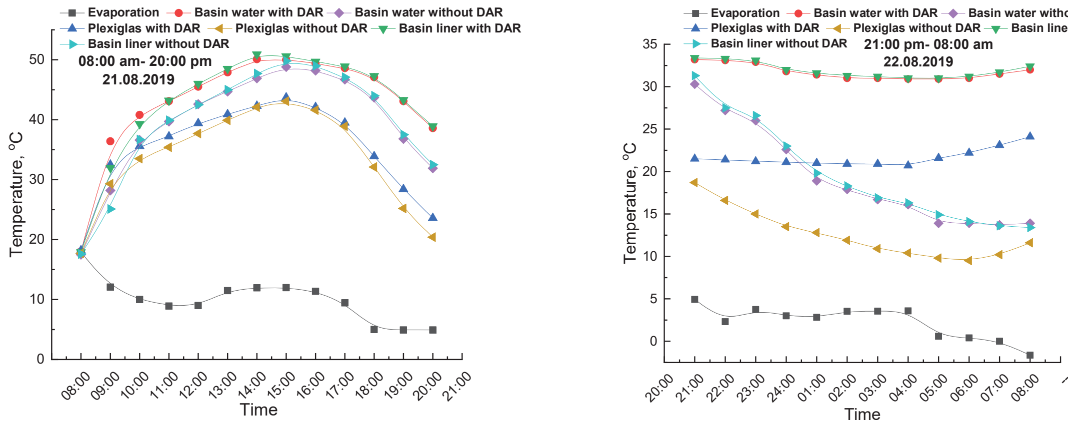

FIGURE 5. The relationship between time per each hour and temperatures at different points within the two models.

Figure 6 shows the freshwater productivity of CSSIDAR hourly from both the evaporator and the Plexiglas cover and total production during the day 21.08.2019 and at night 22.08.2019. It is obvious that the evaporator condenses a large part of the water vapor about 76% in the daytime and 75% in the night and the rest condenses below Plexiglass cover. Because, the evaporator temperature is low, thus allowing a large amount of water vapor to condense very quickly. Total freshwater production during daytime (12 hours) from evaporator and Plexiglass found to be 2970 ml/m^2 and 900 ml/m^2 respectively, while during night times from evaporator and Plexiglass found to be 980 ml/m^2 and 330 ml/m^2 respectively. Therefore, the total production of CSSIDAR from evaporator and Plexiglass was 3870 ml/m^2 and 1310 ml/m^2 respectively during 24 hours. So, integrating DAR with CSS is very useful to increase the production of freshwater.

Figure 7 shows comparing the freshwater productivity of both solar still models for 24 hours for a perfect day 21.08-22.08.2019. It is observed that the freshwater productivity improvement ratio from the CSSIDAR model in comparison with CSS model during the daytime from 08:00 am to 20:00 pm on 21.08.2019 was 251%, while during night-time from 21:00 pm to 08:00 am on 22.08.2019 was 470 %. So freshwater productivity from the CSSIDAR and CSS models from 08:00 am to 20:00 pm on 21.08.2019 are 3870 and 1100 ml/m^2, respectively, and from 21:00 pm to 08:00 am on 22.08.2019 are 1310 and 230 ml/m^2respectively. Thus, the cumulative productivity of CSSIDAR is 289 % higher than that of CSS for 24 hours.

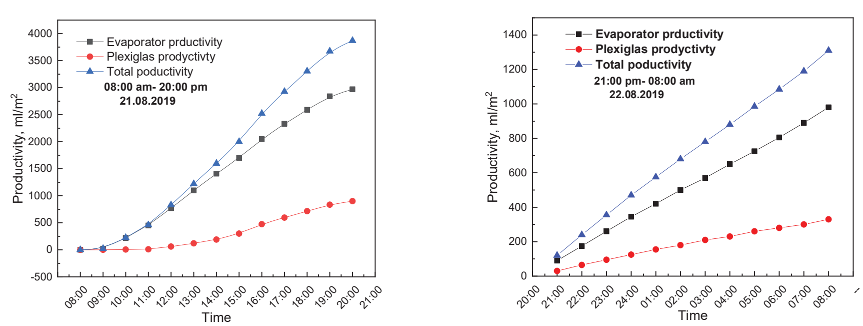

FIGURE 6. The productivity of freshwater for each hour of CSSIDAR from the evaporator and Plexiglas cover and total productivity during daytime 21.08.2019 and night 22.08.2019.

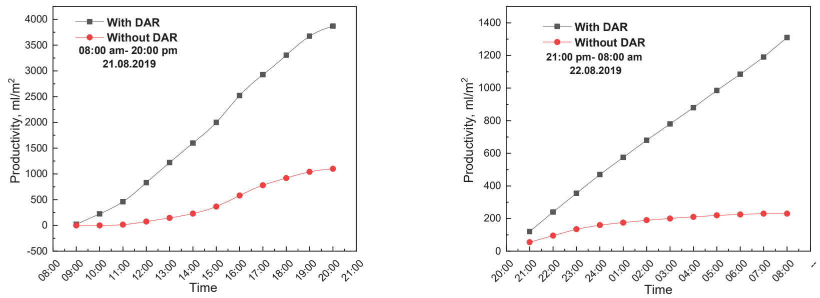

FIGURE 7. Comparison of the productivity of both distillation models during the daytime 21.08.2019 and night 22.08.2019.

ESTIMATE FRESHWATER PRODUCTIVITY COST

The production cost of one liter of freshwater for a perfect day 21-22.08.2019 of two solar still models is calculated as follows:

The total cost of the fabrication of solar still C is equal to summing the fixed (fabrication) costs F and operation (variable) cost V [16]:

$$C = F + V \quad \text{………………..} \ (1)$$

Where

$$V = n \times 0.05 \times F \quad \text{…………} \ (2)$$

Suppose the variable cost V is 0.05 F per year; n: Life expectancy for both solar stills is 10 years, then the total cost for CSS and CSSIDAR from table 2

$$C = 82 + 10 \times 0.05 \times 82 = 123 \ \$$$
$$C = 287 + 10 \times 0.05 \times 287 = 430.5 \ \$$$

The daily productivity from CSS per unit area 0.5 m^2 was 1.33 L/m^2, and for CSSIDAR 5.180 L/m^2 for 24 hours. If assuming both solar stills operating 180 days in the year, therefore the total annual productivity during the work period 10 years for CSS is 2394 L, and for CSSIDAR is 9324 L. So, the cost of production of one littler of freshwater from TSS is $123/2394 = 0.051$ \$ and from MSS is $430.5 / 9324 = 0.046$ \$.

TABLE 2. Fabrication fixed cost for MSS and TSS.

Unit	Quality	Cost of CSSIDAR, $	Cost CSS, $
MDF wooden board, 1.8 cm	2 m^2	14	14
Plexiglas cover 0.3 cm thickness	1.2 m^2	15	15
Galvanized iron sheet basin, 0.08 cm	1.5 m^2	11	11
Solar panel + charge control (100 Watt)	1 piece	100	-
Unit	**Quality**	**Cost of CSSIDAR, $**	**Cost CSS, $**
Solar-Inverter	1 piece	35	-
Battery	1 piece	30	-
Diffusion-absorption refrigerator system	1 piece	50	
Spray paint heat-resistant	2 pieces	3	3
A mechanical float	1 piece	1	1
Heat-resistant silicone glue	2 pieces	3	3
Saltwater feeding system	-	15	15
Other	-	10	20
Total cost	-	287	82

CONCLUSIONS

A conventional solar still integrated with diffusion-absorption refrigerator system studied experimentally. This integration has benefits of increasing the basin water temperature by immersed the condenser in the basin solar still and improving the surface area of condensation by located the evaporator under the upper area of Plexiglas cover. The diffuse absorption refrigerator system used in the current study is characterized by a low power energy consumption of 79 Watts per hour compared to the compression refrigeration system which consumes at least 500 Watts per hour. So, the energy consumed during 24 hours in an experimental day was about 1.85 kWh, at different thermal loads within CSSIDAR system, thus, achieving an increase in the productivity of solar distillation at a lower cost. The results have proven that the CSSIDAR model productivity is 289 % higher than that of the CSS model for 24 hours, and this percentage can be reduced or increased depending on the environmental and operational conditions of the distillation system. The daily freshwater productivity of the CSSIDAR model reached 5180 ml/m^2 and 1330 ml/m^2 from CSS model in perfect days 21-22.08.2019. The current work has been done in Russia (harsh environment conditions), so, it is expected if applied the hybrid system in relatively hot environmental climates such as Iraq, the rate of freshwater production will be increased, which depends mainly on the solar radiation intensity and the ambient temperature.

In general, the estimated production cost of one liter of freshwater form CSS model is 0.051 $, and for CSSIDAR model is 0.046 $. Thus, two objectives were achieved from the current study, the first is to improve the rate of freshwater daily production (day and night), and the second is to reduce the cost of producing one liter of freshwater by 10.8 %.

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