

PERFORMANCE ENHANCEMENT OF SOLAR STILL BY USING REFLECTORS-JUTE CLOTH-IMPROVED GLASS ANGLE

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ABSTRACT: This paper is aimed to improve the productivity of an existing conventional single slope solar still with modifications. In this study, the conventional solar still is modified by using reflectors, jute cloth and improved glass angle. The modified still productivity and performance are investigated experimentally and compared to that of conventional solar still. The results demonstrated that solar still performance is improved with the 10° glass angle due to better water flow properties and higher solar radiation fall on the still. The results reveal that, with all combined modifications, the water productivity and efficiency of modified solar still increase by 72.18% and 41.51% respectively more than the conventional one. This implies that modified solar still could be adopted for higher water productivity at a lower additional cost.

Keywords: Solar still; Efficiency; Jute cloth; Glass angle; Reflector; Productivity.

تحسين أداء جهاز التقطير الشمسي باستخدام العواكس و نسيج الجوت و تعديل زاوية الزجاج ب.ب. ساهو^{أ*} و سي. سوبودي^ب

المخلص : يهدف هذا البحث إلى تحسين إنتاجية جهاز التقطير الشمسي التقليدي أحادي الميل الحالي بإجراء بعض التعديلات. ففي هذه الدراسة، نعمل على تعديل جهاز التقطير الشمسي التقليدي باستخدام العواكس، و نسيج الجوت و تعديل زاوية الزجاج. حيث أننا نقوم بدراسة إنتاجية وأداء جهاز التقطير الشمسي مخبرياً ومقارنتها بمثيلاتها في جهاز التقطير الشمسي التقليدي. وقد أظهرت النتائج أن أداء جهاز التقطير الشمسي يتحسن مع زاوية الزجاج 10° و ذلك يرجع إلى الخاصية الأفضل لتدفق الماء والإشعاع الشمسي العالي الساقط على جهاز التقطير. و أشارت النتائج إلى أنه مع كل تلك التعديلات مجتمعة إلى أن إنتاجية المياه وكفاءة جهاز التقطير الشمسي المعدل تزداد بنسبة 72.18% و 41.51% على التوالي أكثر من مثيلاتها في جهاز التقطير التقليدي. وهذا يعني أنه يمكن تبني جهاز التقطير الشمسي المعدل لزيادة إنتاجية المياه بتكلفة إضافية أقل.

الكلمات المفتاحية : جهاز التقطير الشمسي ؛ الكفاءة ؛ نسيج الجوت ؛ زاوية زجاجية ؛ العاكس ؛ الإنتاجية.

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DOI: 10.24200/tjer.vol16iss1pp1-10

NOTATIONS

A_g	Area of the glass plate (m^2)
cm	Centimeter
E	East
lts	Litere
ml	Millilitre
N	North
Q_s	Solar radiation (W/m^2)
T_{wi}	Water inlet temperature ($^{\circ}C$)
$^{\circ}$	Degree
λ	Transmissivity
CFD	Computational fluid dynamics
CSS	Conventional solar still
h_{fg}	latent heat of water vapour (J/kg)
MCSS	Modified conventional solar still
m_v	Mass of distillate output (kg/s)
Q_{in}	Solar input (W)
T	Temperature ($^{\circ}C$)
W	Watt
$^{\circ}C$	Degree centigrade
η_{st}	Solar still efficiency (%)

1. INTRODUCTION

The shortage of clean, drinking water because of global warming, climate change and population growth is a concern for the world today. Therefore, the challenge for both developing and developed countries is to provide good quality drinking water. Of the total water available on the earth, about 97.5% contains salt and harmful bacteria that cannot be directly used for healthy drinking purpose Kumar *et al.* (2015). Hence, we need a technology which can produce purified drinking water by distilling brackish and saline water. An efficient, cheap and environment friendly technique to supply clean and safe drinking water is the 'solar still'. It is a solar energy system technology that is capable of removing a very wide variety of contaminants from water in just one step distillation process Bhattacharyya (2013).

The solar still is a simple, inexpensive and efficient system. The equipment primarily consists of a shallow basin with a transparent glass or plastic cover. When the radiation heat from the sun falls inside the glass covered chamber, the basin water is heated. Then the higher sun temperature evaporates the heated water in the basin. Moisture rises and the water vapour condenses when it reaches the cool glass or plastic cover. The water droplets run down into a collection trough to give salts, minerals, germs and impurities free pure water Sahoo *et al.* (2008).

In the past, several attempts were made by many researchers to increase water productivity and utilize the maximum solar radiation on the still to increase the system efficiency. Iranian scientists Rahbar and Esfahani have shown splendid interest in the solar still research in all respects; theoretical, numerical

and experimental. The researchers developed a new correlation for estimating the convective heat transfer coefficient which showed good agreement with the published well-known models Rahbar and Esfahani (2012-2). The same researchers improved the solar still productivity at different operating conditions by using CFD simulation work (Rahbar and Esfahani 2013; Rahbar *et al.* 2015). The authors and their colleagues carried out extensive experimental work to improve the performance of various types of solar still. Utilizing a heat pipe and thermoelectric module to a solar still, the authors improved the productivity (Rahbar and Esfahani 2012-1; Rahbar *et al.* 2016). It was due to the reduction in the start of distillation point with a thermoelectric cooler. The productivity of the solar still can be enhanced by adopting different techniques like partitioning of solar still Rashidi *et al.* (2016) and the use of porous media Rashidi *et al.* (2018-1) and nano fluid Rashidi *et al.* (2018-2) in a solar still. The same researchers also performed energy and cost analysis of the modified solar stills (Rashidi *et al.* 2017; Rashidi *et al.* 2018-a). The cost of water from the modified stills were found to be much less than the conventional solar still.

The glass inclination angle is a design parameter of the solar still that influences the productivity from a solar still Kaviti *et al.* (2016). The increase in the still inclination produces a higher surface area and a thin water surface. Hence, the still productivity increased for a higher glass inclination angle Murugavel *et al.* (2013). In an experimental work, five different glass cover inclination solar stills tilted at different angles from 15° to 45° were studied. The results showed that 15° glass cover inclination system was the best among the five models Hashim *et al.* (2010). In another work on a single basin solar still, two glass inclination combinations, 30° and 23° , were tested. The 30° inclination of the solar still was found to be more efficient Dinesh *et al.* (2013). The effect of glass inclination angle was investigated in two previous investigations with covering glass angles of 4° , 7° , 10° , 13° , 15° , 30° and 45° respectively (Edioja *et al.* 2013; Singh *et al.* 2013). Ten solar stills with different glass inclination angles, 10–55 in steps of 5° were experimented for still performance. The results demonstrated that the angles 20° and 25° provide the optimum still performance Azooza and Younis (2016).

The inclusion of reflectors, either externally or internally, to a solar still increases the solar irradiation to basin water and it raises the still efficiency Omara *et al.* (2017). To enhance the performance of solar stills, the use of internal reflectors were tried by the scientists (Abdallah *et al.* 2008; Tankaka, 2009; Omara *et al.* 2016). The water temperature of solar still was increased due to addition of solar reflection into basin water. In 2016, Omara *et al.* (2014) presented two solar still modifications using a double layer wick material and internal reflectors. They found 145.5% higher productivity for the modified stills as compared to the conventional solar still Omara *et al.* (2014).

Increasing the basin water surface area, water temperature increases and hence, increases in the evaporation rate from the top layer of the water. This caused an increase in water productivity from solar still (Manokar *et al.* 2014; Samuel *et al.* 2016). This concept was tried by placing sponge cubes over the water surface of the solar still and it caused an increase of yield by 18% Bassam *et al.* (2003). Few researchers have conducted experiments on this concept on solar still by using jute cloths or wick at different positions, horizontal, vertical and on the water surface (Shukla and Sorayan 2005; Bouchekima *et al.* 1998; Sakthivel *et al.* 2010; Mona *et al.* 2002). With all positions of jute cloth, the modified solar still yield and efficiency improved due to an increase in surface area and rate of evaporation. In some other experimental works, the absorption materials like black rubber mat, charcoals, black dye, black gravel and black ink were tried to enhance the still efficiency (Mona *et al.* 2002; Nafey *et al.* 2001; Bilal *et al.* 1998). The still yield increased from 35% to 60% with charcoal and wick combined modifications.

From the above literature survey, it is found that “solar still” is one of the very important equipment for producing drinking water. Also, several researchers demonstrated the enhancement of simple solar still productivity and efficiency with appropriate modifications in the design of glass cover and basin. With this in mind, in the present work, various combinations of solar still performance enhancement techniques are presented. Then, these combinations are investigated experimentally to find out water productivity rate and efficiency from the modified solar still.

2. WORK OBJECTIVE

Previous studies have attempted various modifications to improve the productivity of solar stills. The objective of the present work is to conduct experimental investigations on three combined modifications on a conventional single slope solar still. The modifications done here to the original solar still are: (i) changes in glass inclination angle; (ii) fixing reflectors to both sides of still; and (iii) placing jute cloth horizontally on the basin water. In this communication, three modified still combinations were examined experimentally and discussed with respect to the system performance.

3. THEORETICAL ASPECT

3.1 Solar Input Measurement

In this work, energy input to the solar still was from sun only. Transmissivity (λ) of the glass was determined by measuring the ratio of solar intensity over and under the glass. The average value of λ was calculated as 0.847 and it was approximated to 0.85 for calculation purpose. The area of glass plate was

assumed equal to the area of the solar still in the calculation of solar input to the still. Solar input (Q_{in}) to the still was evaluated by multiplying the solar radiation by the transmissivity of the glass cover is presented in Equation (1) Tiwari *et al.* (2009).

$$Q_{in} = \tau A_g Q_s \quad (1)$$

where λ = transmissivity of the glass (= 0.85),
 A_g = area of the glass plate (1.10 m × 1.10 m = 1.21 m²), and
 Q_s = solar radiation [W/m²].

Solar radiation (Q_s) was measured hourly by a ‘lux meter’ during the solar still testing period of the day. Its average value of the total testing hours was considered for the solar input calculation. The lux unit reading of the instrument was converted into the unit of W/m² by multiplying by a conversion factor of 0.0161028. The specifications of Testo make lux meter are presented in Table 1.

Table 1. Specifications of Lux Meter.

Sl. No.	Name of the Instrument	Specification of the Instrument
1	Lux meter	Make: Testo – 540 Measuring range: 0 to 99999 Lux Accuracy: ±3 Lux or ±3 % Resolution: 1 Lux (0 to 19999 Lux) 10 Lux (Remaining Range) Measuring rate: 0.5 second

3.2 Still Efficiency Calculation

It is the ratio of the heat energy utilized for water evaporation to the total solar radiation energy received by the still Tiwari *et al.* (2009). It was assumed that a small amount of sensible energy consumed by distillate water is compared to its latent heat and hence, it was neglected in the still efficiency calculation. Due to the glass small angle, it was assumed that the amount of solar radiation on the solar still to slope of glass is unaffected.

$$\eta_{st} = \left[m_v \times h_{fg} \right] \div \left[\lambda A_g Q_s \right] \quad (2)$$

where m_v = mass of distillate output (kg/s),
 h_{fg} = latent heat of water vapor (=2257×10³ J/kg).

3.3 Measurement of Distillate Output

The hourly collected still distillate output was collected and measured in a scaled measuring glass jar on volume basis. This volumetric distillate output was then converted into mass basis and is taken as m_v in kg/s for calculation purpose.

3.4 Measurement of Temperature

The temperature was recorded during the tests with the help of alcohol in-glass thermometer of 0 – 100 °C range at three different places, water, outside glass and ambient temperature.

4. EXPERIMENTAL INVESTIGATION

The tested experimental setup is installed at the Mechanical Department, Synergy Institute of Engineering and Technology, Dhenkanal, India. The schematic diagram of the single slope solar still setup is shown in Fig. 1. The black painted still basin is made from 3 mm thick fibre-reinforced plastic with a maximum of 25 litres water capacity. The top of the still is covered by 6 mm thick and 1.10 m × 1.10 m area glass and placed at 8° inclination to the horizontal. The leakage of heat and water vapour from the solar still are prevented by filling putty between the glass cover and side edges of still space.

4.1 Test Matrix

One set of baseline tests was carried out on the existing conventional solar still. The still was modified with the following alteration by: (i) increasing glass inclination angle to 10° for better water flow conditions; (ii) fixing 20 cm height reflectors at 60° angle to both sides of still top layer to increase solar radiation on water Maambo and Simate (2016); (iii) placing jute cloth horizontally on the basin water to increase evaporation surface area. These three sets of experimentations were conducted on the modified conventional still. The complete particulars on the test matrix adopted for the experiments on solar still are presented in Table 2.

The schematic diagrams of the modified solar still operations setup of MCSS-2 and MCSS-3 the modes are presented in Fig. 2 and Fig. 3 respectively.

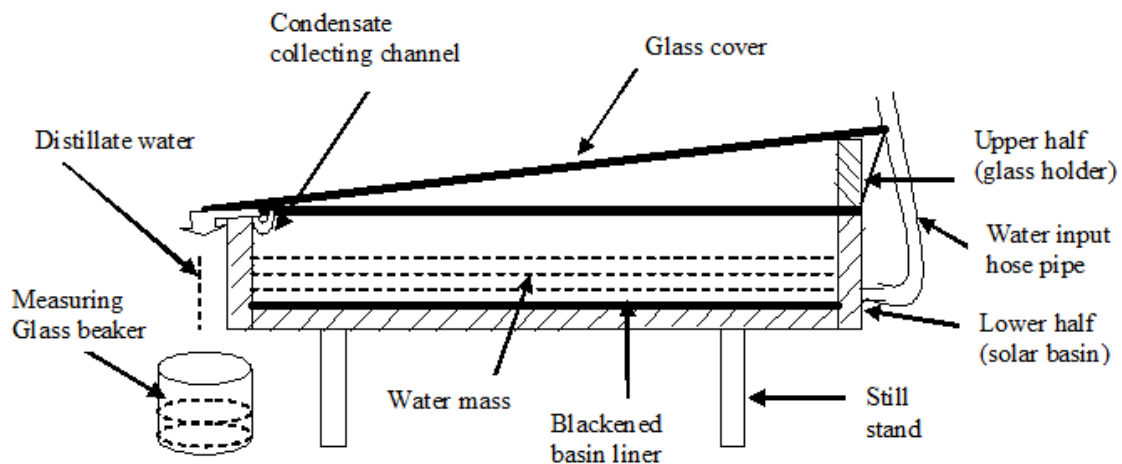


Figure 1. Schematic Diagram of Conventional Solar Still (CSS).

Table 2. Test Matrix.

Designation of Operation	Features of Solar Still	Quantity of Water (Its)
CSS	Conventional solar still (8° inclination)	15
MCSS-1	Modified Conventional solar still – 10° inclination	15
MCSS-2	Modified Conventional solar still – 10° inclination, reflector fixed at 60° angle to both sides of the still	15
MCSS-3	Modified Conventional solar still – 10° inclination, reflector fixed at 60° angle to both sides of the still, placing Jute cloth on the basin water	15

4.2 Experimental Procedure

To the test matrix, all tests were carried out in the Dhenkanal district of Odisha state with geographical coordinates of 20.8424° N, 85.4376° E, India. The experiments were carried out on the south faced solar still from 10 AM to 03 PM during February – March, 2017. The amount of water was kept as 15 liters in the still basin during the experimentation. The amount of water was fed into the still by the fabricated hose pipe arrangement. The initial temperature of water and atmosphere were recorded. The basin water received the solar radiation, got heated and evaporated. The water vaporized and condensed against the glass cover. The glass temperature and solar radiation were recorded at hourly interval basis. The water molecules slide down through the glass inclination to the collecting channel and fell on collected measuring jar. The hourly distillate from the solar still was collected and measured. Three sets of experiments were conducted for each test matrix and the average observed parameters were used for performance analysis of the solar still. The same experimental procedures were followed to evaluate the modified sill performances as per the test matrix and the average recorded parameters were considered for analysis purpose.

4.3 Measurement Errors

$$N_{st} = f(m_v, A_g, Q_s, T_{wi}) \tag{3}$$

The uncertainties associated with the calculation of solar still efficiency were estimated by using sequential perturbation techniques Kline and McClintock (1953). It included contributions from uncertainties in measurement volume of collected distillate (1%), initial water temperature (0.5%), area of the glass plate (0.1%) and solar radiation (0.1%). Based on the above values, the still efficiency was believed to be accurate within ± 2%.

5. RESULTS AND DISCUSSION

The various temperatures, solar radiation and distillate output were measured on hour intervals on the day of experimentation on the solar still with 15 liters water capacity. The results were analyzed and compared for both the modified and the conventional solar stills as per defined test matrix.

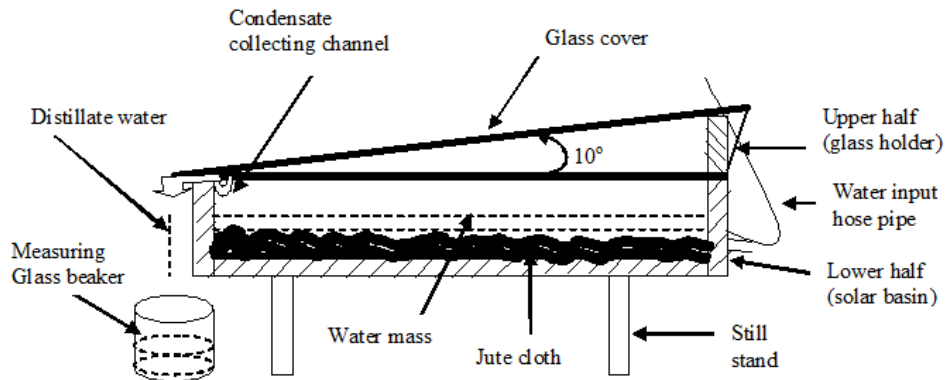


Figure 2. Schematic Diagram of Modified Solar Still (MCSS-2).

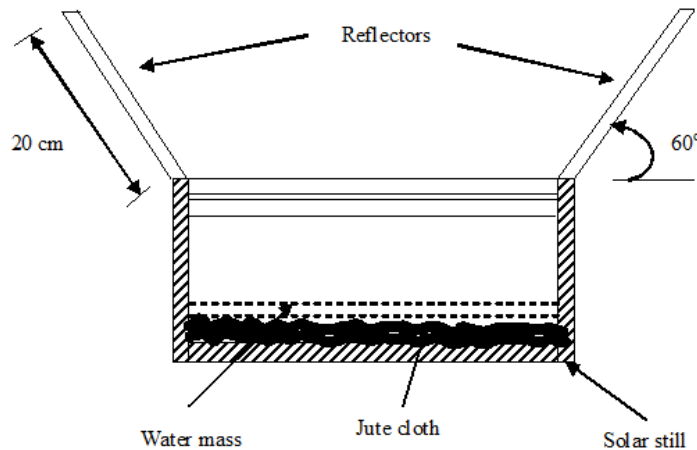


Figure 3. Schematic Diagram of Modified Solar Still (MCSS-3).

5.1 Solar Radiation

The solar radiation is increased gradually from morning hours as the day progresses, as shown in Fig. 4. For all modes of still operation, its highest value is reached at 12 noon and then decreases until 3 pm. The solar intensity values are varied from 583×10^3 to 1000×10^3 lux units during the experimentation.

5.2 Ambient Temperature

Figure 5 shows that the ambient temperatures are varied from 27 °C to 41 °C in the days of still operation. For all the modes, the highest value of ambient temperature is obtained at 1 PM of the day.

5.3 Glass Temperature

In general, the solar radiation on the earth begins to increase from morning hours, reaches to maximum values around mid-day and then decreases in the afternoon. Due to this solar intensity variation, it is observed that the glass temperatures for all modes go up as the day progresses and reaches a maximum

value at 2 pm for all the operation days (Fig. 6). The MCSS-3 mode of operation produced highest glass temperature of 50 °C followed by MCSS-2 (49 °C), MCSS-1 (44 °C) and CSS (44 °C). The increase in solar energy absorption due to reflectors with MCSS-2 and MCCS-3 modes increase the glass temperatures. The increase in solar radiation increases the evaporation and condensation of the basin water. So, the glass temperatures in both MCSS-2 and MCCS-3 modes are higher compared to CSS and MCCS-1 modes. In MCSS-3 mode, the increase in surface area due to jute cloth absorbs more heat energy and hence, it showed the highest glass temperature. The maximum glass temperatures are recorded equal with CSS and MCSS-1 modes. However, the difference in maximum and minimum glass temperatures of MCSS-1 mode is found higher than that of CSS mode. To achieve maximum glass temperature and best performance from the still, the glass angle should be increased further up to the place latitude angle of 20.8424°.

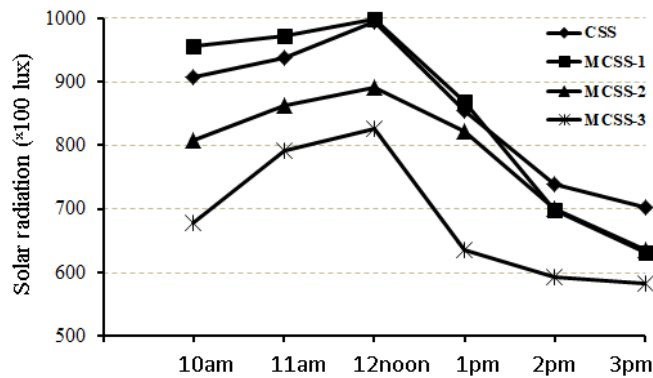


Figure 4. Variation of solar radiation on the days of operation.

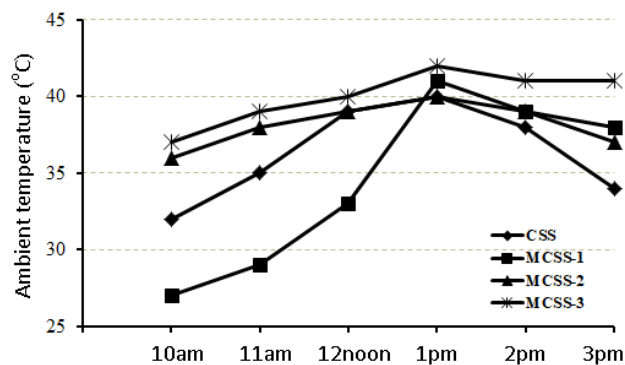


Figure 5. Variation of ambient temperature on the days of operation.

5.4 Distillate Output

The hourly distillate output variation with the day progress is shown in Fig. 7. It is observed that the distillate output began at nil in the morning at 10 am, increased and till 2:00 pm of the day. After 2 pm, the water productivity of CSS and MCSS-1 modes are reduced. But, MCSS-2 and MCSS-3 modes showed enough water production potential even after 2:00 pm. In general, the distilled water productivity of the still varies proportionally to solar radiation and ambient temperature. Due to more solar absorption capability, more water yield is found with MCSS-2 and MCSS-3 modes modified solar stills. The maximum distillate output is recorded 189 ml and 181 ml per hour from MCSS-2 and MCSS-3 modes respectively around 3:00 PM.

The ability of higher evaporation and condensation rates of the modified stills (MCSS-2 and MCSS-3) produced more water yield than CSS and MCSS-1 modes of operation. This is the same reason that generates more glass temperatures. So, the daily water production from the MCSS-2 (707 ml) and MCSS-3 (718 ml) are found more than that of the other modes CSS (417 ml) and MCSS-1 (664 ml) as shown in Fig. 8. The water yield output of MCSS-1 and MCSS-2 are increased by 59.23% and 69.54% respectively

compared with the CSS mode. The distillate water yield in the MCSS-3 mode is increased by 72.18 % as compared to the CSS mode. This is due to the combined modifications effect of 10° glass inclination, reflectors and jute cloth operation of MCSS-3 mode which produced increased solar radiation absorption, higher evaporation and condensation water rate.

5.5 Still Efficiency

Figure 9 shows the comparison of efficiency for all four modes of operations solar still. The still efficiencies are found to be 10.6%, 12.31%, 13.6% and 15% for the modes CSS, MCSS-1, MCSS-2 and MCSS-3 respectively. The MCSS-3 mode operation of solar still showed 42.31% higher efficiency than that of the original CSS mode. The increase in the glass inclination to 10° provided better water flow slope and also improved solar radiation fall on basin water as compared to the original 8° inclination. The amount of solar radiation on water is increased due to reflectors. Jute cloth inside the basin increased the water evaporation surface area. Combining the benefits all together, the water productivity and, hence, the still efficiency is increased by a huge margin of 42.31% for MCSS-3 mode as compared to the original CSS setup.

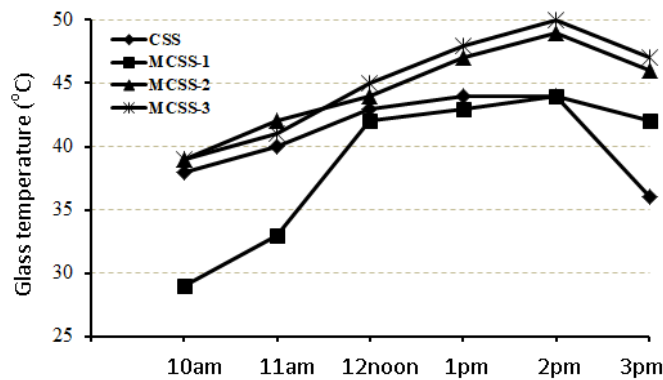


Figure 6. Variation of glass temperature on the days of operation.

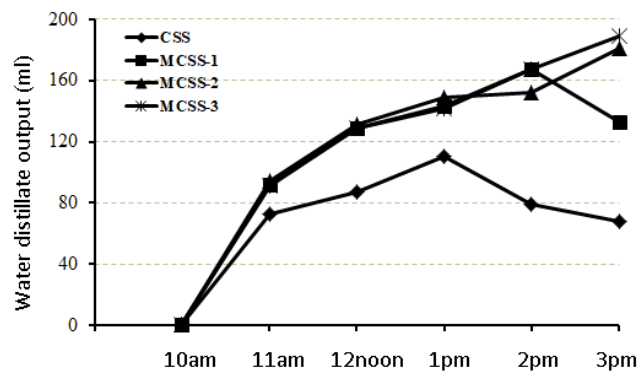


Figure 7. Variation of hourly distillate water output on the days of operation.

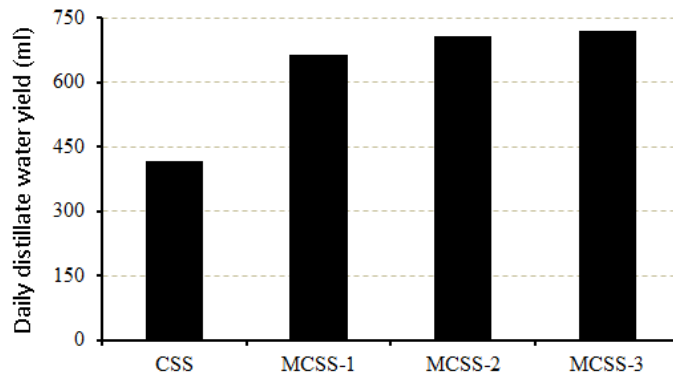


Figure 8. Average distillate water output for all modes operation.

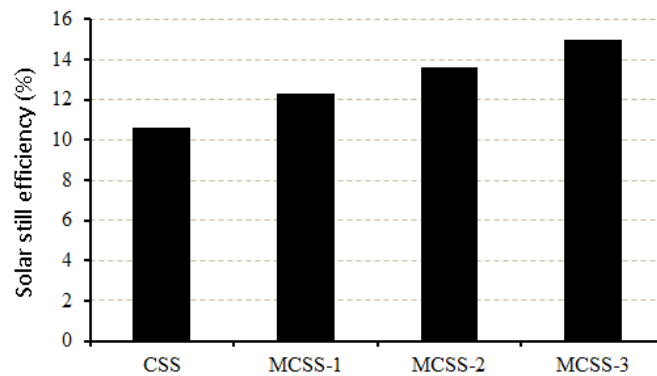


Figure 9. Variation of solar still efficiency for all modes of operation.

Table 3. Comparison of Water Productivity of Different Single Slope Solar Stills.

Still Specifications	Increase in Productivity
Still with asphalt and sprinkler [Badran, 2007]	51 %
Still with internal mirrors and step-wise basin [Abdallah et al. 2008]	180 %
Stepped solar still with internal reflectors [Omara et al. 2013]	75 %
Still with fins at bottom [Velmurugan et al. 2008]	45.5 %
Still with water coral fleece with stepped wire mesh absorber [Hansen et al. 2015]	71.2 %
Present work (Still with increased glass angle, jute cloth and reflectors)	72.18

5.6 Comparison of Productivity of Different Single Slope Solar Stills

The comparison of water productivity of previous Researchers' works and present work is represented in Table 3.

6. CONCLUSION

This study deals with the performance enhancement of a conventional solar still by using low cost modifications such as reflectors, jute cloth and improved glass angle. The collected data during the

experimentation days were analyzed and the findings were summarized below.

- The modified solar still with 10° inclination angle in MCSS-1 mode produces better water angular flow water properties with 16.31% more still efficiency than that of the original CSS mode. Also, the water productivity of MCSS-1 mode moves up by 59.23% as compared to CSS mode.
- By fixing reflectors on the sides of the still (MCSS-2 mode), the water productivity and still efficiency increases by 69.54% and 28.3% respectively as compared with the CSS

operation. Water production increases by 290 ml with MCSS-2 mode for the solar still hours of operation as compared to that of CSS mode.

- The MCSS-3 mode produces a maximum glass temperature of 50°C when solar radiation absorbing capacity of the still is increased by using jute cloth to the basin water area along with reflectors and improved glass angle.
- Water productivity of the MCSS-3 mode is 718 ml on the day of operation which is an enhancement amount of 72.18% over CSS mode.
- The MCSS-3 mode produces 41.5% higher still efficiency with all combined modifications as compared to that of 10% efficient CSS mode.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

FUNDING

No funding was received for this research.

ACKNOWLEDGMENT

The authors wish to thank and acknowledge their B.Tech and M.Tech students, Vellore Institute of Technology, for their assistance towards experimentation and data collection for the entire experiment days.

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