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Effect of shading and evaporative cooling of glass cover on the performance of evacuated tube-augmented solar still

Mohit Bhargva[1] · Avadhesh Yadav[1]

Abstract

Solar still is a promising device used worldwide for water distillation due to its simple design, easy construction and low cost. However, the freshwater output from a solar still is moderate. Several active techniques have been emerged over the years to solve this problem. In this paper, an experimental study is carried out on a single-slope solar still augmented with an evacuated tube collector (ETC) and a heat exchanger working on thermosyphon. The effects of shading and evaporative cooling of glass cover on the active solar still performance were explored and analyzed on separate days under the meteorological conditions of Kurukshetra, India. The experiments were conducted at a constant water depth of 4 cm. The main aim of this study is to enhance the productivity and efficiency of ETC-coupled solar still by increasing the condensation rate. The experimental results showed remarkable increment in freshwater productivity of the still with a maximum of 2114 ml/day achieved for the case of ½ shading and cooling of glass cover. An increase of 16.4% and 3.8% in freshwater productivity and overall efficiency was achieved with ½ shading and cooling of glass cover in comparison with solar still without glass cover shading and cooling. The solar still performance was decreased when the shading and cooling are done on more than half the area of glass cover.

Keywords Solar still · Shading and cooling · Evacuated tube collector · Productivity · Efficiency

1 Introduction

Water is the most precious resource on planet earth for the survival of living beings. In the present situation, the existing freshwater resources are getting depleted due to industrialization, increased population, freshwater mismanagement and wastage in the past few decades. Being a developing nation, India's water problems are much larger and the country

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is on the verge of potable water crisis due to enormous population and over-withdrawal of groundwater to be used in agriculture especially in the rural areas. Therefore, wastewater treatment and utmost use of alternate energy resources become indispensable to fulfill freshwater requirements of the people. Solar still is a very convenient device used for water distillation and desalination especially in the rural areas of developing countries like India, Pakistan and Bangladesh. Chandrashekara and Yadav (2017) exhaustively reviewed different designs of solar stills. Moderate freshwater output is one major challenge in the practical implementation of solar still. Numerous solar still-related studies have been carried out by different researchers in the past to increase the still productivity. Fins installed in still basin increase the energy transfer area and bolster the still productivity. Ali et al. (2015) experimentally compared the performance of a solar still with and without pin fin absorber. The results showed 12% rise in freshwater output of still with pin fins. The use of straight fins also increased the distillate output by approximately 13% (El-Naggar et al. 2016). The use of a wick reduces the active water depth in still basin and increases the evaporation rate of basin water which leads to enhancement in freshwater productivity (Hansen et al. 2015; Haddad et al. 2017; Karthick Munisamy et al. 2017). Arjunan et al. (2011) used sponge liners of different thicknesses on the bottom plate of still basin. This modification increases the evaporation rate of water and enhanced the still output. Gnanaraj et al. (2018) modified a solar still using external mirror reflector for maximum trapping of solar radiations and pebbles in still basin to enable evening time output. The results showed 41% increase in the freshwater output of the still. The rate of condensation is enhanced by increasing the temperature difference between water vapors and inner surface of glass cover. Bacha and Zhani (2013) developed a solar still by combining with an external condenser to increase the condensation rate and freshwater output. Connecting evacuated tubes with solar still enhances the still performance as evacuated tube collector is very well suited for high-temperature applications in comparison with other non-concentrating collectors (Mehla and Yadav 2017; Yadav and Bajpai 2012). Issa and Chang (2017) increased the distillate output by combining evacuated tubes to the single-slope still. Winston et al. (2018) designed and fabricated a photovoltaic thermal collector-augmented solar still and enhanced the productivity by six times than that of conventional still. Hosseini et al. (2018) experimentally examined the impact of using parabolic trough concentrator and a condenser on the performance of a solar still. The results showed an energy efficiency of approximately 61% for the entire system. Omara and Eltawil (2013) increased the freshwater output by 347% by preheating the saline water using a parabolic dish concentrator. Cooling of glass cover increases the condensation rate and still productivity. Bani-Hani et al. (2017) examined a simple basin type solar still integrated with a cooling fan and a flat plate collector. The flat plate collector is used to preheat oil which further exchanges heat indirectly with the basin water. This modification resulted in increasing freshwater productivity by 50%. Nagarajan et al. (2017) observed an improvement in still productivity by blowing air on the entire outer surface of glass cover of a pyramid solar still. Morad et al. (2015) experimentally compared the performance of a double-slope active solar still with and without glass cooling. The result showed 28.9% increase in productivity and 23.5% increase in internal thermal efficiency using glass cover cooling.

The present literature on solar stills indicated that the use of fins, wicks and solar collectors increases the still productivity in comparison with simple basin type solar stills. Also, the use of ETC resulted in attaining higher basin water temperature and the evaporation rate. The prime objective of this study is to further enhance the freshwater productivity of ETC-augmented active solar still by increasing the condensation rate of vapors. In the current experimental study, the effect of glass cover shading and evaporative cooling on freshwater

productivity and efficiency of the still is analyzed. An ETC-augmented solar still is developed with a copper tube heat exchanger installed in still basin. Therminol is used as a heat transfer fluid in ETC and heat exchanger circuit. The glass cover is shaded and cooled partially and fully using wet cotton wick to understand their effect on condensation rate and still performance. The results are compared with a solar still without glass shading and cooling.

2 Experimental setup

In this work, a simple basin type solar still of 0.36 m^2 basin area is constructed for the experimentation at NIT Kurukshetra (29.9490°N, 76.8173°E), India. The still is integrated and modified with evacuated tubes and a copper tube heat exchanger. The still basin is made up of galvanized iron sheet. The heat exchanger and still basin are painted black for most absorption of sun's radiations. To curtail the energy losses from still to the atmosphere, 30 mm thick glass wool insulation is utilized. The outside layer of solar still is made from 20-mm-thick wooden ply board. The inclination of glass cover equals latitude angle of the location. The salinity of feed water is 3.2%, and to keep the desired water depth of 4 cm all through the experiments, a saline water storage tank of capacity 40 l is used in the experimental setup. The schematic diagram of the experimental setup is shown in Fig. 1.

Silicon sealant is used to avert vapor leakage between inclined glass cover and still edges. ETC consists of similar-sized evacuated tubes which are connected to a stainless steel header. Therminol is utilized as a working fluid is heated in ETC and circulated through heat exchanger via header and flexible PVC connecting pipes. The header is well insulated with glass wool insulation, and connecting pipes are insulated with 10-mm-thick polyolefin foam insulation. The copper tube heat exchanger situated in still basin is inclined at 10° for smooth and efficient functioning of thermosyphon. Due to this, a minimum water depth of 4 cm is required for complete immersion of heat exchanger in basin water. The photograph of experimental set-up is shown in Fig. 2. The technical specifications of the experimental setup are mentioned in Table 1.

A steel expansion tank is located at inlet of heat exchanger to liberate additional pressure evolved in the pipes. Working fluid heated at high temperature in ETC flows past the heat exchanger by free convection transferring heat to the basin water. The inclined glass cover is evaporatively cooled and shaded to 1/4th, 1/2nd, 3/4th and full area using wet cotton wick to increase the condensation rate of vapors formed inside the still as shown in Fig. 3. The dates on which different experiments conducted are given in Table 2.

All experiments are performed in October 2018, and experimental data are recorded from 9 a.m. to 6 p.m. The experiments are conducted at same water depth of 4 cm. The experimental data are obtained in the form of basin water temperature, glass temperature, ambient temperature and hourly freshwater productivity. Also, the temperature values at various points in the system, namely heat exchanger inlet, outlet and header inlet–outlet, are noted down every hour.
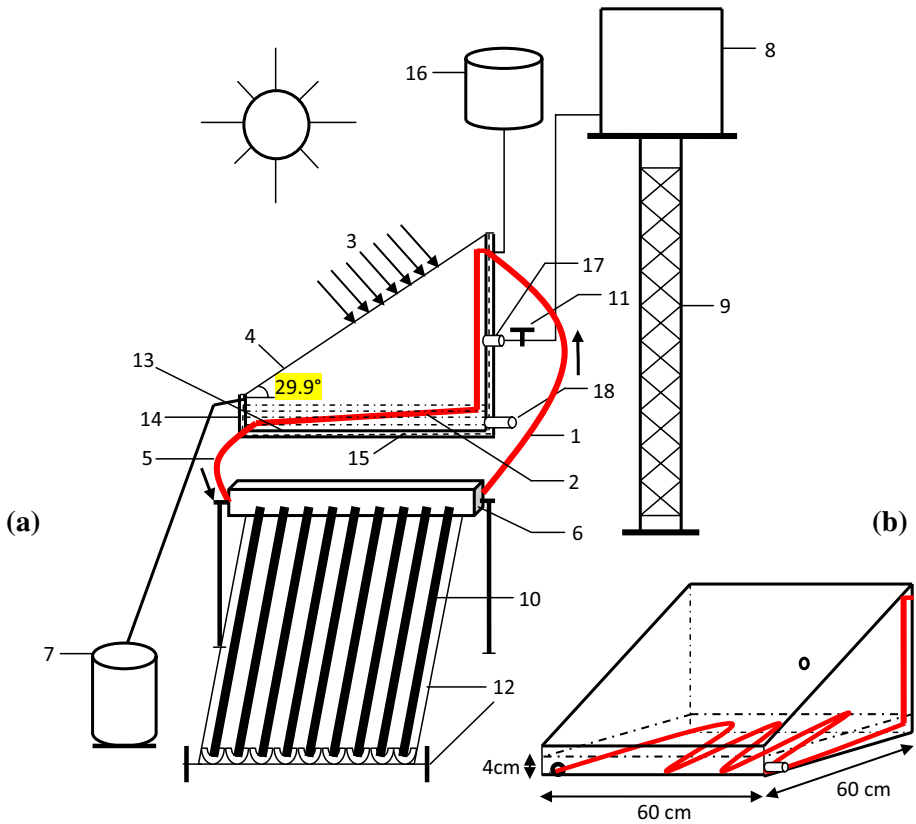
Fig. 1 **a** Schematic diagram of modified still: 1—header outlet pipe; 2—copper tube heat exchanger; 3—solar radiations; 4—glass cover; 5—header inlet pipe; 6—header; 7—freshwater container; 8—saline water storage tank; 9—stand of storage tank; 10—evacuated tube; 11—flow control valve; 12—ETC stand; 13—still basin; 14—wooden box; 15—glass wool insulation; 16—expansion tank; 17—saline water inlet; 18—hot brine outlet; **b** schematic diagram of heat exchanger installed in still basin

3 Error analysis

In the current study, the error or uncertainty in results is estimated using the method presented by Holman and Gajda (2001). Let us assume a measurement set for measuring a total of '*n*' variables. These measurements are utilized to determine the coveted results from experiment (*E*).

Therefore,

$$E = E\left(X_1, X_2, X_3 \ldots X_n\right) \tag{1}$$

Let U_R and U_1, U_2, U_3,…U_n are uncertainties in the experimental result and independent variables, respectively. The uncertainty in result is determined by using the following equation as presented by (Holman and Gajda 2001):

$$U_R = \left[\left(\frac{\delta E}{\delta X_1} U_1\right)^2 + \left(\frac{\delta E}{\delta X_2} U_2\right)^2 + \cdots + \left(\frac{\delta E}{\delta X_n} U_n\right)^2\right]^{\frac{1}{2}} \tag{2}$$

Fig. 2 Experimental setup photograph

Table 1 Technical specifications of experimental setup

Parameter	Value
Basin thickness	1 mm
Thickness of insulation	30 mm
Thickness of glass cover	4 mm
Storage tank capacity	50 l
Number of evacuated tubes	15
Insulation thickness of header	30 mm
Insulation thickness of connecting pipes	30 mm
Glass cover inclination	29.9°
Length of evacuated tube	152.4 cm
Expansion tank capacity	5 l
Length of inlet pipe	60.9 cm
Length of outlet pipe	91.4 cm
Effective solar collector area	1.3 m^2
Heat exchanger pipe inner dia.	2.54 cm
Heat exchanger pipe outer dia.	2.64 cm

Equation 2 can be expressed in terms of relative uncertainty as follows:

$$\frac{U_R}{U} = \left[\left(\frac{\delta E}{\delta X_1}\right)^2 \left(\frac{\Delta X_1}{U}\right)^2 + \left(\frac{\delta E}{\delta X_2}\right)^2 \left(\frac{\Delta X_2}{U}\right)^2 + \cdots + \left(\frac{\delta E}{\delta X_n}\right)^2 \left(\frac{\Delta X_n}{U}\right)^2\right]^{\frac{1}{2}} \quad (3)$$
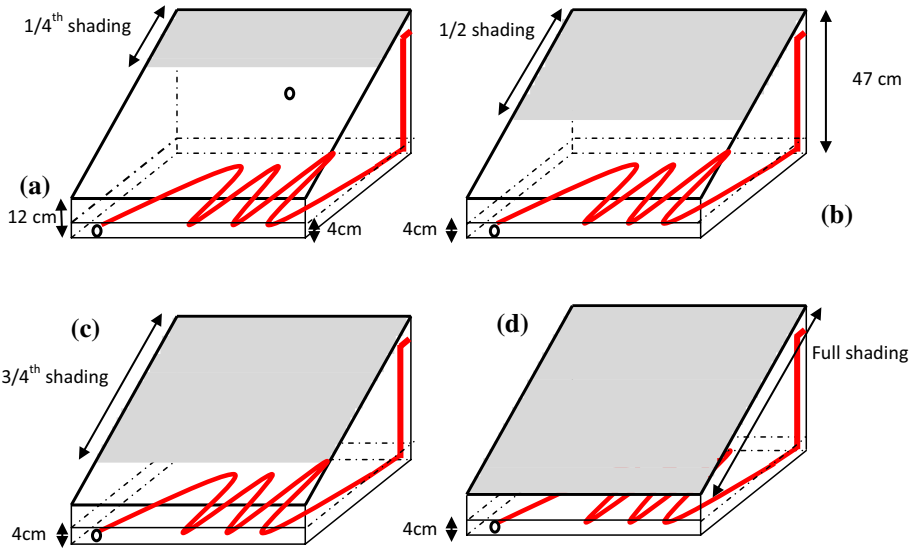
Fig. 3 Glass cover shading and cooling to **a** 1/4th surface area, **b** 1/2nd surface area, **c** 3/4th surface area, **d** full surface area

Table 2 Different dates on which experiments are conducted

Experimental test date	Glass cover shaded and cooled area
October 04, 2018	No shading
October 06, 2018	1/4th area
October 09, 2018	1/2nd area
October 10, 2018	3/4th area
October 12, 2018	Full shading

where U is the dependent variable and $\Delta X_1, \Delta X_2, \Delta X_3 \ldots \Delta X_n$ are absolute uncertainty values. Uncertainty in the experimental result U_R can be determined using Eq. 2 if the relationship between measurement uncertainties of every quantity and measured parameters, and also, the result is known. PT-100 thermocouples (accuracy—± 0.1 °C) are situated at distinct locations in the experimental setup to record temperatures. The temperature values are displayed by using a digital temperature indicator (DTI) unit to which thermocouples are connected. Solar radiation intensity is recorded using a pyranometer (accuracy—± 1 W/m^2), and hourly freshwater output is measured using a cylindrical flask (± 1 ml accuracy) and 2 l capacity. Srithar (2003) calculated the minimum error by dividing least count to the lowest value of measured output. The hourly freshwater output $d = f(y)$, where y is depth of water in the cylindrical flask. The total uncertainty using equation for the hourly freshwater output is represented as follows:

$$U_d = \left[\left(\frac{\delta d}{\delta y_1} U_y \right)^2 \right]^{\frac{1}{2}}$$

(4)

For calculating the total uncertainty for hourly productivity, Eq. (4) can be represented as follows:

$$U_d = \left[\left(\frac{d_i - d_f}{\delta y_1} U_y \right)^2 \right]^{\frac{1}{2}} \tag{5}$$

where d_i and d_f are the initial and final corresponding values of hourly productivity for any one time interval at the constant water depth of 4 cm. Substituting the values in Eq. (5), we have:

$$U_d = \left[\left(\frac{180 - 320}{4} \times 0.025\% \right)^2 \right]^{\frac{1}{2}} = 0.875\% \tag{6}$$

where U_y is the percentage uncertainty in hourly productivity measurement and is equal to 0.025%. Using the above analysis, the percentage error or resulting uncertainty in average daily productivity measurement is approximately $\pm 1.5\%$. Considering %errors in solar intensity measurement as 1% and different temperatures measurement as 0.2%, the total uncertainty is calculated as around $\pm 2.5\%$.

4 Results and discussions

Experimental examination is carried out covering various parameters, namely radiation intensity, ambient, glass cover and basin water temperature at 4 cm saline water depth. An ETC is used to provide additional heat to the basin water through a heat exchanger which is installed in the still basin. This modification increases the basin water temperature and its evaporation rate. The heat exchanger is inclined at 10° for smooth operation of thermosyphon. The minimum water depth at which heat exchanger is completely immersed in water is 4 cm. Water depth is the most important parameter that affects still output. The maximum freshwater output is obtained at lowest possible water depths (Elango and Murugavel 2015; Abderachid and Abdenacer 2015). To increase the condensation rate of the active solar still, the glass cover is shaded and evaporatively cooled to different areas. Cooling the glass cover increases the temperature difference between the basin water surface and inner glass cover and enhances the rate of condensation. Five different cases, namely no shading, 1/4th shading, 1/2nd shading, 3/4th shading and full shading of inclined glass cover, are experimentally studied on October 04, 2018, October 06, 2018, October 09, 2018, October 10, 2018 and October 12, 2018. The shading and cooling of glass cover are done after 12 noon for all cases. This is because the thermosyphon in ETC becomes fully effective and operational after 12 noon. Therefore, glass cover of solar still in all cases is entirely exposed to the solar radiations to absorb maximum sun's energy up to 12 noon. The still productivity largely depends on the environmental state of the location like radiation intensity and ambient temperature.

Figure 4 shows the hourly variation in radiation intensity, and Fig. 5 shows the hourly variation in ambient temperature on five different testing days. It is observed from the experiments that the value of radiation intensity rises before noon, reached topmost values at around 2 p.m. and finally decreases at the end of the day. The ambient temperatures reach the maximum values later between 2 p.m. and 3 p.m. Experimental results shown in
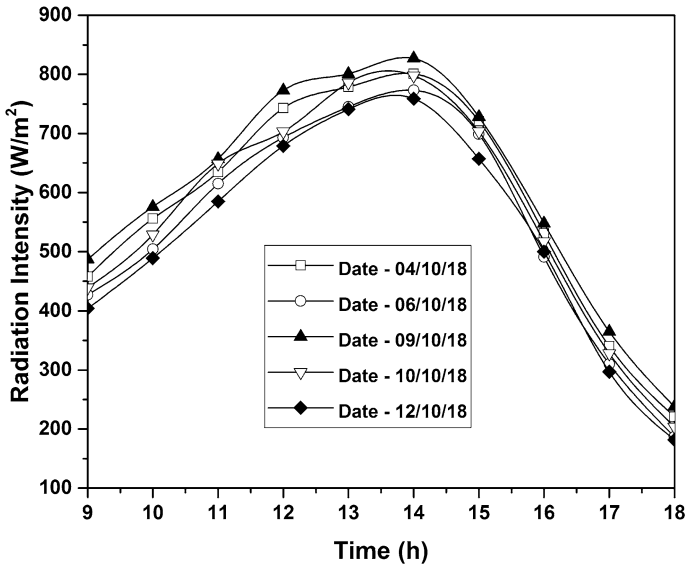
Fig. 4 Hourly variation in radiation intensity on different testing days
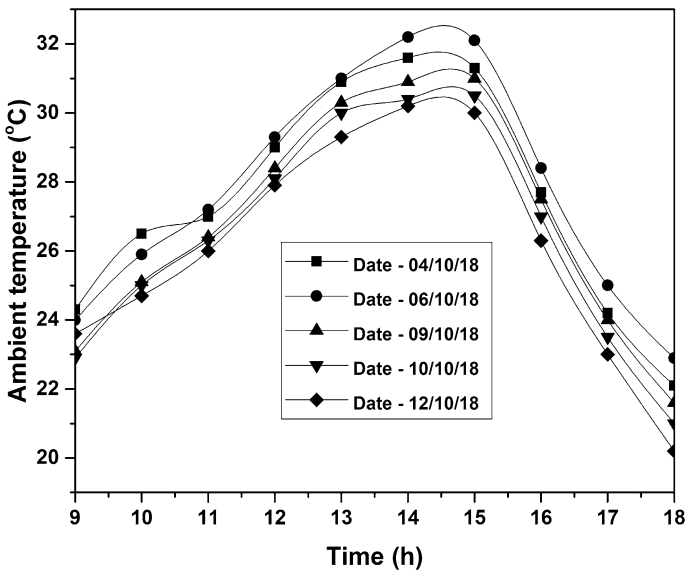

Fig. 5 Hourly variation in ambient temperature on different testing days

Figs. 6 and 7 indicates a rise in basin water and glass cover temperatures with time reaching a highest value in the afternoon around 2 p.m. and starting declining afterward.

Reason behind this is the increase in radiation intensity in the morning time with the maximum values reaching around early afternoon hours and then dropping in the late afternoon. Results indicate that the basin water and glass cover temperatures of still
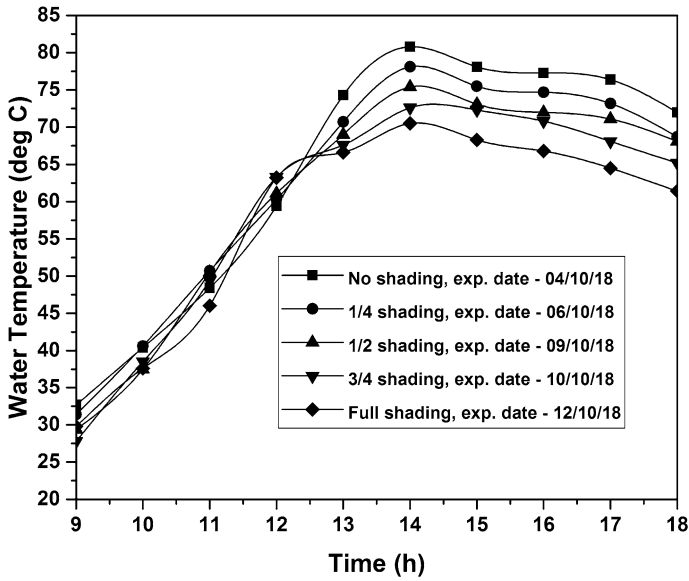
Fig. 6 Hourly variation in basin water temperature for different cases
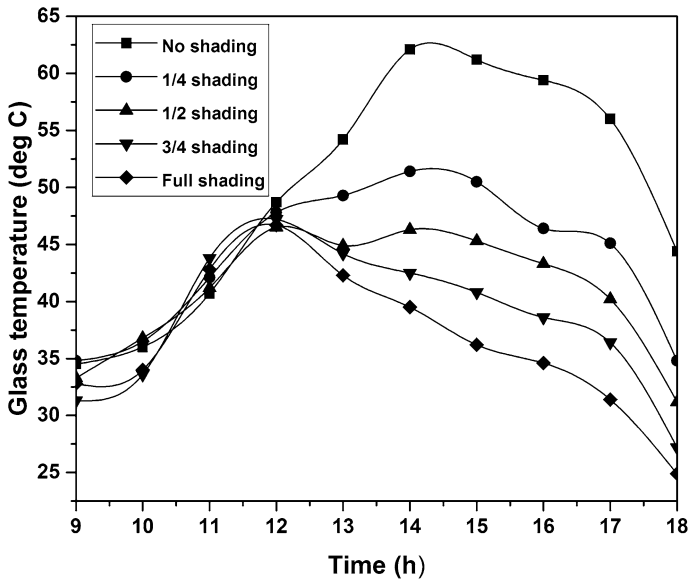
Fig. 7 Hourly variation in glass cover temperature for different cases

without shading of glass cover reached highest values at 80.8 °C and 62.1 °C, respectively. This is because the shading and cooling of glass cover decreased the amount of solar radiations entering the still basin in all other cases. Also, glass temperature decreases in all other cases due to evaporative cooling. This accordingly ushered to a rise in basin water and glass cover temperatures of solar still without glass shading. Up
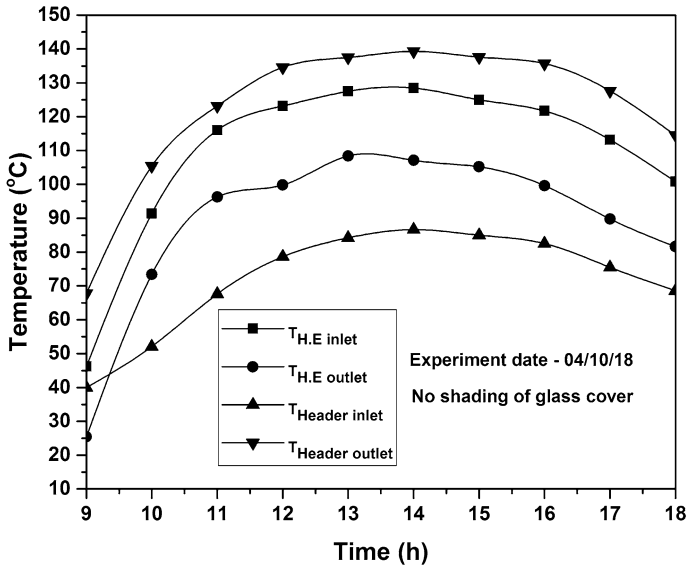
Fig. 8 Hourly variation in heat exchanger and header inlet–outlet temperatures for no glass cover shading
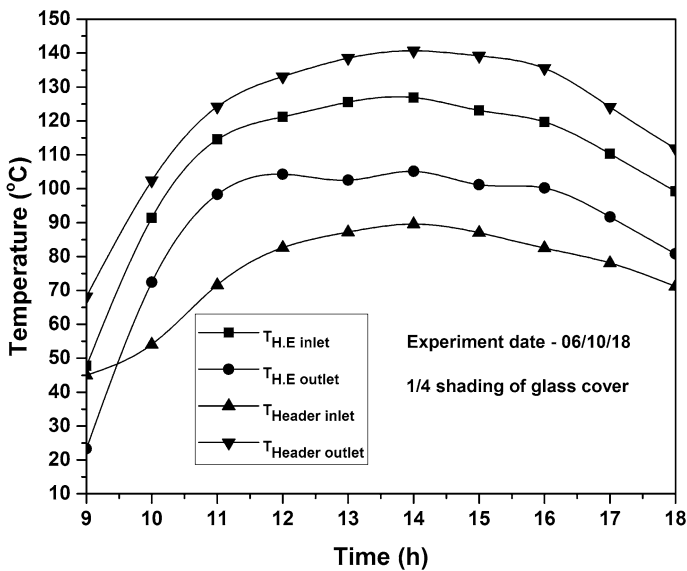
Fig. 9 Hourly variation in heat exchanger and header inlet–outlet temperatures for 1/4th glass cover shading

to 12 noon, the basin water and glass temperatures are nearly same for all cases. The basin water and glass temperatures drop down to lower values as shading and cooling area increases. Figures 8, 9, 10, 11 and 12 show the temperatures of header inlet, header outlet, heat exchanger inlet and heat exchanger outlet for all five cases. The differences in header inlet–outlet and heat exchanger inlet–outlet temperature values
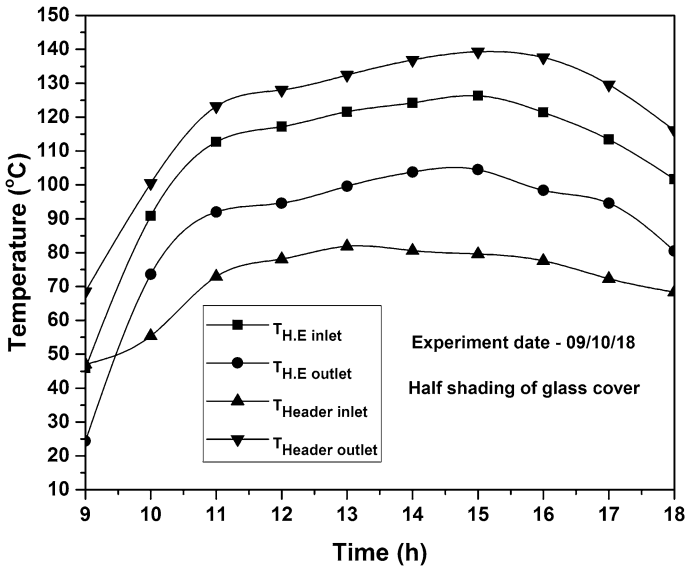
Fig. 10 Hourly variation in heat exchanger and header inlet–outlet temperatures for 1/2nd glass cover shading
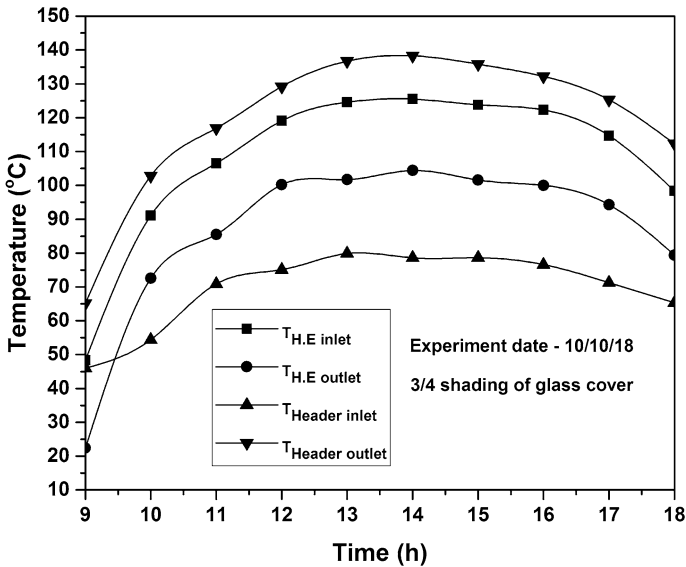

Fig. 11 Hourly variation in heat exchanger and header inlet–outlet temperatures for 3/4th glass cover shading

for all cases are very small as they are independent of the shading and cooling effects of the glass cover. The maximum header outlet and heat exchanger inlet temperatures are found to be 139.3 °C and 124.9 °C for the case of 1/2nd glass cover shading and
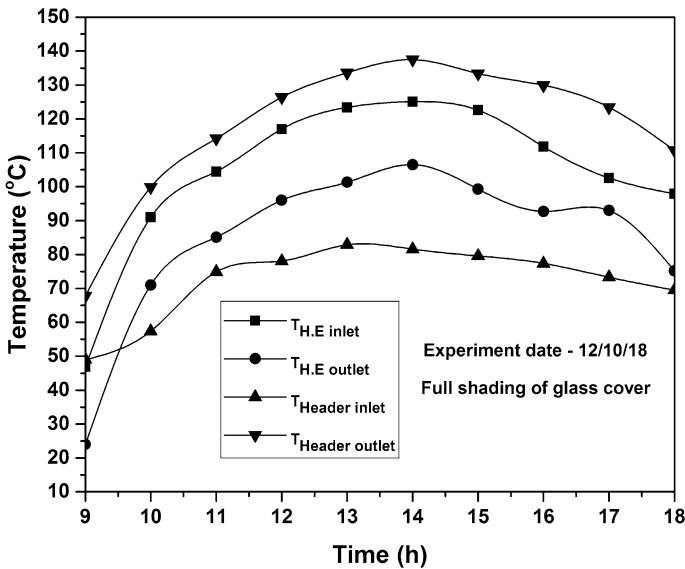
Fig. 12 Hourly variation in heat exchanger and header inlet–outlet temperatures for full glass cover shading

cooling. This difference in header outlet and heat exchanger inlet temperatures are due to heat losses from connecting pipes that are evident in other cases as well. Although the connecting pipes are well insulated, there is always some heat loss from oil to the surroundings due to high temperature difference between the two. Also, the effect of glass shading and cooling on the rate of heat transfer from the oil in heat exchanger to the basin water is little. Therefore, in all cases the temperature difference between heat exchanger inlet and outlet is small as clearly shown in Figs. 8, 9, 10, 11 and 12.

Freshwater productivity (416 ml) is observed to be highest in case of ½ shading of glass cover as shown in Fig. 13. This is due to the greater ability of both evaporation and condensation rates in ½ shading of glass cover. As the shaded area increases, the evaporation rate decreases to higher values than increase in condensation rate due to lesser amount of solar radiations entering the still. This resulted in an overall decline in freshwater productivity for 3/4th shaded and fully shaded cases. It is also observed from the experiments that the freshwater productivity continues for few hours after 6 p.m. as high temperature of basin water is maintained due to good heat storage capacity of oil in heat exchanger.

Figure 14 shows that the highest accumulated productivity (2114 ml) is achieved for a solar still with ½ shaded glass cover from 9 a.m. to 6 p.m. which is 16.4% higher than without glass cover shading and cooling case. It is followed by the accumulative productivities of solar still with 1/4th shaded glass (1954 ml), without shading (1815 ml), 3/4th shading (1565 ml) and full shading (1343 ml). The productivities using ½ glass cover shading and cooling are higher by 8.2%, 35% and 57.4% in comparison with 1/4th, 3/4th and full glass shading and cooling, respectively. Suneesh et al. (2014) achieved the freshwater productivity of 4300 ml/m² day using a wet cotton gauze spread over the glass cover for cooling. Sharshir et al. (2017) reported a 47.8% increase in productivity using water flowing over the glass surface for cooling. Bani-Hani et al. (2017) observed a rise of 50% in freshwater productivity using a fan for glass cooling and oil in heat exchanger for heating
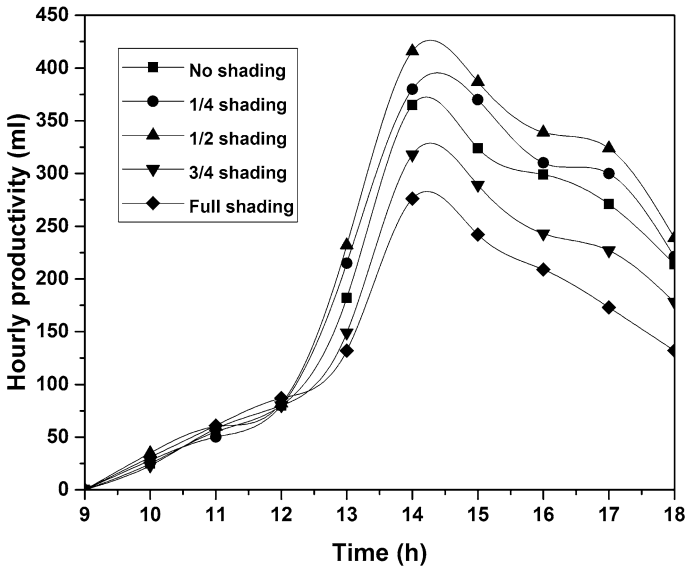
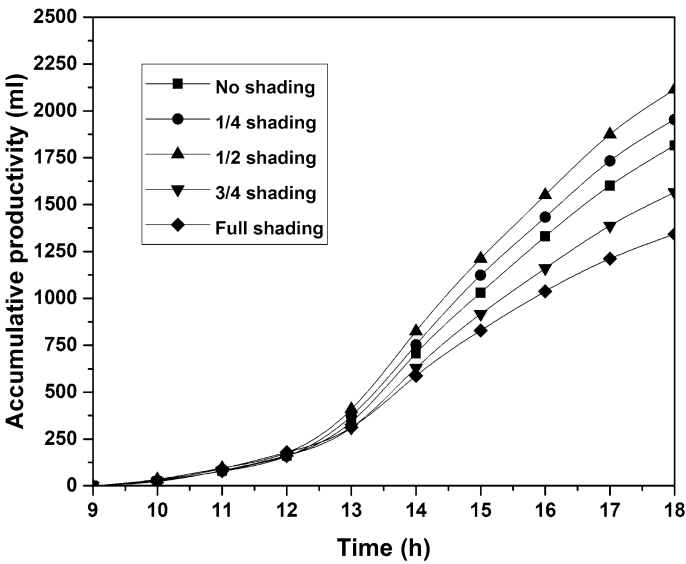**Fig. 13** Hourly variation in freshwater productivity for all cases

Fig. 14 Accumulative freshwater productivity variation for all cases

basin water in a flat plate collector-integrated solar still. The efficiency of this active solar still is calculated using the following formula:

$$\eta_a = \frac{\sum m_h \times h_{fg}}{(\sum I_s \times A_b + \sum I_e \times A_e) \times 3600} \tag{7}$$
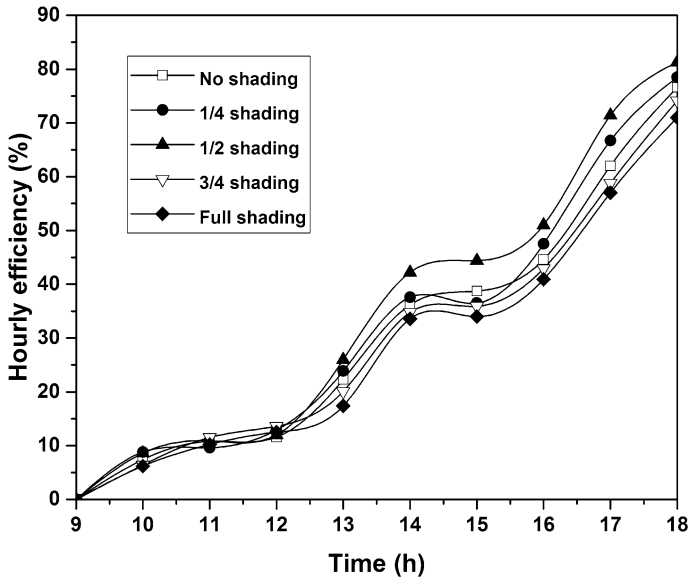
Fig. 15 Hourly variation in thermal efficiency for all cases

where m_h is the hourly distillate in (kg/s), h_{fg} is the latent heat of water vapors in (kJ/kg), I_s is the solar intensity entering the still in (W/m^2), A_b is the still basin area in (m^2), I_e is the solar intensity falling on evacuated tubes in (W/m^2) and A_e is the area of ETC in (m^2). The hourly efficiency is observed to be lower in the morning time as shown in Fig. 15 due to low productivity and moderate solar intensity. Also, the hourly efficiency is higher in the late afternoon hours due to high freshwater output and decreased input solar radiations as shown in Fig. 15. The maximum overall daily efficiency (38.3%) is obtained for a solar still with ½ shading of glass as shown in Fig. 16.

This is due to high freshwater output and comparatively low overall heat input. Therefore, ½ shading and cooling of glass cover of a solar still are proved to be more productive and efficient in comparison with all other cases. From the results obtained, it can be inferred that different calculated parameters had a remarkable impact on freshwater productivity from the still. Moreover, experimental results show least freshwater output during morning and before afternoon periods due to less heating of water. The saline water feed to the still basin is at low temperature in the morning and takes more time to heat up. Also, thermosyphon in the ETC and heat exchanger started working to its best potential in the early afternoon hours. Generally it is observed for all cases that the highest freshwater productivity was obtained in the afternoon hours at around 2 p.m. The water productivity from the system continues to be moderate up to 4 p.m. and it then started decreasing gradually till the evening. Moreover, in the current study, the experimental comparison of evacuated tube-integrated solar still (SS) with solar still without evacuated tubes is also made on October 04, 2018. The results indicated a considerable rise in water temperature and productivity of evacuated tube-integrated solar still in comparison with solar still without evacuated tubes. Both the solar stills are of exactly same dimensions, and the photograph of simple basin type solar still and evacuated tube-integrated solar still is shown in Fig. 17.

The hourly variation in water and glass cover temperatures for both stills is represented in Fig. 18. The highest water temperature (T_w) and glass cover temperature (T_g) of solar
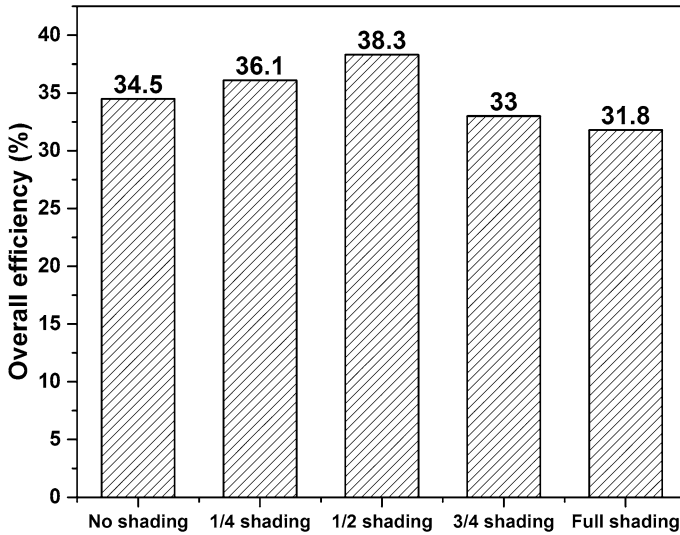
Fig. 16 Overall daily efficiency for all cases

Fig. 17 Photograph of simple basin type solar still and evacuated tube-integrated solar still

still without using evacuated tubes were obtained as 66.6 °C and 51.4 °C at 2 p.m. which is 14.2 °C and 10.7 °C less than those of solar still with evacuated tubes, respectively. Figures 19 and 20 show maximum hourly and accumulative freshwater productivity values of solar still without using evacuated tubes as 165 ml and 789 ml, respectively. These values are 121.2% and 130% lower than those of solar still with evacuated tubes. This is because evacuated tubes
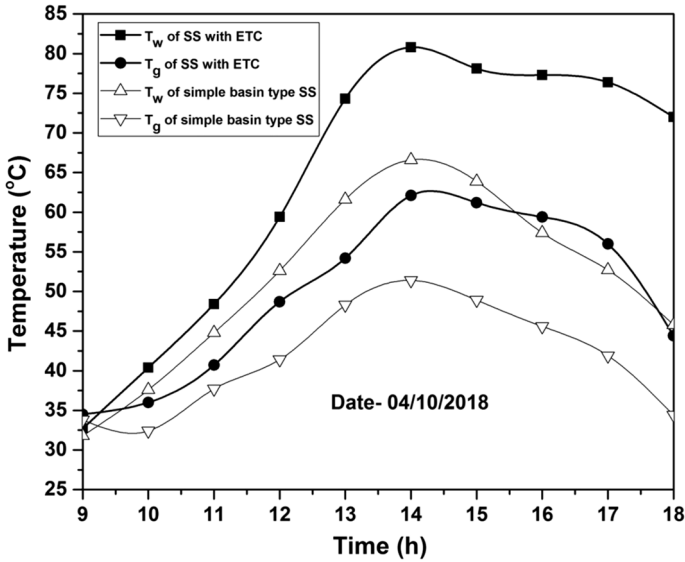
Fig. 18 Hourly variation in water temperature and glass temperature for solar still with and without evacuated tubes
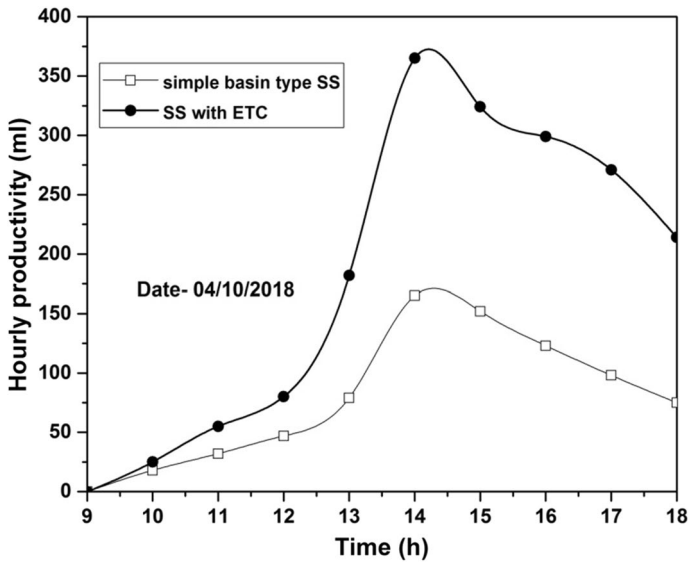

Fig. 19 Hourly productivity variation for solar still with and without evacuated tubes

provide extra heat to the basin water by thermosyphon which enhanced the water temperature, its evaporation rate and hence the freshwater productivity. The overall efficiency of solar still without evacuated tubes (η_s) is calculated using the following expression:
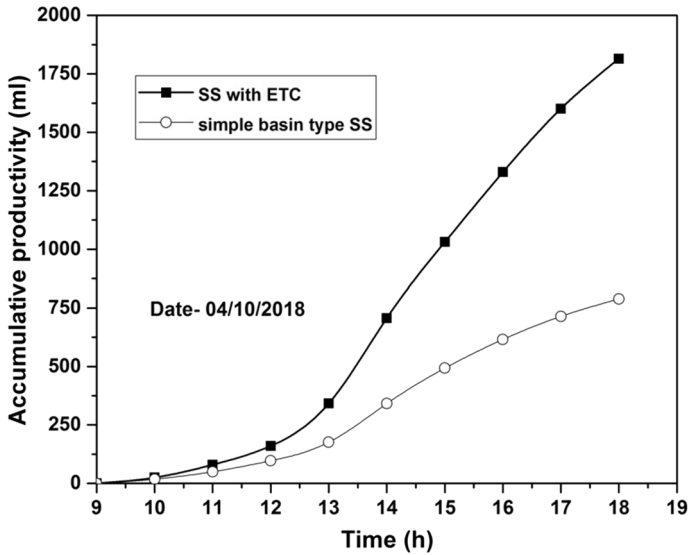
Fig. 20 Accumulative productivity variation for solar still with and without evacuated tubes

$$\eta_s = \frac{\sum m_h \times h_{fg}}{(\sum I_s \times A_b \times 3600)} \tag{8}$$

where m_h is the hourly distillate in (kg/s), h_{fg} is the latent heat of water vapors in (kJ/kg), I_s is the solar intensity entering the still in (W/m^2) and A_b is the still basin area in (m^2), The overall efficiency of solar still without evacuated tubes is calculated as 33.1% which is lower than only 1.4% in comparison with solar still with evacuated tubes.

5 Conclusions

An experimental investigation was conducted on an ETC-integrated solar still working on thermosyphon at 4 cm water depth. Experiments were carried out on different days to examine the effect of glass cover shading and cooling on the solar still performance. The glass cover is shaded and cooled to 1/4th, 1/2nd, 3/4th and full surface area using wet cotton wick, and the performance of these four cases was compared with solar still without glass shading and cooling. On the basis of experimental results, the following conclusions are drawn in this study:

- The hourly variation in solar intensity and ambient temperature values was nearly same on all experiment days. The maximum productivity is achieved at high-solar intensity hours.
- The use of glass cover shading and cooling to ½ surface area resulted in productivity enhancement of 8.2% in comparison with 1/4th shading and cooling of still. Further

shading and cooling of glass cover to 3/4th and full surface areas decreased the productivity of the still by 35% and 57.4%, respectively.

- The maximum freshwater productivity and overall efficiency for the active solar still were 2114 ml/day and 38.3%, respectively, in case of ½ shading and cooling of glass cover. This marked a respective increase of 16.5% and 3.8% in comparison with that without glass shading and cooling case.
- The highest basin water temperature of 80.3 °C is achieved when no shading and cooling were applied to the glass cover.
- The freshwater output and overall efficiency of evacuated tube-augmented solar still are 130% and 1.4% higher than the solar still without evacuated tubes.
- There was no considerable effect of glass shading and cooling on the performance of heat exchanger installed inside the still basin.

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