SSRG International Journal of Mechanical Engineering
ISSN: 2348-8360/ https://doi.org/10.14445/23488360/IJME-V10I9P101

Volume 10 Issue 9, 1-17, September 2023

Original Article

Experimental Performance Assessment of Two Identical Single Basin Solar Stills Differing in Cover Slope Angle

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Received: 06 July 2023 Revised: 19 August 2023 Accepted: 08 September 2023 Published: 30 September 2023

Abstract *- Two identical single-basin single-slope solar stills differing in cover slope angles, viz. 10° and 27° have been tested simultaneously under the local climatic condition of Jorhat (Assam), India, with latitude 26.7509° N, and their performance has been compared. It has been found that the 10° solar is still more efficient than that of the 27° solar. This also conforms to the previous research claiming that 10° solar is still more effective irrespective of geographic region. The distillate quality is also tested in the Public Heath Engineering Laboratory, Jorhat (Assam) and distillate is found to be free from fluoride, chlorine, and arsenic, and the TDS level is also within acceptable limits. Moreover, the yield water is also free from bacterial contamination and safe for use.*

Keywords **-** *Distillation, Renewable energy, Solar energy, Solar still, Water distillation.*

1. Introduction

Solar stills are simple devices that work on the principle of the greenhouse effect. Solar radiation evaporates the raw or salty water in the basin, and the evaporated water molecules are condensed on the inner surface of the condensing cover. The condensed water droplets adhering to the cover surface move towards the bottom of the condensing body under gravity, trickle down on a collection trough and collect in an outside container connected to the collection trough. Figure 1 shows a typical single-basin single-slope solar still working in passive mode.

The effectiveness of solar stills lies in the fact that the water present in the basin is only evaporated, which requires a lower temperature than the boiling temperature of the water, and the evaporated vapour, when it leaves the water surface, also leaves behind all the solid impurities and heavy metals present in the salty water. The direct solar radiation exposure also kills the microorganisms in the salted water. As such, the output is pure potable water. Ward [40] has observed a decrease in sea water's Total Dissolved Solids (TDS) value from 35,000 ppm to 1-2 ppm in the distilled water obtained using solar still. Besides this, the distillation process in solar still working in passive mode does not leave any carbon footprint as it uses only solar energy.

The performance of a solar still can be expressed either in terms of Efficiency (η) or in terms of Conversion Ratio (CR) [18]. The CR value of 49.4% means that 49.4% of the saline water has been converted into distillate output.

2. Broad Classification of Solar Stills

Based on the mode of operation, solar stills can be divided into two categories: passive solar stills and active solar stills. Active solar stills have attached work-consuming devices to accelerate the heat transfer processes. As shown in Figure 2, the electric pump accelerates the flow of preheated water between the FPC and the still.

But, when this electric pump is removed, the preheated water flows to and from the FPC and is still due to convection current only. This is shown in Figure 3.

The still is placed at a higher level than the FPC from the ground. Also, in the absence of an FPC, if an electric fan is attached inside the solar still to increase the circulation of water vapour [20] or if an external water pump is attached to flow water over the outer surface of the condensing cover to improve the condensation process, then also, the still is said to work on active mode. However, Telkes [34] has commented that the artificial cooling of condenser plates using water spray on the outside surface lowers the device's efficiency.

Another classification of solar stills could be single-stage (or single-effect) and multi-stage (multi-effect) stills based on the number of basins present in the still. Figures 1, 2 and 3 show single-stage solar stills where only one basin is present and the latent heat of condensation is directly released to the ambient air. But, when one basin is stacked over the other, like in two-stage solar still having two basins stacked the other, the bottom of the upper basin acts as the condensing cover to the lower basin, and the latent heat of condensation is re-used to preheat the water contained in the upper basin. Figure 4 shows a typical two-stage solar still working in passive mode. Moreover, solar stills can be classified as single-slope and double-slope solar stills. Figures 1, 2, 3 and 4 show typical single-slope solar stills. But, when two condensing covers are used, one opposite at the same level, as shown in Figure 5, the still is called a double slope solar still.

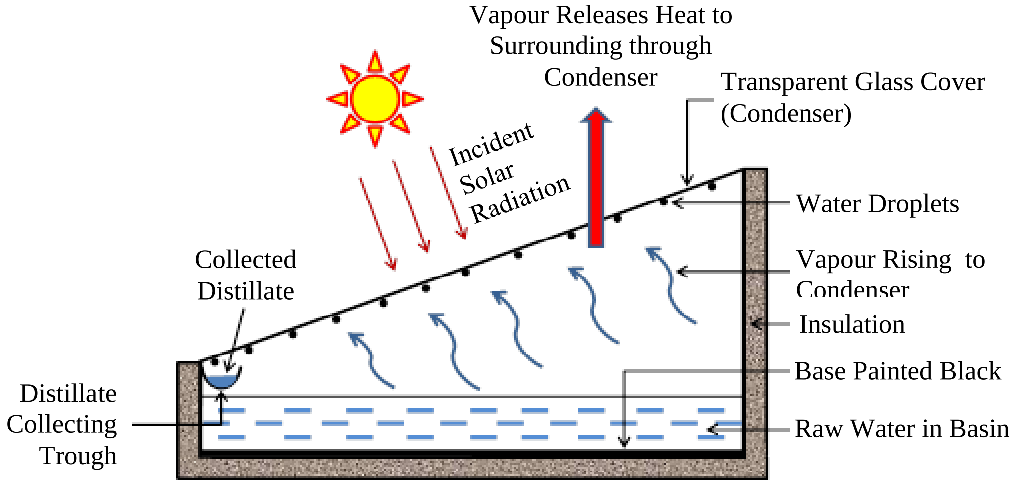

Fig. 1 A typical single-basin passive solar still in operation

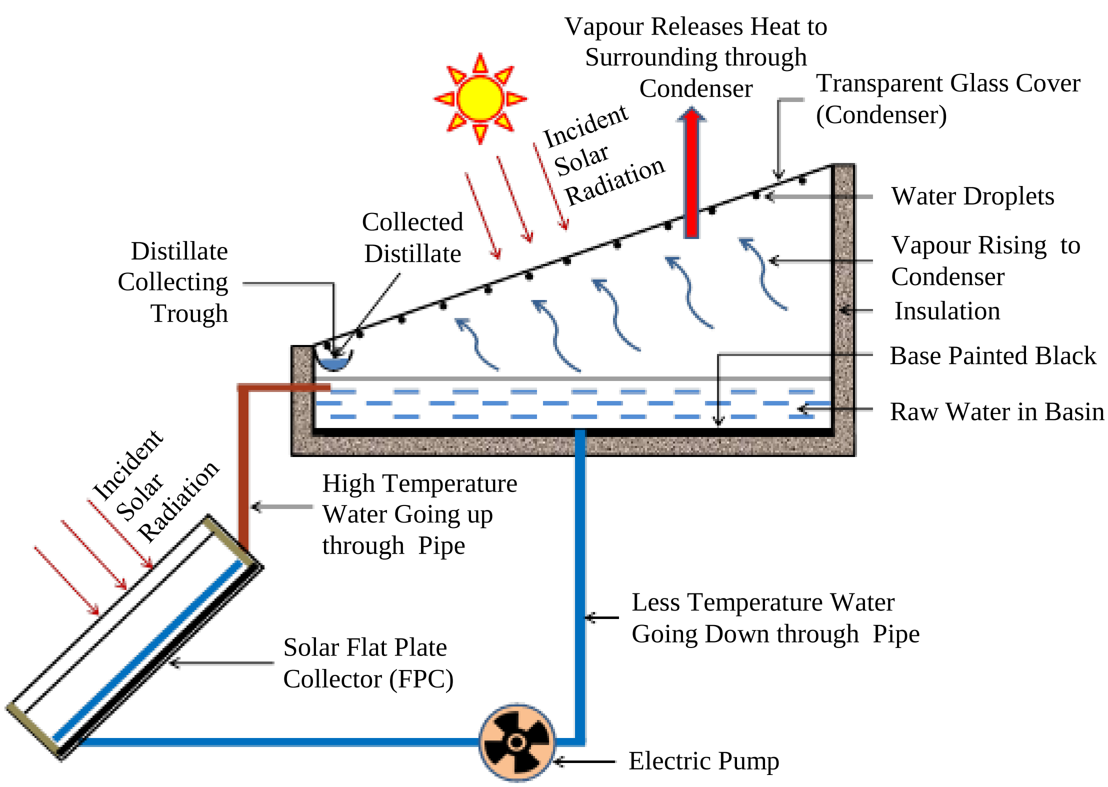

Fig. 2 A single-basin single-slope solar still working in active mode

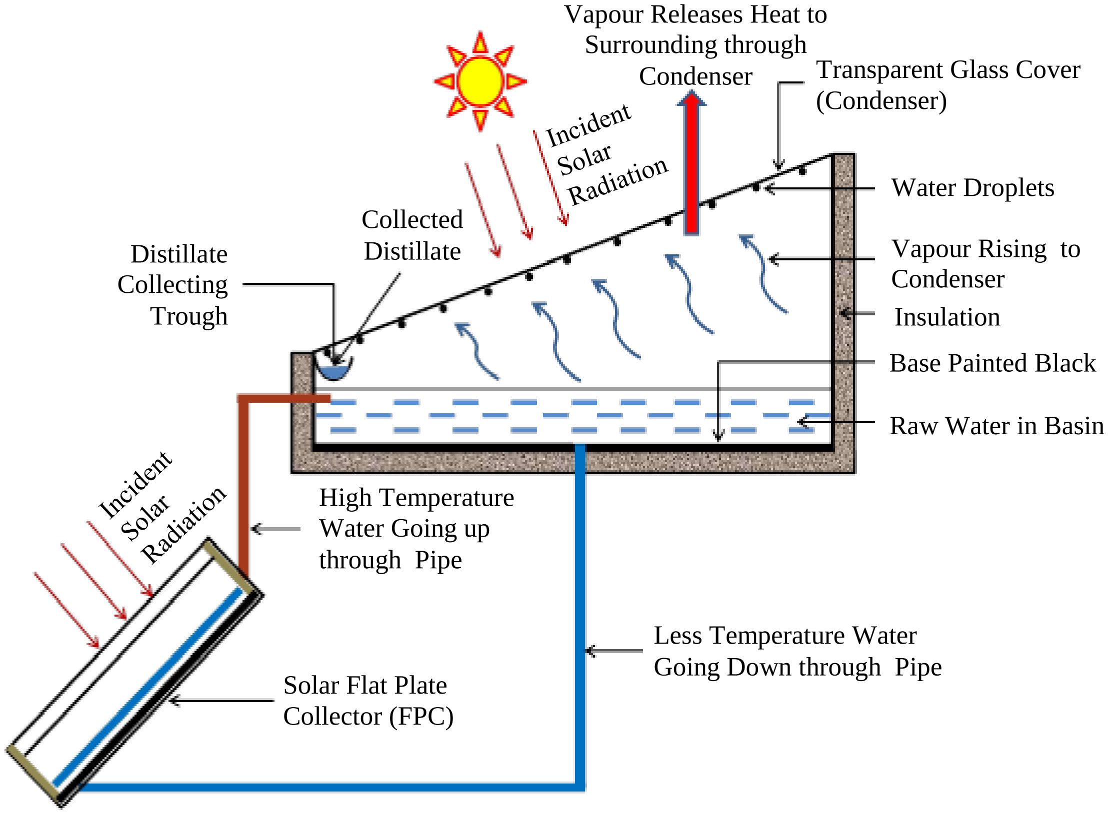

Fig. 3 A single-basin single-slope solar still working in passive mode

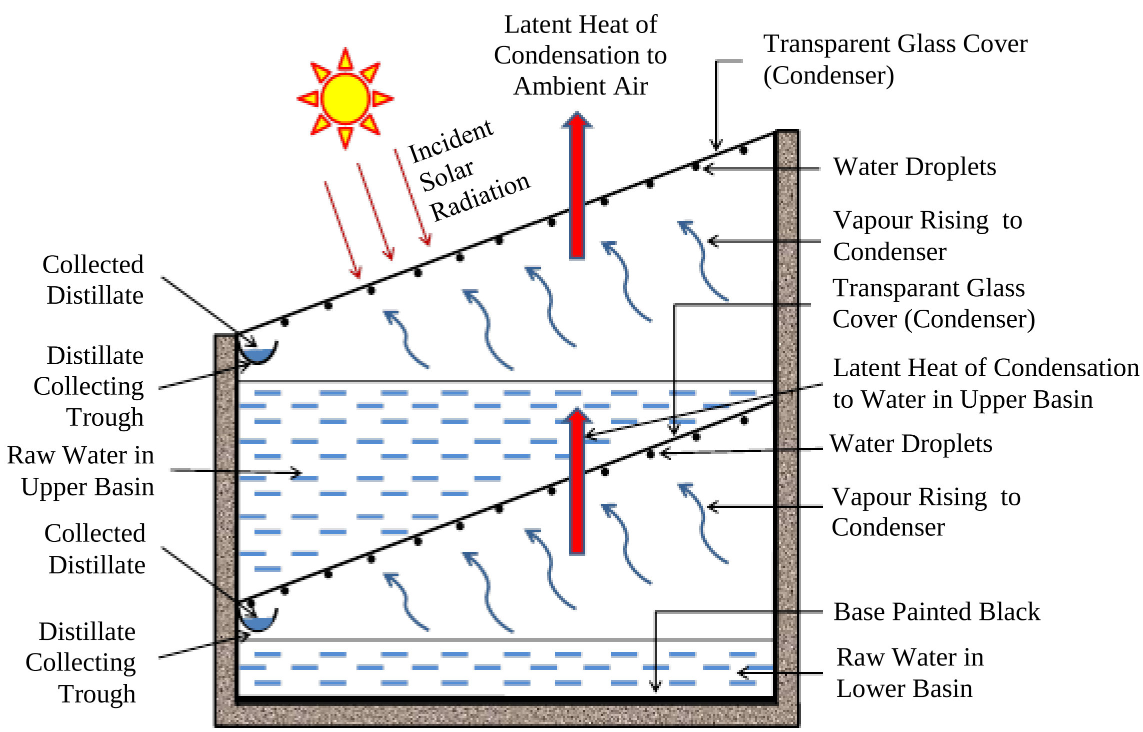

Fig. 4 Two-stage solar still working in passive mode

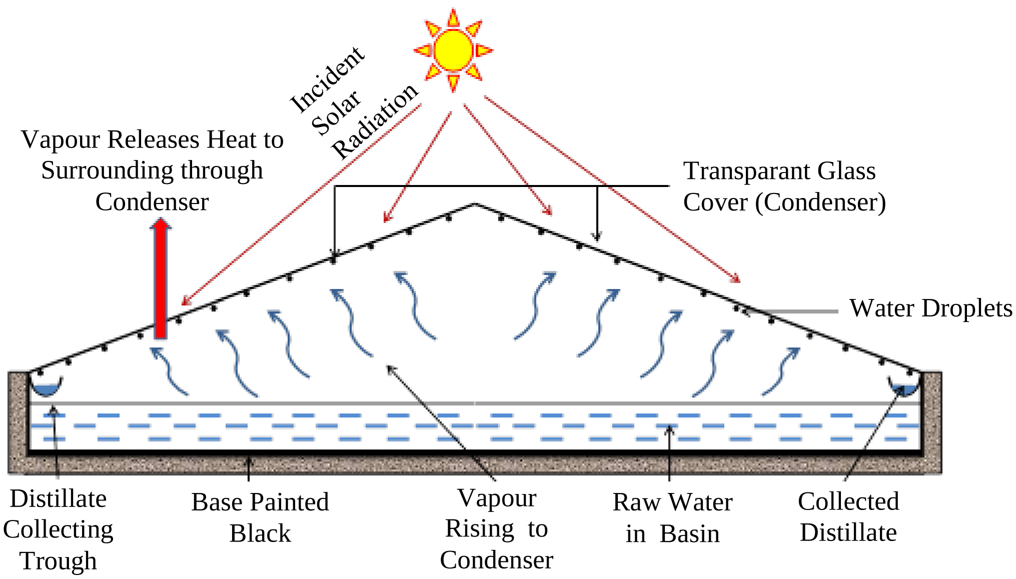

Fig. 5 Double-slope solar still working in passive mode

3. History of Solar Stills

The previously published literature found that solar stills' use dates back to the 16th century. The first solar still plant was constructed in 1872 at Las Salinas in Northern Chile. The still basins were wood, and the combined total basin area was 51,000 sq. feet. This desalination plant supplied drinking water to a nearby mining community and was found to work at an efficiency of 30%.

It was only during World War II that the solar stills received much attention from researchers, and much research was performed to make portable and more efficient solar stills. Approximately 2,00,000 inflatable solar stills were manufactured and kept in the life rafts for use by US Navy sailors during emergencies. These stills were found to work at an efficiency of 50%-60%.

4. Literature Survey

Solar energy is a low-grade, low-density thermal energy [10]. The concept of an ideal solar still was given by Cooper [10]. Such a solar still has no conductive losses. The water depth is sufficiently tiny that it minimizes the sensible heat storage in the water mass, and this heat storage effect is negligible compared to the energy transfer rates to and from the water. For a given ambient temperature value, wind velocity and solar radiation rate, an ideal still instantaneously reaches the steady state condition.

A standard still will cease to produce distillate during the night when there is no solar radiation. As understood by reading the work published by Ghoneyem and lleri [14], increasing the condensing cover thickness decreases the output. The amount of yield can be increased by increasing the transmissivity of the cover glass, and the impact of the thickness of the cover glass on the output is more than that of the transmissivity. The authors have also commented that Plastic should not be used as the condensing cover unless it is mechanically treated for thermal stability under solar heating and has a high degree of wettability. Otherwise, fogging will happen on the inside surface of the plastic cover and water droplets will drop back into the water in the basin.

Therefore, the surface of the condenser plate should be kept clean and water-wettable, e.g., a glass of window grade; otherwise, fogging may happen, which will increase the reflection and scattering of the incident solar radiation [34, 35].

The condensing cover used by Sodha et al. [31], Madani and Zaki [24], Kumar and Tiwari [21], Toure and Meukam [38], El-Bahi and Inan [13], Al-Hayek and Badran [3], Badran and Al-Tahaineh [8], Taamneh and Taamneh [33] and Kianifar et al. [20] are clear glasses with thickness ranging from 3 mm to 6 mm and transmissivity around 0.88.

4.1. Angle of Inclination for the Condensing Cover

Telkes [34] mentioned that the amount of transmitted radiation decreases when the angle of incidence of solar radiation on the condensing cover is less than 50°. Nearly 90% of the total incident solar energy gets transmitted through the condensing surface at normal or near-normal incidence.

Moustafa et al. [25], citing the experimental findings of Datta et al. (1965), have mentioned that when larger cover angles are used, the reflection of solar energy by the glass cover is higher and thermal radiation from the basin to the surface is lower.

Soliman [32] has also mentioned that the output increases with a decrease in the angle of inclination of the cover. However, some researchers found that the glass cover's rise in preference does not affect the output.

Contrary to that, Singh et al. [29] have optimized the glass cover inclination for higher yield in a double slope solar still and mentioned that instantaneous thermal efficiency and the overall thermal efficiency increase with the increase in preference (but < 90°). This is due to the rise of solar radiation on the inclined surface.

Again, Cooper [10] has mentioned that increasing the cover slope will decrease the mean operating temperature of the still. This ultimately results in lowering the efficiencies of the still. The incidence of solar radiation on a surface would be maximum if the surface is always oriented perpendicular to the sun's rays. Also, the cover glass's reflectance increases with the incidence angle.

However, Cooper and Read [11] have stated that the cover slope minimally affects thermal performance for pitches up to 60°. For structural stability and good distillate discharge, cover slopes should be as small as possible (around 10°).

Sodha et al. [31] have designed multiple wick solar stills where blackened jute cloths form the liquid surface, and 3 mm thick window-grade glass is placed parallel to the wick surface as the cover of the still. Analyzing the experimental results, the authors have mentioned that solar efficiency can still be increased by placing the transparent glass cover parallel to the water surface to minimize reflection losses. Still, efficiency can be increased by placing the water surface at an optimum inclination angle to receive maximum solar radiation.

Cover slope angles used by Hollands [17], Kumar and Tiwari [21], Toure and Meukam [38], and Ghoneyem and lleri [14] are 10°, 15°, 16° and 20° respectively, which were more petite that the latitude values of the place of experimentation. Whereas Singh and Tiwari [30], Aybar and Assefi [7], Kianifar et al. [20], and Patel and Kumar [26] have used cover slope angles of 28.25°, 35°, 36° and 23° which are equal to the latitude of the test location.

As such, from the research mentioned above works, there are two types of beliefs: first, the cover slope inclination should be slight for optimum performance of the still irrespective of the geographic region, and second, the cover slope angle should be equal to the latitude of the test region.

Again, in the research work published by Al-Hinai et al. [4], it is mentioned that, during winter months, an increase in cover tilt angle increases the yield, whereas, during summer months, an increase in body tilt decreases the output. As per the authors, this happens because the declination angle δ has negative values in winter and positive values in summer. A positive δ-value increases the reflectivity of the incident radiation on the cover as the cover angle decreases.

4.2. Still Orientation

In the research works performed by El-Bahi and Inan [12], El-Bahi and Inan [13], and Kumar et al. [22] in the places situated in the Northern Hemisphere, all the single-slope stills were placed facing the South direction.

Badran and Al-Tahaineh [8] have also experimented with a single slope basin type solar still. The condensing cover was facing the South direction to receive maximum solar radiation. The authors have also commented that tracking the sun is one of the preferred methods to increase the still yield, though this effect is insignificant.

On the contrary, as per Gupta et al. [16], the input end should face the South in the Southern Hemisphere, and in the Northern Hemisphere, the input end should face the North direction. But Zaki et al. [41], based on the experimental results, have commented that orientation has no significant effect on productivity.

In the case of double slope solar still, Singh et al. [29] have inferred that the East-West orientation gives the maximum yield. In contrast, Akash et al. [2] have found that, in the Northern Hemisphere, distillate obtained from the condensing surface facing North is more than that facing the South. This is because the North face is not directly exposed to sunlight; hence, the outer surface of the condensing cover is more excellent. Thus, the rate of condensation is higher.

Therefore, regarding the orientation of single-slope solar stills, there exist two types of beliefs: one, that the still should be facing the north direction in the Northern Hemisphere, and it should face the south direction in the Southern Hemisphere, and two, that the still should be facing the south direction in the Northern Hemisphere, and it should be facing the north direction in the Southern Hemisphere. The second thought is supported by most of the researchers.

4.3. Effect of Water Depth in the Basin

The heat capacity of water in the pan (basin) and pan material determines the minimum heat required to heat the evaporating pan [34].

As such, shallow water depth is preferable for rapid production of distillate. Higher water depth in the basin is responsible for the higher thermal inertia of the system. To start the distillation process, it requires more solar energy to establish the minimum temperature difference between the water and the glass cover. The thermal inertia of the system will be low if a shallow water depth is maintained in the basin and helps to achieve this temperature difference quickly at a lesser solar energy input to the system [17].

Also, lower basin water depth decreases the thermal storage effect [10]. This is true for both passive and active solar stills. Opposite to this, the internal heat loss coefficient increases with a decrease in water depth in the still basin. This happens because the operating temperature range is maximum for the most minor water depth [36, 37].

Toure and Meukam [38] have also found that the lowest water depth gives maximum total still productivity. Singh et al. [29] have also mentioned that the instantaneous and overall thermal efficiency of the still decreases with an increase in basin water depth. This is because when the water depth in the basin is high, most of the thermal energy gets stored in the water mass instead of being utilized for evaporation.

Such a decrease in the productivity of the solar still and its thermal efficiency with higher water depths in the basin is also observed by Patel and Kumar [26], Al-Hayek and Badran [3], Lawrence and Tiwari [23], Sanjeev and Tiwari [28], Kumar et al. [22], Akash et al. [2], Al-Hinai et al. [5], Badran and Al-Tahaineh [8], and Ismail [18].

Again, to reduce salt deposition on the basin liner, as the water evaporates, the flow rate input of makeup water should be twice the maximum distillation rate [10], [11].

4.4. Effect of Temperature Difference between Basin Water and Glass Cover

For proper evaporation, there must be a minimum temperature difference between the basin area and the glass [17]. The temperature difference between the water and glass cover is the driving potential that controls the evaporation rate in a solar still [27].

Soliman [32] has commented that output still increases with the temperature difference between the water and glass cover. The evaporation rate also increases with the temperature difference between the glass cover and the water in the basin [13]. Cooper [10] has observed a linear relationship between the water-glass temperature difference and the production rate at a given water temperature. Similar observations were also made by Gugulothu et al. [15], Patel and Kumar [26], and Kumar and Tiwari [21].

Valsaraj [39] has mentioned that when the feed water is preheated, the basin water temperature increases, and a higher basin temperature results in a proportionally higher output from the still. But, contrary to this, Al-Hinai et al. [5] have mentioned that the effect of feed water preheating on the still performance is not very prominent. The temperature of the condensing surface can also be decreased by flowing water uniformly over the outer surface of the glass cover [21]. By doing so, El-Bahi and Inan [13] have also observed that the daily yield of the efficiency of the still increases.

The temperature difference between the cover glass and water in the basin increases with increased solar radiation intensity and decreased ambient temperature [14]. Higher ambient temperature causes the still to operate at higher temperatures, reducing the heat losses by convection and radiation; hence, higher efficiency is obtained [17].

Rajvanshi [27] has also mentioned that at higher ambient temperatures, the heat losses from the sides and bottom get reduced, and as such, the distillate output increases. A similar observation is also made by Al-Hinai et al. [5].

However, Kumar et al. [22] have observed that convective and radiate heat transfer coefficients do not significantly depend on the operation temperature. In contrast, the evaporative heat transfer coefficient depends on the operation temperature.

Badran and Al-Tahaineh [8] have mentioned that productivity increases with an increase in the ambient temperature, but up to a specific limit. With further rise in the ambient temperature, the yield starts to decrease.

For a constant mean water temperature, Soliman [32] mentioned that the yield can be increased by conducting experiments at lower ambient temperatures or increasing the cooling rate. The condensing cover's cooling rate can be increased by increasing the wind speed or the exposure area of the condensing surface to the wind.

Ismail [18] has mentioned that Hourly variation of cover temperature, basin water temperature, still productivity, efficiency and distillate yield follows the same trend as solar radiation. Solar radiation increases in the morning hours reaches a maximum value around the noontime, and then decreases in the afternoon.

Hourly variation of the cover and basin water temperatures throughout the day has similar trends. However, the rate of increase and decrease in the cover temperature is faster than that of the basin water temperature. This happens because of the higher thermal inertia (i.e. heat capacity) of the water mass in the basin than that of the condensing cover. As such, the water mass tends to gain and lose heat relatively slower than the still cover.

A similar comment is also made by Taamneh and Taamneh [33], who mentioned that, due to the higher thermal heat capacity of saline water than that of the glass cover, the glass cover attains the maximum temperature faster than salted water. Still efficiency increases in the morning, reaches a maximum value around noontime, and decreases slower in the afternoon [18].

4.5. Effect of Wind Velocity on Still Performance

In the research work of Hollands [17], the author mentioned that solar still production can be increased by blowing ambient air through the still.

Soliman [32] has mentioned that, at higher water temperatures, an increase in the temperature difference between the water and glass cover due to the rise in the wind velocity will increase the output of the still since, under such conditions, the rate of evaporation is higher than the total heat transfer through the cover by convection and radiation But, at low water temperature, increase in temperature difference between the water and glass cover due to increase in wind velocity may not increase the output of the still. This is because the evaporation rate at low water temperatures is lower than that of the total heat transfer through the glass cover by convection and radiation.

Citing some earlier research works, Soliman [32] has stated that, according to some researchers, output still increases with an increase in wind velocity. In contrast, some other researchers found that the production of the still decreases with increased wind velocity. Some researchers also claim that wind velocity does not affect a still's output; hence, it is unimportant. The author has also mentioned that these investigators have neither considered the angle of inclination of the cover nor the direction of wind w.r.t. the surface.

Based on the experimental results obtained from a roof-type solar still working under forced convection conditions, Soliman [32] has stated that, at constant mean water temperature, the yield increases with an increase in the cooling rate. This can be achieved by increasing wind speed, aligning the inclined surface of the cover parallel to the flow of wind, increasing the Inclination Angle (ϕ), or conducting experiments at lower ambient air temperature.

A similar observation was also made by Rajvanshi [27]. However, the author has also mentioned that since the glass material has a definite conductance value, this imposes a limiting value on the wind speed beyond which the heat transfer rate through the glass cover does not increase further. On the contrary, Toure and Meukam [38] have found that wind speed has no significant effect on the still productivity for a single basin solar still. A similar observation is also made by Toure and Meukam [38]. They have also mentioned that increasing wind speed positively affects productivity during the morning hours, which gets reversed in the afternoon. When the water temperature is high, an increase in wind speed increases the temperature difference between the water and glass cover, increasing the evaporation rate. In the same line of observation, Ismail [18] has found that at higher solar insolation levels, the evaporation rate becomes higher and higher wind speed tends to cause higher condensation rates at the still cover.

4.6. Heat Losses in a Still

Telkes [34] has mentioned some of the heat losses in a solar still and must be minimized as far as possible. These include reflection and scattering of the incident solar radiation due to droplet-type condensation or fogging, heat loss due to incomplete absorption of solar radiation at the basin liner, convection and radiation losses from the high-temperature water surface and basin liner to the condenser plate at a lower temperature, etc.

As mentioned by Moustafa et al. [25], the most significant single loss of solar energy is the thermal radiation from the basin water to the still cover, followed by the radiation losses from the basin water and still cover through reflection. They have also mentioned that the heat losses due to conduction and convection from the still to the surrounding, through sides, bottom and the still cover is relatively small. Therefore, the investment in still insulation is uneconomical.

Contrary to this, Cooper and Read [11] have mentioned that the increase in insulation cost to minimize conduction losses through the sides and base of the still is justified by the greater output for a given radiation level compared to an un-insulated still. Heat is also lost in sensible heat transfer between the basin water and the cover through the condensing cover through convection and radiation. Finally, the authors have commented that by controlling radiation losses from the basin and re-using the latent heat of condensation, the efficiency of a solar still plant can be increased.

4.7. Economics of Solar Distillation

After the economic analysis, Kianifar et al. [20] have seen that the cost of the generated fresh water per litre from an active system is roughly 8% - 9% lower than that obtained from the passive approach.

A similar type of cost analysis done on active solar still by Arunkumar et al. [6] revealed that the potable water produced costs \$0.018/kg water and \$0.015/kg water with air and water cooling of the condensing cover, respectively. The authors have also concluded that, though the arrangement with water cooling costs a little more than that of air cooling, more excellent water production results in a lower cost of purified water.

After a cost analysis, Jubran et al. [19] found the cost of producing distilled water to be \$0.0256 per gallon.

According to Cooper and Read [11], an amortization period of at least ten years should be considered due to the high initial cost of installing a solar still. They have also mentioned that a solar's performance is still not sensitive to the construction materials' quality. Hence, the capital cost can be reduced by using less expensive and cheap construction materials, but this would certainly decrease the life span of the still.

For a single slope basin type solar still, Madani and Zaki [24] calculated the cost of producing potable water to be USD 2.4/m3 and commented that this could not be cut further. The authors have mentioned that the installation cost of a solar distillation unit is the determining factor in Solar Distillation Economics as the operation and maintenance prices are relatively small.

Chaibi [9], in his research work, has mentioned that the high cost associated with the construction of a solar still cannot be offset by the savings resulting from free solar energy. But if the still is appropriately designed, the operating and maintenance costs will be minimal.

For cost analysis, Al-Hinai et al. [4] have assumed the water consumption per person to be 10 litres/day and to fulfil this demand for a community of 100 persons, 1000 litres of water per day will be required. The cost of production has been calculated to be 16.2 $\$/m^3$ and 13.7 $\$/m^3$ for single-effect and double-effect solar stills, respectively. The same type of calculation has also been performed by Al-Hinai et al. [5].

4.8. Efficiency of a Solar Still

Telkes [34] has calculated the efficiency of the insulated solar stills to be a maximum of 70% and that of uninsulated stills to be a maximum of 35%. The author has also commented that if the losses are kept to a minimum, the maximum efficiency of an inclined plate still cannot be higher than 74%. The results of the experimentation performed by Hollands [17] showed that solar efficiency still falls in the range of 40-60% depending on the insolation and ambient conditions. The same type of statement is also given by Cooper [10], where the author mentioned that the upper limit of a solar still is 60% under ideal conditions (ideal efficiency). However, the experimental results performed under actual environmental situations revealed that the ultimate efficiency is restricted to 50% only when both the solar radiation intensity and ambient temperature are high. Again, Moustafa et al. [25] have commented that the overall efficiency is 30% or lower for basin-type solar desalination units.

5. Experimental Still Design

Two identical solar stills have been constructed with the same basin area of 0.32 m^2 (0.57 m × 0.57 m) made of a 3 mm thick cold roll steel sheet. The condensing cover slope angle for the first still is kept at 10°, and the second one is held at 27° (nearly equal to the latitude of Jorhat, Assam). The plain clear glass of 3 mm thickness is used as the condensing cover. To give structural rigidity to the stills, 12 mm thick water resistant plywood is used to construct the outer shell, and 20 mm thick polystyrene insulation is used in both the stills. 5 mm water depth is maintained in both the stills.

K-type thermocouples have been used to measure the temperature, and the Apogee SP-110 pyranometer, placed on a horizontal surface, has been used to measure solar radiation intensity. The DL-35W data acquisition system has recorded the estimated data from the thermocouples and pyranometer.

Both the stills are tested simultaneously and exposed to the same weather conditions. The place of experimentation is Jorhat Engineering College, Jorhat (Assam). The stills and pyranometer are placed so solar radiation falls on them throughout the day, and there is no shading due to any obstacle.

6. Result and Discussion

The results of the experimentation performed on 6^{th} January 2022 from 07:16:55 am to 04:39:55 pm have been discussed here. The solar intensity data up to 03:41:55 pm only has been considered, as shown in Figure 6, because, after this time, the solar intensity becomes too weak for the pyranometer to measure (shown as zero values in Table 1 in Appendix-1). But the data in Figures 7 and 8 are up to 04:39:55 pm.

The data acquisition system has recorded the solar radiation intensity and temperature at 1-minute intervals. However, the average data at 5 min intervals have been manually calculated from the retrieved data of the data acquisition system and represented in Figures 6, 7 and 8. Table 1 in Appendix 1 shows the measured values, calculated at 5 minute intervals, of solar radiation and temperature against the time of the day. Figure 6 shows a few sudden downfalls in the solar intensity data, mainly due to clouds, can be observed.

As seen in Figures 7 and 8, the temperature profiles of Basin water and Glass Cover follow the same trend, and there is a markable temperature difference between the ambient air, cover glass and basin water. Due to this temperature difference, water vapour flows from the basin to the cover glass. The latent heat of condensation is released to the ambient air, forming the condensate droplets through the cover glass. Moreover, on comparing Figures 6, 7 and 8, it is clear that the temperature profiles of basin water, glass cover and ambient air follow the solar radiation intensity profile, which conforms to the comment made by Ismail [18].

Total distillate yield from 10° still is 152 ml, and that of 27° still is 50ml. The theoretical distillate output and efficiency of the solar still can be calculated from the equations mentioned in the research work by Abhay et al. [1].

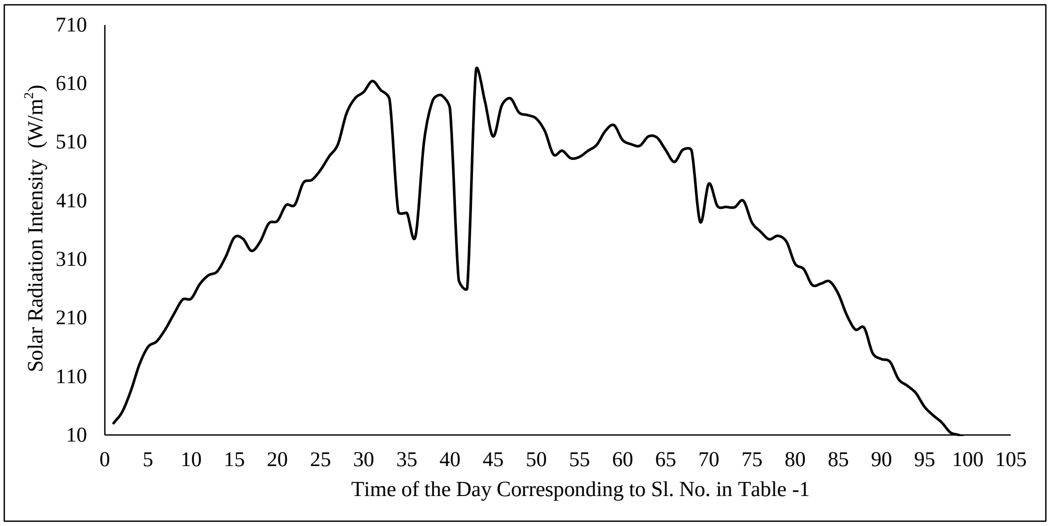

Fig. 6 Solar intensity vs Time of the day (ref. table 1 for time of the day corresponding to sl. no. on the *x*-axis)

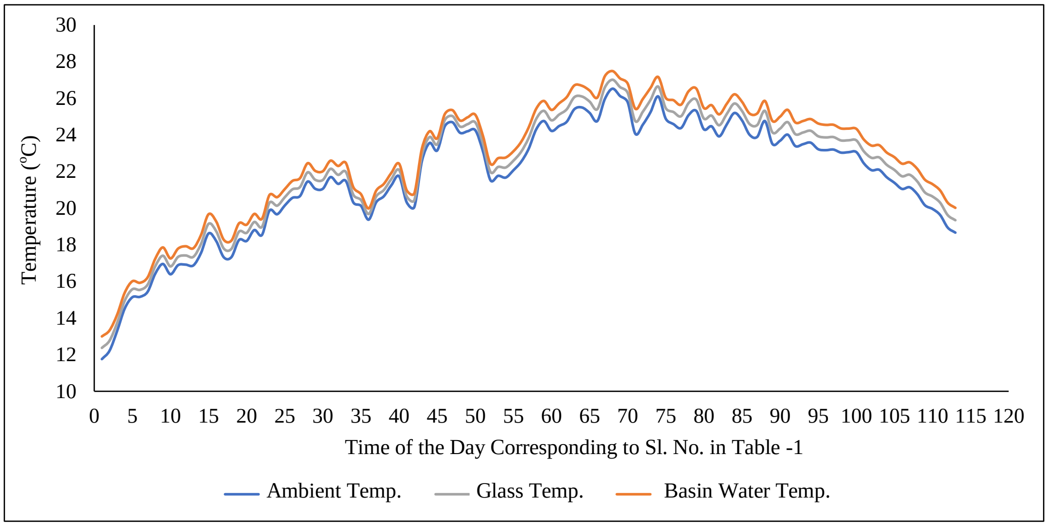

Fig. 7 Basin water and cover glass temperature profile alongside ambient temperature for 10° still

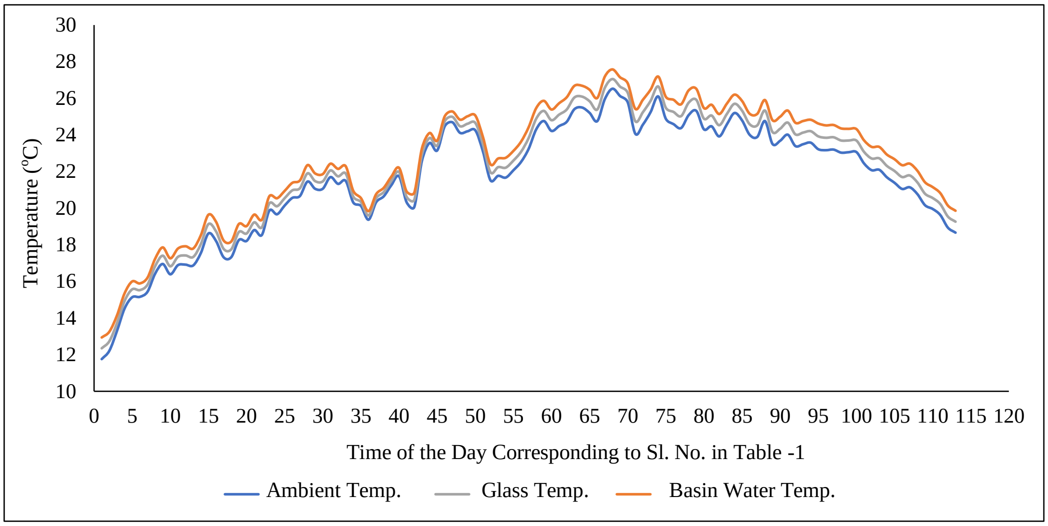

Fig. 8 Basin water and cover glass temperature profile alongside ambient temperature for 27° still

Theoretical distillate output:

$$M_w = \frac{q_{ewg}}{L_{ev}} \quad (\mathrm{kg}/m^2/h) \tag{1}$$

Efficiency of the solar still:

$$\eta = \frac{M_w \times L_{ev}}{I(t)} \tag{2}$$

Here,

- M_w - Hourly distillate output per unit basin area (Kg/m^2/h)
- q_{ewg} - Evaporative heat transfer from basin water to glass cover (W/m^2)
- L_{ev} - Latent heat of vaporization of water (kJ/kg)
- I(t) - Solar Intensity (W/m^2)

Again,

$$q_{ewg} = h_{rwg}\left(T_w - T_g\right) \tag{3}$$

and

$$h_{rwg} = 0.9\sigma \frac{\left[(T_w+273)^4-\left(T_g+273\right)^4\right]}{\left(T_w-T_g\right)} \tag{4}$$

Here,

- hrwg - Radiative heat transfer coefficient from basin water to glass cover (W/m^2°C)
- T_w - Basin water temperature (°C)
- T_g - Glass cover temperature (°C)
- σ - Stefan- Boltzmann constant (5.6697×10^{-8} W/m^2K^4)

The hourly distillate output values corresponding to hourly average water temperature, glass temperature and solar radiation intensity are shown in Table 2 in Appendix-1 for 6th January 2022.

One sample calculation has been shown for 10° still below. All other calculated values are tabulated in Table 3 in Appendix 1

Till 07:45 am for 10° Still:

From Equation 4,

$$h_{rwg} = 0.9 \times 5.6697 \times 10^{-8} \times \frac{[(14.64+273)^4-(14.15+273)^4]}{(14.64-14.15)}$$

$$\boxed{h_{rwg} = 4.84508\ \mathrm{W/m^2°C}}$$

Putting this value in Equation 3,

$$q_{ewg} = 4.845 \times (14.64 - 14.15)$$

$$\boxed{q_{ewg} = 2.37409\ \mathrm{W/m^2}}$$

Putting this value in Equation 1 considering the boiling point of water to be 100°C at sea level, the Latent heat of vaporization of water (kJ/kg) at 1 atm pressure is Lev = 2257.92 kJ/kg.

$$M_w = \frac{2.374}{2257.92} \Rightarrow \boxed{M_w = 0.001051\ \mathrm{kg/m^2/h}}$$

Finally, putting this value in Equation 2,

$$\eta = \frac{0.0011 \times 2257.92}{102.30} = 0.023197$$

$$\boxed{\eta = 2.32\%}$$

Figures 9 and 10 show the calculated hourly efficiencies of 10° and 27° stills from Table 3 in graphical form.

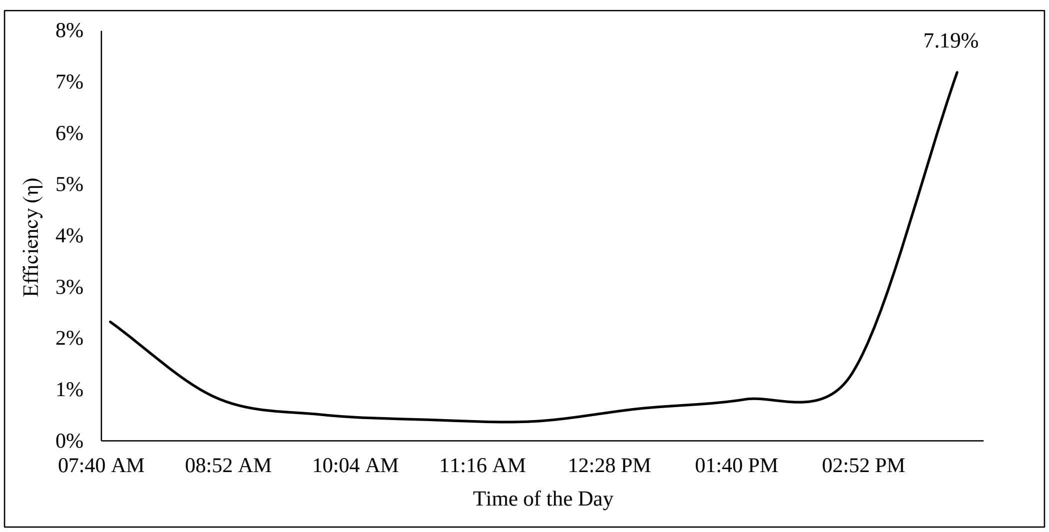

Fig. 9 Hourly efficiency values of 10° still

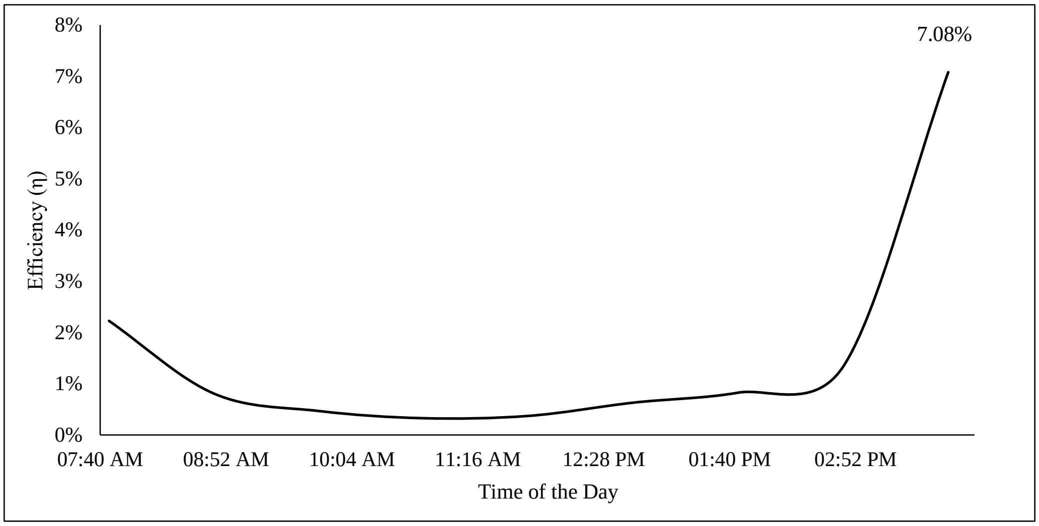

Fig. 10 Hourly efficiency values of 27° still

From Figures 9 and 10, it can be observed that the efficiency is higher during the morning, gradually decreases during noon hours and then again increases and reaches the maximum value during the evening hours when the solar intensity becomes minimum. This happens because, during morning time, ambient temperature is low; therefore, the temperature difference between the basin water and glass cover becomes high. The same happens during the evening hours. But, during the evening, the water mass has some stored energy, which increases the temperature difference between the water mass and glass plate, the difference being more than in the morning hours, and as such, the efficiency becomes higher.

7. Conclusion

The basin water, glass and ambient temperature follow the trend of solar radiation intensity, as evident from Figures 6, 7 and 8. This conforms to the comment made by Ismail [18].The hourly efficiency profiles, as shown in Figure 9 and 10, show that hourly efficiency is less during the noon hours, with a comparatively higher value during the morning hours and reaches a maximum value during the evening hours. This finding is not in conformance with Ismail's [18]. Maximum hourly efficiency attained by the 10° still is higher than that of 27° still. This finding also matches the comment made by Cooper [10].

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Appendix-1

Table 1. Values of solar radiation intensity, ambient, basin water & glass temperature

Sl. No.	Time	Solar Radiation Intensity	Ambient Temperature	10° Still		27° Still	
				Basin Water Temperature	Glass Temperature	Basin Water Temperature	Glass Temperature
		(Watt/metre^2)	Degree Celsius				
1	07:21:55 AM	29.95	11.76	12.94	12.35	13.00	12.38
2	07:26:55 AM	49.20	12.21	13.26	12.74	13.33	12.77
3	07:31:55 AM	85.11	13.29	14.14	13.72	14.18	13.74
4	07:36:55 AM	130.38	14.52	15.35	14.94	15.39	14.95
5	07:41:55 AM	160.31	15.14	16.00	15.57	16.01	15.57
6	07:46:55 AM	169.76	15.16	15.90	15.53	15.93	15.54
7	07:51:55 AM	190.31	15.43	16.20	15.82	16.22	15.83
8	07:56:55 AM	216.54	16.42	17.23	16.83	17.24	16.83
9	08:01:55 AM	240.92	16.95	17.86	17.41	17.86	17.41
10	08:06:55 AM	242.82	16.39	17.27	16.83	17.26	16.82
11	08:11:55 AM	267.62	16.89	17.80	17.34	17.79	17.34
12	08:16:55 AM	282.53	16.91	17.92	17.42	17.92	17.42
13	08:21:55 AM	288.94	16.87	17.80	17.34	17.81	17.34
14	08:26:55 AM	314.19	17.55	18.52	18.03	18.53	18.04
15	08:31:55 AM	347.15	18.62	19.65	19.13	19.67	19.15
16	08:36:55 AM	344.87	18.20	19.26	18.73	19.28	18.74
17	08:41:55 AM	324.25	17.31	18.23	17.77	18.27	17.79
18	08:46:55 AM	340.24	17.33	18.19	17.76	18.23	17.78
19	08:51:55 AM	371.25	18.26	19.14	18.70	19.18	18.72
20	08:56:55 AM	375.54	18.21	19.02	18.62	19.10	18.65
21	09:01:55 AM	402.41	18.80	19.65	19.23	19.69	19.25
22	09:06:55 AM	402.68	18.53	19.37	18.95	19.42	18.98
23	09:11:55 AM	440.50	19.87	20.66	20.27	20.73	20.30

24	09:16:55 AM	445.59	19.67	20.54	20.11	20.60	20.13
25	09:21:55 AM	462.53	20.14	20.95	20.55	21.04	20.59
26	09:26:55 AM	485.85	20.56	21.39	20.97	21.49	21.02
27	09:31:55 AM	506.09	20.66	21.52	21.09	21.64	21.15
28	09:36:55 AM	559.00	21.45	22.36	21.90	22.46	21.96
29	09:41:55 AM	584.91	21.06	21.90	21.48	22.04	21.55
30	09:46:55 AM	595.79	21.06	21.87	21.46	22.02	21.54
31	09:51:55 AM	614.31	21.70	22.43	22.06	22.60	22.15
32	09:56:55 AM	598.30	21.33	22.15	21.74	22.31	21.82
33	10:01:55 AM	582.09	21.49	22.30	21.90	22.48	21.99
34	10:06:55 AM	391.44	20.31	20.95	20.63	21.14	20.73
35	10:11:55 AM	388.97	20.13	20.56	20.34	20.77	20.45
36	10:16:55 AM	349.17	19.37	19.84	19.60	19.99	19.68
37	10:21:55 AM	511.99	20.32	20.77	20.55	20.96	20.64
38	10:26:55 AM	581.05	20.65	21.12	20.88	21.33	20.99
39	10:31:55 AM	590.13	21.26	21.73	21.49	21.94	21.60
40	10:36:55 AM	566.30	21.74	22.21	21.98	22.43	22.09
41	10:41:55 AM	275.63	20.32	20.91	20.62	20.98	20.65
42	10:46:55 AM	261.48	20.06	20.85	20.45	20.82	20.44
43	10:51:55 AM	631.02	22.57	23.26	22.92	23.26	22.92
44	10:56:55 AM	582.65	23.56	24.11	23.83	24.20	23.88
45	11:01:55 AM	519.75	23.15	23.69	23.42	23.81	23.48
46	11:06:55 AM	572.57	24.47	25.02	24.75	25.14	24.81
47	11:11:55 AM	584.83	24.69	25.28	24.99	25.36	25.02
48	11:16:55 AM	560.60	24.11	24.84	24.47	24.79	24.45
49	11:21:55 AM	556.12	24.20	25.02	24.61	24.96	24.58
50	11:26:55 AM	550.19	24.25	25.07	24.66	25.10	24.68
51	11:31:55 AM	528.62	23.11	23.90	23.50	23.96	23.53
52	11:36:55 AM	488.79	21.52	22.40	21.96	22.42	21.97
53	11:41:55 AM	495.34	21.77	22.72	22.24	22.73	22.25
54	11:46:55 AM	482.46	21.67	22.76	22.21	22.77	22.22
55	11:51:55 AM	484.77	22.07	23.13	22.60	23.11	22.59
56	11:56:55 AM	495.28	22.52	23.63	23.08	23.61	23.07
57	12:01:55 PM	505.25	23.23	24.42	23.83	24.41	23.82
58	12:06:55 PM	528.95	24.31	25.47	24.89	25.44	24.87
59	12:11:55 PM	539.04	24.76	25.86	25.31	25.86	25.31

60	12:16:55 PM	513.68	24.22	25.39	24.80	25.37	24.79
61	12:21:55 PM	506.41	24.48	25.73	25.11	25.73	25.10
62	12:26:55 PM	503.78	24.72	26.06	25.39	26.07	25.39
63	12:31:55 PM	519.68	25.40	26.68	26.04	26.71	26.05
64	12:36:55 PM	517.68	25.50	26.69	26.09	26.69	26.09
65	12:41:55 PM	496.55	25.20	26.47	25.84	26.43	25.82
66	12:46:55 PM	476.18	24.75	26.02	25.38	26.04	25.39
67	12:51:55 PM	497.09	25.96	27.19	26.58	27.21	26.58
68	12:56:55 PM	495.51	26.52	27.58	27.05	27.49	27.01
69	01:01:55 PM	373.75	26.12	27.15	26.64	27.09	26.60
70	01:06:55 PM	439.02	25.78	26.82	26.30	26.80	26.29
71	01:11:55 PM	400.87	24.06	25.43	24.74	25.43	24.75
72	01:16:55 PM	399.34	24.57	25.93	25.25	25.97	25.27
73	01:21:55 PM	398.81	25.24	26.48	25.86	26.57	25.91
74	01:26:55 PM	409.94	26.10	27.19	26.65	27.17	26.63
75	01:31:55 PM	372.72	24.88	26.08	25.48	26.02	25.45
76	01:36:55 PM	357.11	24.59	25.92	25.26	25.90	25.25
77	01:41:55 PM	344.05	24.37	25.68	25.02	25.65	25.01
78	01:46:55 PM	349.97	25.08	26.44	25.76	26.39	25.74
79	01:51:55 PM	340.06	25.31	26.52	25.92	26.53	25.92
80	01:56:55 PM	302.24	24.30	25.47	24.89	25.47	24.89
81	02:01:55 PM	293.22	24.47	25.65	25.06	25.63	25.05
82	02:06:55 PM	265.93	23.92	25.14	24.53	25.12	24.52
83	02:11:55 PM	268.32	24.57	25.71	25.14	25.70	25.14
84	02:16:55 PM	272.13	25.20	26.20	25.70	26.22	25.71
85	02:21:55 PM	251.24	24.79	25.86	25.32	25.81	25.30
86	02:26:55 PM	214.53	24.00	25.16	24.58	25.17	24.59
87	02:31:55 PM	189.79	23.89	25.16	24.53	25.18	24.54
88	02:36:55 PM	193.23	24.76	25.91	25.33	25.86	25.31
89	02:41:55 PM	149.37	23.50	24.80	24.15	24.76	24.13
90	02:46:55 PM	139.55	23.68	25.00	24.34	25.00	24.34
91	02:51:55 PM	134.82	24.01	25.33	24.67	25.37	24.69
92	02:56:55 PM	105.00	23.39	24.67	24.03	24.68	24.04
93	03:01:55 PM	94.08	23.49	24.76	24.13	24.76	24.13
94	03:06:55 PM	81.47	23.58	24.83	24.20	24.87	24.22
95	03:11:55 PM	58.04	23.22	24.63	23.92	24.63	23.92

96	03:16:55 PM	43.48	23.16	24.52	23.84	24.55	23.86
97	03:21:55 PM	31.30	23.20	24.55	23.87	24.56	23.88
98	03:26:55 PM	14.17	23.03	24.36	23.69	24.35	23.69
99	03:31:55 PM	9.66	23.06	24.34	23.70	24.35	23.70
100	03:36:55 PM	2.79	23.06	24.32	23.69	24.34	23.70
101	03:41:55 PM	0.79	22.44	23.71	23.07	23.75	23.09
102	03:46:55 PM	0.00	22.07	23.35	22.71	23.42	22.75
103	03:51:55 PM	0.00	22.09	23.35	22.72	23.44	22.77
104	03:56:55 PM	0.00	21.68	22.93	22.31	23.04	22.36
105	04:01:55 PM	0.00	21.39	22.68	22.03	22.79	22.09
106	04:06:55 PM	0.00	21.05	22.35	21.70	22.43	21.74
107	04:11:55 PM	0.00	21.14	22.43	21.79	22.50	21.82
108	04:16:55 PM	0.00	20.77	22.04	21.41	22.15	21.46
109	04:21:55 PM	0.00	20.16	21.42	20.79	21.56	20.86
110	04:26:55 PM	0.00	19.96	21.16	20.56	21.31	20.64
111	04:31:55 PM	0.00	19.63	20.83	20.23	20.97	20.30
112	04:36:55 PM	0.00	18.94	20.15	19.54	20.30	19.62
113	04:39:55 PM	0.00	18.66	19.86	19.26	20.02	19.34

Table 2. Hourly average values

Time	Solar Intensity	10° Still			27° Still		
		Distillate Output	Basin Water Temperature	Glass Temperature	Distillate Output	Basin Water Temperature	Glass Temperature
	(W/m^2)	(ml)	Degree Celsius		(ml)	Degree Celsius	
07:45 AM	102.30	0	14.64	14.15	0	14.60	14.13
08:45 AM	279.92	0	17.94	17.47	0	17.92	17.47
09:45 AM	464.98	0	20.70	20.24	0	20.62	20.20
10:45 AM	479.66	0	21.52	21.14	0	21.36	21.06
11:45 AM	547.39	20	24.02	23.63	0	23.99	23.61
12:45 PM	506.70	30	25.36	24.77	5	25.37	24.78
01:45 PM	404.16	45	26.41	25.81	10	26.43	25.82
02:45 PM	243.00	40	25.54	24.96	15	25.56	24.96
03:45 PM	49.17	15	24.48	23.82	20	24.46	23.81
04:39 PM	0.00	14	21.95	21.27	12	21.83	21.21

Table 3. Calculated values of hourly still efficiencies for 10° and 27° still

Time	Solar Intensity	10° Still				27° Still			
		h_{rwg}	q_{ewg}	M_w	η	h_{rwg}	q_{ewg}	M_w	η
	(W/m^2)	(W/m^{2o}C)	(W/m^2)	(kg/m^2/h)	(in %)	(W/m^{2o}C)	(W/m^2)	(kg/m^2/h)	(in %)
07:45 AM	102.30	4.84508	2.37409	0.00105	2.32	4.84356	2.27647	0.00101	2.23
08:45 AM	279.92	5.01442	2.35678	0.00104	0.84	5.01390	2.25625	0.00100	0.81
09:45 AM	464.98	5.15886	2.37308	0.00105	0.51	5.15570	2.16539	0.00096	0.47
10:45 AM	479.66	5.20435	1.97765	0.00088	0.41	5.19798	1.55940	0.00069	0.33
11:45 AM	547.39	5.33782	2.08175	0.00092	0.38	5.33647	2.02786	0.00090	0.37
12:45 PM	506.70	5.40500	3.18895	0.00141	0.63	5.40555	3.18927	0.00141	0.63
01:45 PM	404.16	5.46205	3.27723	0.00145	0.81	5.46287	3.33235	0.00148	0.82
02:45 PM	243.00	5.41507	3.14074	0.00139	1.29	5.41562	3.24937	0.00144	1.34
03:45 PM	49.17	5.35538	3.53455	0.00157	7.19	5.35457	3.48047	0.00154	7.08
04:39 PM	0.00	5.21922	3.54907	0.00157	0.00	5.21444	3.23295	0.00143	0.00