Productivity Enhancement of Solar Water Desalination Unit Using a Solar Electric Water Heater

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ABSTRACT

The biggest problem faced by the world these days is pure drinkable water, and in a few years, pure drinkable water will not be easily available, as it is becoming brackish and saline due to pollution. By using solar energy, a solar still can produce pure water which can be used for drinking, cooking, and also for industrial purposes. In this research, a solar still based on clean technology using solar energy to drive the system is used that can be operated easily and with an approximately negligible maintenance cost. A pyramid solar water desalination unit with modification of the solar electric water heater (used to increase water temperature) is developed to increase the water yield per day. A theoretical model of the solar still unit is developed and performance is evaluated. Based on this theoretical design, fabrication is carried out and experiments are performed to predict the overall output. It is observed that the output distilled water has a total dissolved salts value much lower than the total dissolved salts of groundwater. Additionally, the average output of a solar water desalination unit with an electric water heater is found to be enhanced compared with the unit without an electric water heater.

Keywords: Solar desalination; Solar water heater; Environment; Design; TDS.

INTRODUCTION

Good quality of drinkable water is a necessity for life and there are only a few available sources of water, such as lakes, rivers, and underground water. Mostly underground water is used for drinking but this underground water commonly has a high amount of different salts which are not good for human health. Because of this, it cannot be directly used for drinking. Thus, there is a need to extract these salts from water (Attia et al., 2021; Hassan et al., 2020a). To produce fresh water that can be used for drinking purposes on a broader scale requires a high amount of energy. There are many purification methods of water, such as reverse osmosis, humidification, dehumidification, electrodialysis, etc. (Essa et al., 2020a; Xu et al., 2020).

For the purification of water, the simplest technology used is water desalination by solar energy. This system may use a single, double, or pyramid slope solar still (El-Gazar et al., 2021). The increase in energy utilization and its harmful results on the environment has produced interest in this simple technology (Katekar and Deshmukh, 2020; Mahboob et al., 2021c). Solar energy is available on Earth free of cost, is available easily, and reduces the cost of transportation(Mahboob et al., 2019a; Mahboob et al., 2019b). This energy can be utilized as thermal energy and has no pollution effect (Mahboob et al., 2018a; Mahboob et al., 2021b; Mahboob et al., 2018b). By using solar energy, a solar still can easily produce pure water which can be used for drinking, cooking, and also at an industrial scale. This is a very simple technology that uses solar energy and drives the system. It can be operated easily and approximately at a negligible maintenance cost (Mahboob et al., 2021a).

The purification of water through distillation is now considered a modern technique where solar radiation is used to purify water and make it drinkable. By using solar energy water heads on the glass, impurities remain down in the basin and water condenses on the glass cover which has a low temperature as compared with water in the basin, and due to this temperature difference, the vapor condenses and move down to be collected through channels and an output pipe. This is the basic principle of the solar still, of any type and design. With time, solar still has been modified in new shapes with different radiation-absorbing materials and techniques to increase its output and efficiency, such as double-slope, cone, pyramid, and double-basin solar stills, and many others have studied and compared their productivity (Abdullah et al., 2020b; Essa et al., 2020b; Hassan et al., 2020b). The main considerations in a solar still are solar intensity, solar hours, and type of still. The productivity of any solar still depends upon the previous modifications made in solar stills such as using sun trackers, reflecting mirrors, and a stepwise basin to gain as much radiation in a day as possible. These modifications increased the productivity of the solar still but further modifications can be made to make the solar still more efficient with a higher output of distilled water (Abdullah et al., 2020a).

In this research, an experimental investigation of the solar still will be carried out to evaluate the performance. An effort will be made to study the theoretical model of already developed solar stills and then carry out modifications. A 3D model will be created based on these modifications having different parts of the still assembled in the CAD assembly and manufacturing drawings for these parts and assembly will be created. The fabrication of the solar still will be carried out and experiments will be performed. Based on these experiments a parametric analysis of the solar still will be performed.

MATHEMATICAL MODEL OF THE SOLAR STILL

The working and performance of solar still can be determined using energy balance equations. The flux at different components of the still is explained by the researchers (Medugu and Ndatuwong, 2009; Tiwari et al., 1989).

The absorbed flux α'_{glass} by the glass is as follows:

$$\alpha'_{glass} = \left(1 - R_{glass}\right) \alpha_{glass} \tag{1}$$

The reflected flux R'_{water} by the water is as follows:

$$R'_{water} = \left(1 - R_{glass}\right)\left(1 - \alpha_{glass}\right)R_{water} \tag{2}$$

The absorbed flux α''_{water} by the water is as follows:

$$\alpha''_{water} = \alpha'_{water}\left(1 - R_{glass}\right)\left(1 - \alpha_{glass}\right)(1 - R_{water})\alpha_{water} \tag{3}$$

The absorbed flux α'_{basin} by the basin is as follows:

$$\alpha'_{basin} = \alpha_{basin}\left(1 - R_{glass}\right)\left(1 - \alpha_{glass}\right)(1 - R_{water})(1 - \alpha_{water}) \tag{4}$$

The lost flux L'_{atm} by the water and glass together is as follows:

$$L'_{atm} = (1 - \alpha_{basin})\left(1 - R_{glass}\right)\left(1 - \alpha_{glass}\right)(1 - R_{water})(1 - \alpha_{water}) \tag{5}$$

All absorbed radiations are utilized for thermal losses and evaporation for the case in which evaporation inside still is considered as isobaric at thermal equilibrium. Then the energy balance is as follows (Tamini, 1987):

$$(\alpha'_{water} + \alpha'_{basin})I(t)A_{still} = \dot{Q}_{distiled} + \dot{Q}_{loss} \tag{6}$$

and energy $\dot{Q}_{distiled}$ used for water distillation can be calculated as follows:

$$\dot{Q}_{distiled} = L \times \dot{m}_{water} \tag{7}$$

where L is the latent heat of vaporization and m_{water} is the mass of water distilled. The energy lost $\dot{Q}_{loss}$ can be calculated as follows:

$$\dot{Q}_{loss} = U'_{water}(T_{water} - T_{atm})A_{still} \tag{8}$$

where U'_{water} is total heat transfer coefficient, A_{still} is the area of the sill, T_{water} is the temperature of the water, and T_{atm} is the temperature of the atmosphere.

The outer glass surface of the still is in thermal equilibrium with the external atmosphere and losses of this glass surface q_{glass} to the external atmosphere are in the form of convection and radiation calculated as follows:

$$q_{glass} = q_{c,glass} + q_{r,glass} \tag{9}$$

The convection losses of the glass $q_{c,glass}$ can be calculated as follows:

$$q_{c,glass} = h_{c,glass}(T_{glass} - T_{atm}) \tag{10}$$

The radiative losses of the glass $q_{r,glass}$ can be calculated as follows:

$$q_{r,glass} = \varepsilon_{glass}\, \alpha(T_{glass}^4 - T_{sky}^4) \tag{11}$$

Which can be written as

$$q_{r,glass} = h_{r,glass}(T_{glass} - T_{atm}) \tag{12}$$

Where

$$h_{r,glass} = \varepsilon_{glass}\, \alpha\, \frac{(T_{glass}^4 - T_{sky}^4)}{(T_{glass} - T_{atm})} \tag{13}$$

By substitution, we can obtain

$$q_{glass} = (h_{r,glass} + h_{c,glass})(T_{glass} - T_{atm}) \tag{14}$$

For the free radiation and convection of the glass

$$(h_{r,glass} + h_{c,glass}) = 5.7 + 3.8v \tag{15}$$

For separate calculation of radiative and convective coefficients, radiative coefficients $h_{r,glass}$ can be calculated from eq. 13 and convective coefficient $h_{c,glass}$ can be calculated as follows (Watmuff et al., 1977):

$$h_{c,glass} = 2.8 + 3.0v \tag{16}$$

For the heat losses from the basin the rate can be found as follows:

$$q_{basin} = h_{basin}(T_{basin} - T_{atm}) \tag{17}$$

Convection, radiation, and evaporation are three heat transfer modes for the water in the basin. The rate of radiative heat $q_{r,water}$ transferred to the glass from the water can be expressed as follows:

$$q_{r,water} = \varepsilon_{glass}\, \sigma(T_{water}^4 - T_{glass}^4) \tag{18}$$

where $\sigma$is Stefan-Boltzmann constant and ε_{glass} is the emissivity of the glass

$$q_{r,water} = h_{r,water}(T_{water} - T_{glass}) \tag{19}$$

Where $h_{r,water}$ is determined as follows (Watmuff et al., 1977):

$$h_{r,water} = \varepsilon_{glass}\,\sigma\left(T_{water}^2 + T_{glass}^2\right)\left(T_{water} + T_{glass} + 546\right) \tag{20}$$

where the temperature of the water T_{water} and temperature of the glass T_{glass} are in Kelvin units. The rate of convective heat $q_{c,water}$ transferred to the glass from the water can be expressed as follows:

$$q_{c,water} = h_{c,water}\left(T_{water} - T_{glass}\right) \tag{21}$$

Where $h_{c,water}$ is determined as follows (Dunkle, 1961):

$$h_{c,water} = 0.884\left[T_{water} - T_{glass} + \frac{\left(P_{water} - P_{glass}\right)T_{water}}{268.9 \times 10^3 - P_{water}}\right]^{1/3} \tag{22}$$

where the pressure of water at the temperature of the water is P_{water} and pressure of water at the temperature of the glass is P_{glass}.

The rate of evaporative heat $q_{e,water}$ of the surface of the water can be expressed as follows:

$$q_{e,water} = h_{e,water}\left(T_{water} - T_{glass}\right) \tag{23}$$

Where evaporative coefficient $h_{e,water}$ is determined as follows (Cooper, 1973):

$$h_{e,water} = 16.27x10^{-3}\,h_{c,water}\quad\frac{P_{water} - P_{glass}}{T_{water} - T_{glass}} \tag{24}$$

P_{water} and P_{glass}can be calculated as follows (Fernández and Chargoy, 1990):

$$P(T) = exp\left(25.3117 - \frac{5144}{T}\right) \tag{25}$$

Where T is in kelvin units and the equation is valid for 283K to 363K. The hourly production of the still can be calculated as follows (Tiwari et al., 1989):

$$m_{e,water} = h_{e,water}\left(\frac{T_{water} - T_{glass}}{L}\right) \times 3600 \tag{26}$$

The efficiency of the still can be calculated as follows:

$$\eta_{still} = h_{e,water}\left(\frac{T_{water} - T_{glass}}{I(t)}\right) \times 100 \tag{27}$$

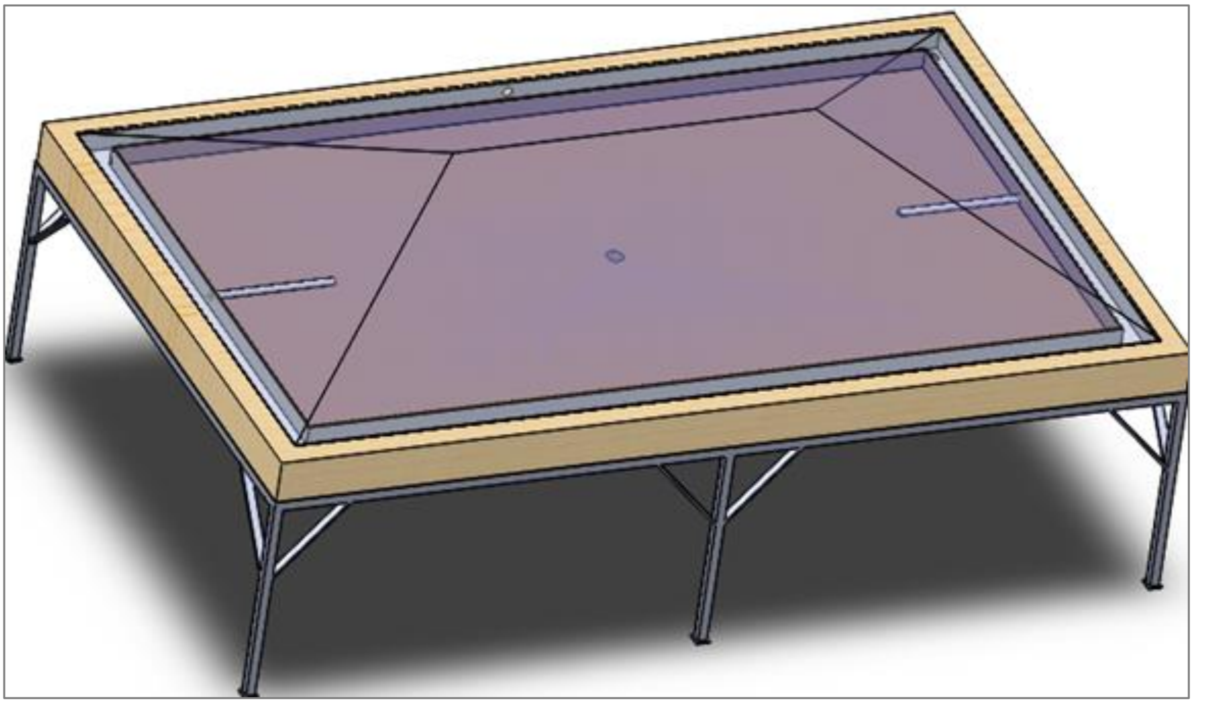

Figure 1. CAD model of pyramid solar water desalination unit.

MODIFICATION IN SOLAR STILL

A study of previous work on solar water desalination units and a literature review is performed so that the development of a theoretical model is possible. The performance of the solar still is calculated by the theoretical modeling of a solar still and by energy balance equations. Using these equations, one can easily calculate the output of a solar still. Through the performance and efficiency of a solar still, important characteristics and the effect of modifications of the solar still are studied that are helpful in further improvement. The design of single-basin pyramid solar still is used, and modification involved the design of glass. A CAD model is developed for the modified still and the assembly of different components is shown in Figure 1. The manufacturing drawings are created and sent to the shop floor for the manufacturing of the physical model of the still as shown in Figure 2.

Figure 2. Physical model of pyramid solar water desalination unit

Most importantly, the use of an Electric Water Heater (EWH) operated using a solar panel is incorporated. The type of water heater used is DC that will operate using a 12V battery. This battery is charged using the Solar PV Panels and the heater will operate using solar energy that means the Still is working on additional solar energy. The heater is insulated and can work in water easily so it has a long life as well and can bear temperature without any drawbacks. The model desalination unit as shown in Figure 2 is analyzed to install the electric water heater and PV panels as shown in Figure 3. The Parameters for the solar still model are enlisted in Table 1.

Figure 3. Physical model of pyramid solar water desalination unit with EWH.

Table 1. Solar Still Parameters.

Parameter	Value
Water absorptivity (α_{water})	.050
Area of Basin	1.5 m^2
No. of Glass Cover	1.0
Thickness of Glass	5mm
Glass Slope	23.1 Degree
Area of Glass	2.52m^2
Glass absorptivity (α_{glass})	.050
Glass emissivity (ε_{glass})	0.90
Basin absorptivity (α_{basin})	0.95
Water emissivity (ε_{water})	0.90

RESULTS AND DISCUSSION

The site selected for conducting experiments is Gujranwala situated in the northern part of the Punjab province of Pakistan. The Direct Normal Irradiance (DNI) available of the site for the complete year is presented in Figure 4. The experiments are carried out to find the performance of both solar stills, the modified with water heater and without a water heater from 9 am - 3 pm.

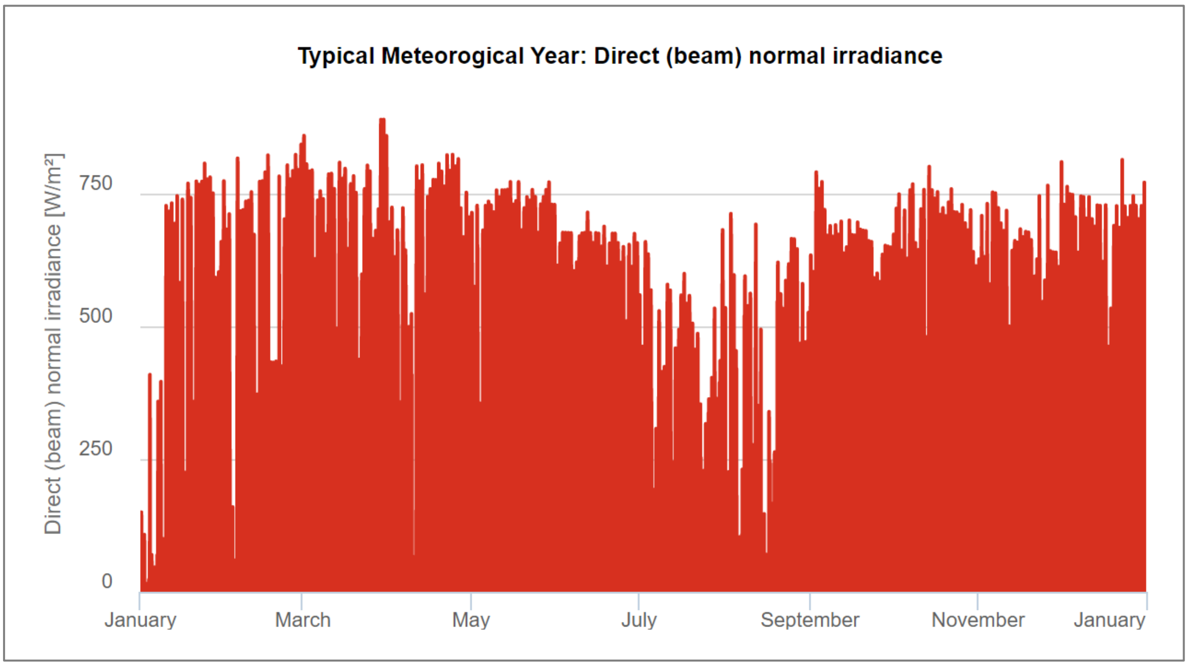

Figure 4. Yearly plot direct normal irradiance at Gujranwala, Pakistan

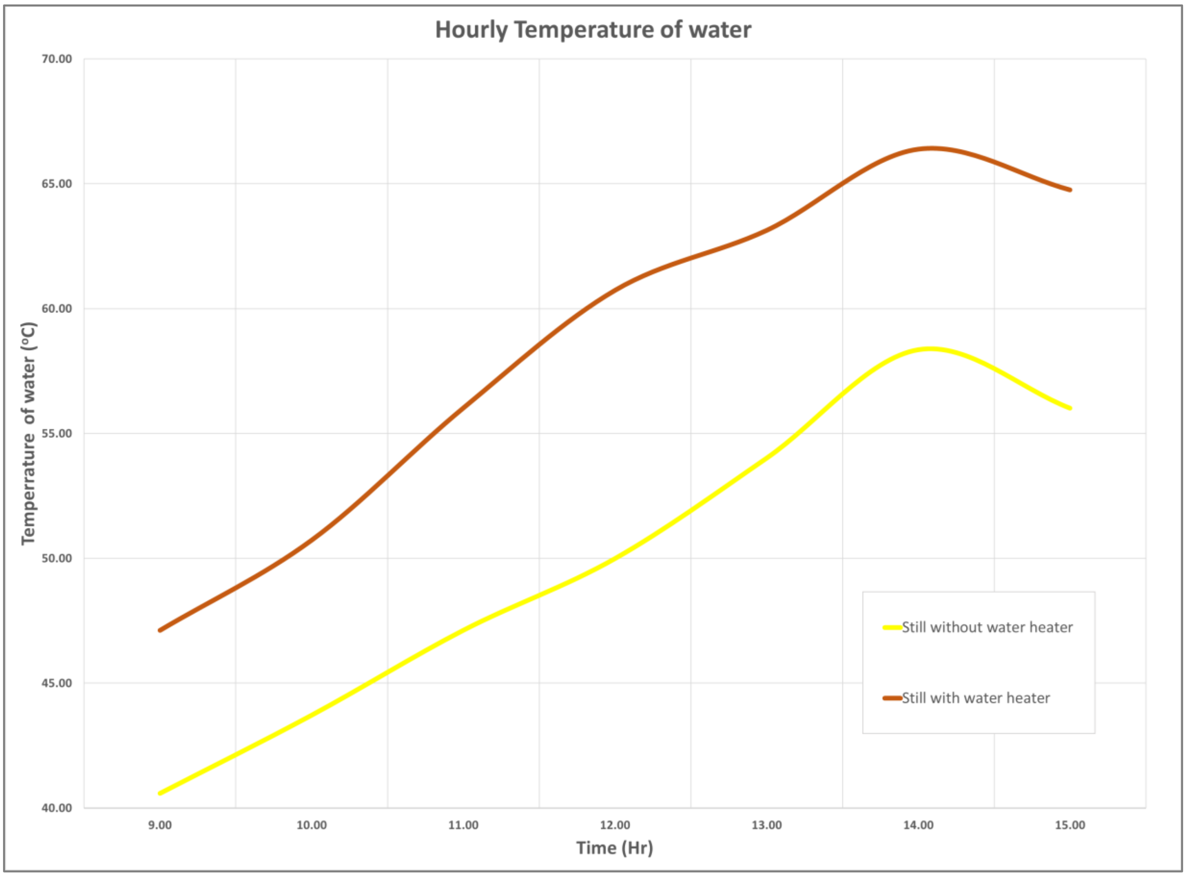

Figure 5. Time plot of the temperature of water in both solar stills at Gujranwala, Pakistan

Figure 5 represents the temperature of water plotted against time for the modified still with water heater and without water heater at Gujranwala, Pakistan. It is evident that with the increase in DNI values the temperature of water increases for both stills. A substantial gain is observed in the water temperature for the still having water heater throughout the observed duration. The maximum temperature for the still without water heater is around 58^{o}C and the maximum temperature for the still with the water heater is around 66^{o}C. A net gain of more than 7^{o}C is observed at all times for the still with water heater than the without water heater.

Figure 6 represents the distilled water quantity plotted versus time for both stills at Gujranwala, Pakistan. It is clear from the plot that distilled water quantity increases with the DNI increment for both stills. However, the amount of water collected from the still with the water heater is higher compared to the other still and this gain is maximum at the peak DNI hours.

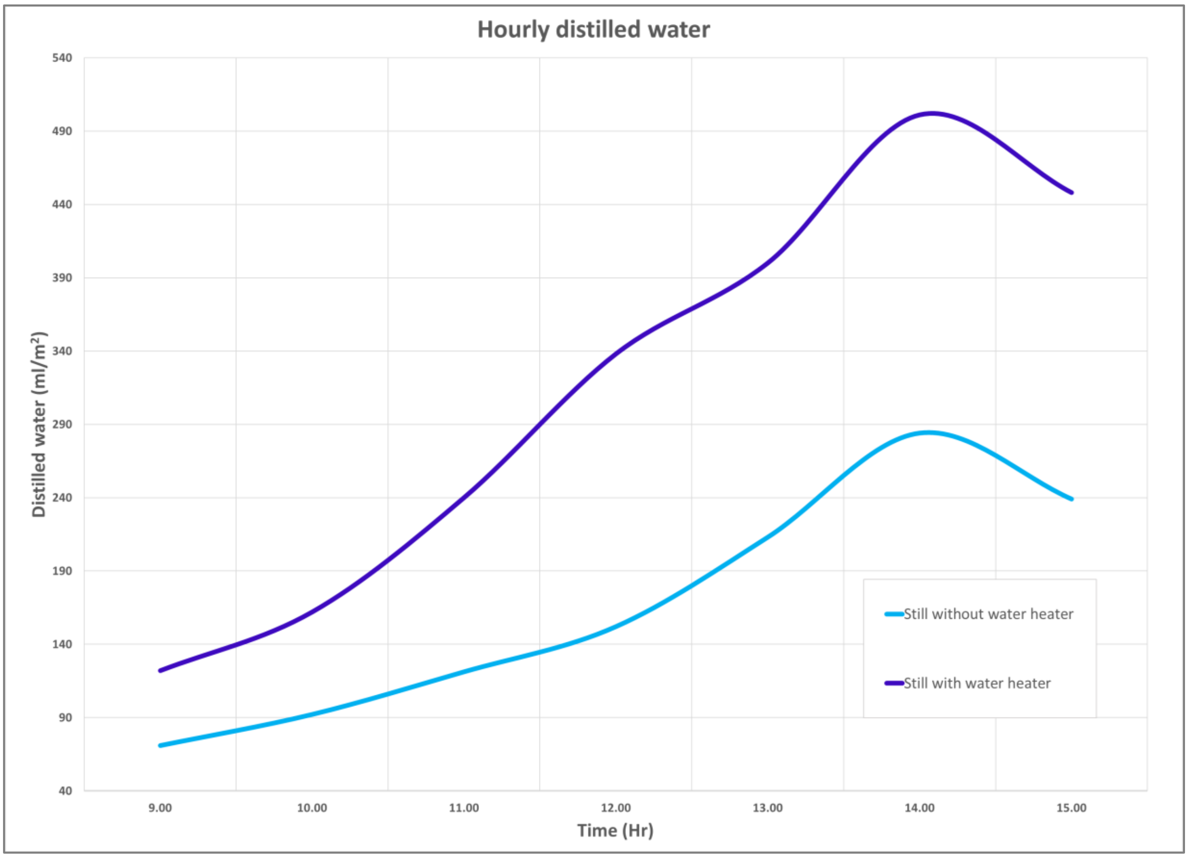

Figure 6. Time plot of distilled water quantity for both solar stills at Gujranwala, Pakistan

The maximum amount of hourly distilled water for the still without water heater is around 284 ml/m^2 and the maximum amount of hourly distilled water for the still with the water heater is around 501 ml/m^2. The water quantity collected from the still with the water heater is nearly double the amount of water collected from the still without water heater.

Table 2. The Output distilled water for the modified design of still without using the water heater.

Experiment Time (Hour)	Available Radiation (W/m^2)	Temperature of Water (°C)	Distilled Water (ml/m^2)
9	525	40.59	70.89
10	560	43.72	92.13
11	625	47.12	121.2
12	651	49.99	152
13	660	54.01	213
14	630	58.35	284
15	600	56.01	239

Table 3. The Output distilled water for the modified design of still using the water

heater.

Experiment Time (Hour)	Available Radiation (W/m^2)	Temperature of Water (°C)	Distilled Water (ml/m^2)
9	525	47.12	122
10	560	50.73	162
11	625	56.02	240
12	651	60.73	338
13	660	63.13	400
14	630	66.38	501
15	600	64.75	448

The data for these experiments are enlisted in Table 2 for the solar still without a water heater and Table 3 for the solar still with a water heater.

CONCLUSION AND RECOMMENDATIONS

The design of a solar still was carried out in this study by first studying its mathematical design using standard parameters. Analysis of the model showed that our model will work smoothly and be reliable. Based on this a solar still was fabricated with modification in the design and incorporating a solar system based DC water heater. It was noticed that the use of a water heater has increased the temperature of water in less time and increased the output of solar still as compared to traditional still. Hence the performance and efficiency of solar still increased by modification in design and by using the electric water heater. Some of the key observations from the above experiments are as follows:

Using black paint, the productivity of distillate is increased.

The TDS of salted water is reduced to the drinkable water level.

The use of an electric water heater increased the output and efficiency of the solar still.

The efficiency and output of this solar water desalination unit can further be increased from 10% to 20% by using reflectors that increase the amount of available radiation. By using a double cover of glass on the top, the temperature difference in water between the basin and glass cover can be increased. This unit can also be operated in no sun conditions with the grid electricity input.

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