

## PERFORMANCE ANALYSIS OF MODIFIED SOLAR STILL WITH FORCED WATER CIRCULATION

by

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*This work is aimed to enhance the evaporation rate of water in the basin and the condensation rate of water vapour on the glass cover of a solar still. The evaporation rate is enhanced by supplying more solar thermal radiation and the condensation rate of water vapour is improved by removing more thermal energy from the glass cover. For enhancing the evaporation rate of water, the evacuated tubes were integrated with the stepped basin to increase the water surface area exposed to solar radiation. The internal and external reflectors reflect solar radiation on the water of the stepped still basin and inside the evacuated tubes. The forced water circulation maintains the thin film of water on the basin. Water sprinkling on the glass cover removed more thermal energy from it. As a result, the condensation rate was high. Comparisons between the modified stepped solar still with conventional solar still was carried out to evaluate the performance under the same climatic conditions. The productivity of the modified stepped solar still with reflectors and sprinkled glass cover cooling was 8660 mL per day.*

*Key words: stepped solar still, evacuated tube collector, forced water circulation, sprinkled water glass cover cooling, internal reflectors, external reflectors*

### Introduction

On the Earth, 71% of its surface is water. Only 3% of the world's water is fresh. The available fresh water is continuously contaminated by industries, agriculture, and households. The expanding agriculture, growing industrialization and the rising standard of living of humans further push-up the demand for fresh water. Water shortage is a serious problem facing many countries. Recycling and desalination of water are the best options. But cost involved is high. Solar still is one of the simplest methods of desalination on a small scale. No skilled labor is required and the operation is simple. However, the daily productivity of solar stills is very low. Solar still is more advantageous to the people living in islands or remote areas, where the transport cost of the fresh water is high. But productivity of conventional solar still is less. Many research works are being carried out to enhance the productivity of the solar still. Sampathkumar *et al.* [1] reviewed the different modifications of the active solar distillation system. Toure and Meukam [2] studied the different water depth from 6 cm to 0.5 cm and found that distillation productivity is increased by 19% on lower water depth. The sponge cubes have capillary effects which increase the free surface area of the water in the solar still is studied by

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Bassam and Himzeh [3] and found that the productivity increased by 18% when compared with the conventional solar still. Nafey *et al.* [4] concluded that the water productivity increases at shallow water depth. The external solar flat plate collectors were used to heat the basin water. Tiris *et al.* [5] found that the average daily production of distilled water was 100% higher than a conventional solar still when two flat plate collectors were integrated in a natural circulating closed loop. Velmurugan *et al.* [6] integrated fins to increase the basin area exposed to water for enhancing the heat transfer rate and sponges for its capillary effects. They found that the maximum distillation occurred when both fin and sponge effects were combined. Shailendra and Ajeet [7] studied the factors affecting the heat transfer co-efficient of double slope solar still. They instituted that the shape, material of the condensing glass cover, temperature difference between the water and inner glass cover were the driving factors of distillation. Badran *et al.* [8] studied the effect of a conventional flat plate collector together with a single basin type solar still. They found that the productivity was increased by 231% and 52% in the case of tap water and salt water as a feed, respectively. Abu-Hijleli and Mousa [9] utilized the water film cooling over the glass cover to increase the still efficiency by 20%. Since the water film cooling over the glass cover reduces the glass cover temperature. Tiwari and Bapeshwara Rao [10] studied about the flow of water continuously over the glass cover at a constant rate and concluded that the productivity is increased by 100% due to the decrease of its temperature. Badran [11] applied enhancers such as water sprinkler, asphalt basin liner in a single slope solar still and showed that the still productivity was increased up to 51%. Tanaka [12] studied the different inclination angles of the external reflectors throughout the year from 10-50° and proved that the still with internal and external reflectors gave 67% higher productivity than a conventional solar still. Kostić and Pavlović [13] used the reflectors to enhance the energy input to the thermal collectors and concluded that the 35-45% of energy gains in the summer period for thermal collectors with aluminum sheet reflectors. Tanaka [14] integrated the internal and external reflectors with a solar still to deflect more solar radiation into the still and found that the water distillation was increased about 70-100%. Monowe *et al.* [15] modelled a portable thermal-electrical solar still with an external reflecting booster and an outside condenser. The latent heat of condensation of vapour was absorbed in the outside condenser and thermal energy is recycled to preheat saline water for domestic purposes or to operate the still during night times. They showed that the productivity is enhanced up to 10 L/m<sup>2</sup> per day. A basin type solar still and a tilted wick solar still with flat plate external bottom reflectors were presented by Tanaka [16, 17]. Sampathkumar [18] constructed and tested the solar still coupled with evacuated tubes. Also he found that the productivity of the solar still coupled with evacuated tubes was 49.7% higher than the ordinary still. Kalidasa Murugavel and Srithar [19] analysed the year round performance of a single basin double slope solar still and found that the average productivity of the still was 2.1 L/m<sup>2</sup> per day. Rajaseenivasan and Srithar [20] integrated the circular and square fins at the solar still basin. They found that the daily productivity of the still was increased by 26.3% and 36.7% for circular and square finned stills and it increased to 36% and 45.8% for fins covered with wick materials. Arunkumar *et al.* [21] experimentally investigated the performance of compound parabolic concentrator coupled tubular solar still and compound parabolic concentrator-concentric tubular solar still. They found that the daily productivity was 3710 and 4960 ml, respectively. Velmurugan and Srithar [22] experimentally investigated the mini solar pond integrated with conventional solar still to increase the productivity. The fin is integrated with mini solar pond and still basin to increase the convective heat transfer from basin to water is fabricated by Appadurai and Velmurugan [18]. They achieved 50% higher productivity when fin type mini solar pond is integrated with fin type solar still.

Sampathkumar [18] directly coupled evacuated tubes with a single basin solar still to increase its productivity. The water circulated between the evacuated tubes and still basin naturally. The 5 cm water depth is maintained in the still basin.

In this work, the similar evacuated tubes are integrated with stepped still basin but thin water film is flown over the stepped basin. The thin water film thickness has minimum water depth and lower heat capacity. The evaporation rate of water is enhanced due to the smaller heat capacity. The evacuated tube increases the water surface area exposed to solar radiation. Also the internal and external reflectors reflect more solar radiation on the water of the stepped still basin and inside the evacuated tubes which enhances the distillation rate.

### Experimental set-up

The experimental set-up consists of two systems, namely conventional single slope single basin solar still and modified solar still. The experimental set-up of the present study was located at the Department of Mechanical Engineering, Francis Xavier Engineering College, Tirunelveli, India (Latitude  $8.44^\circ$  N and longitude  $77.44^\circ$  E). The experiments were carried out to evaluate the performance of different modifications in solar still.

#### Conventional solar still

The conventional single slope single basin contains the black paint coated basin which is enclosed by wooden box on its five sides. The transparent glass cover of thickness of 4 mm is placed over the still at an inclination of  $10^\circ$  to horizontal, which is the latitude of Tirunelveli. The still basin is made up of a galvanized iron (GI) sheet with an effective basin area of  $1 \text{ m}^2$ . The saw dust is placed between the still basin and wooden box for reducing the conduction losses.

The conventional single slope single basin still consists of a basin, insulated wooden box, glass cover and distilled water collection arrangement. The wooden box is made of plywood having four sides with dimensions of  $1.1 \text{ m} \times 1.1 \text{ m}$  and thickness of 0.025 m. The outer sides of the wooden box are covered by sheet metal to prevent from environmental conditions. The basin of the still is fabricated with a GI sheet with an effective basin area of  $1 \text{ m}^2$ . The basin is placed inside the plywood box. The space available between the basin and the plywood box is filled by sawdust for insulation. The basin is coated with matte black paint for higher absorptivity. Window glass with a thickness of 4 mm is used as transparent covers placed over the still at an inclination of  $10^\circ$  to horizontal, which is the latitude of Tirunelveli.

#### Modified solar still

Figure 1 shows a schematic diagram of the experimental set-up of a modified solar still. The modified solar still consists the basin area of  $2 \text{ m} \times 0.5 \text{ m}$ , enclosed inside the insulated wooden box. The five rectangular fins are

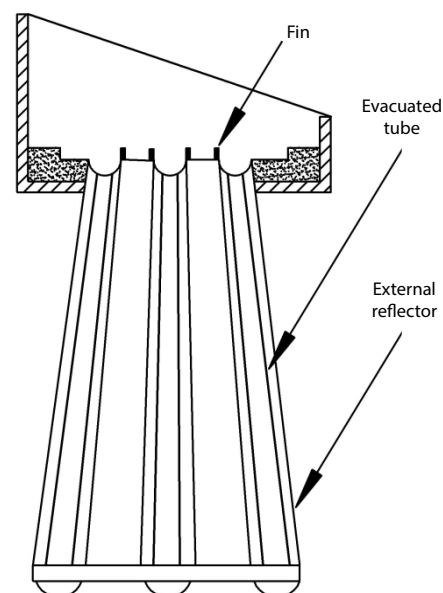
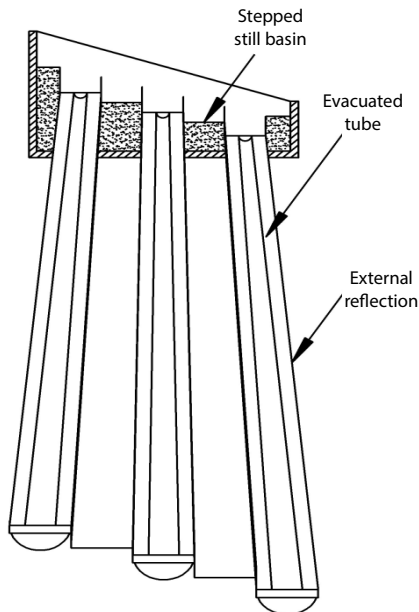
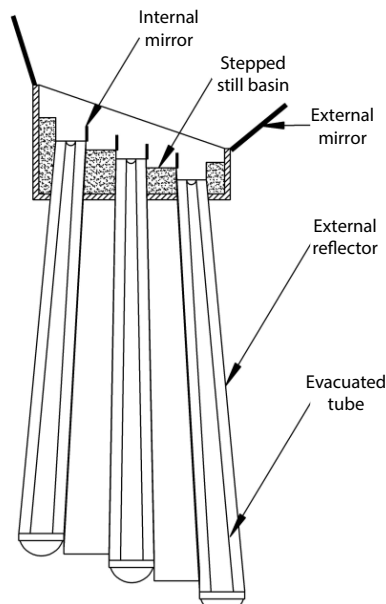


Figure 1. Schematic diagram of modified solar still

welded on the basin by gas welding. The length, breadth and thickness of the fins are 195, 1, and 0.2 cm, respectively. The five evacuated tubes are integrated with the still basin for increasing the water surface area exposed to solar radiation. To absorb maximum solar radiation, the outer surface of the inner glass of the evacuated tubes is coated with a solar selective coating. The di-



**Figure 2. Schematic diagram of modified stepped solar still**



**Figure 3. Schematic diagram of modified stepped solar still with reflectors**

mensions of the evacuated tubes are 1.5 m long and an absorber diameter of 0.05 m, which is mounted on a diffuse reflector with centre – line spacing of 0.01 m at an angle of 45° horizontal. The 12 V DC pump is installed to produce the forced water circulation inside the solar still at the mass-flow rate of 0.03 kg/s. The water was continuously circulated through the evacuated tubes as well as over the finned still basin.

#### *Modified stepped solar still*

Figure 2 shows a schematic diagram of the modified stepped solar still. When compared with the conventional solar still, the gap between the basin and glass cover is minimum in the stepped solar still. The stepped still basin has five trays, each of size 0.1 m × 2 m × 0.01 m. The five evacuated tubes are integrated with the stepped still basin to supply more solar energy. The basin is kept in an insulated wooden box. The space between the wooden box and the basin is filled with sawdust for insulation. The top surface of the basin is covered with a glass cover.

#### *Modified stepped solar still with reflectors*

The schematic diagram of the modified stepped solar still with reflectors and sprinkled glass cover cooling is shown in fig. 3. The mirrors are placed on the vertical sides of the steps as internal reflectors in the stepped still to deflect the solar radiation on the water. The 200 cm length and 25 cm width external reflectors are fixed on the top and bottom side of the modified stepped solar still. The provisions are made to adjust the angle of inclination of the two reflectors in line with the seasons. The top reflector should be inclined slightly forward in winter and backward in summer because the altitude angle of the Sun decreases in winter and increases in summer. The inclination angle of the reflector would be less than 25° throughout the year [22]. The optimum reflector angles of the top and bottom external reflectors are set at 15° and 50° in the summer season [22].

Calibrated copper constantan type thermocouples are used to measure the basin, water, ambient temperature, and outside glass temperatures of the solar still. For every 1 hour, the solar intensity, wind velocity and the productivity are measured by solarimeter, vane type digital anemometer and measuring jar, respectively. The total productivity during the day was also measured.

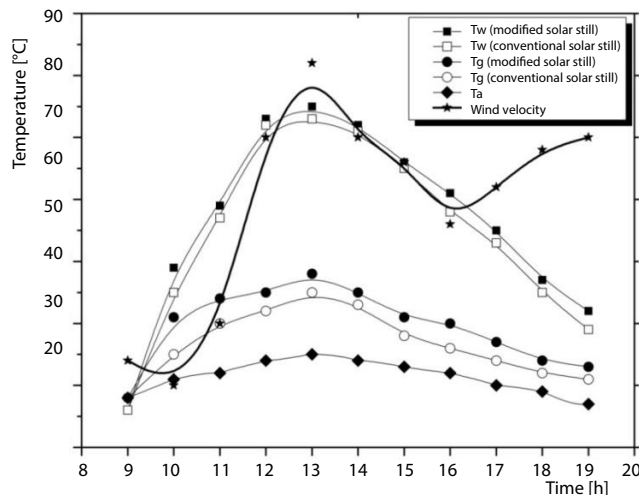
**Result and discussion**

The outdoor experiments were carried out for various modifications in the solar still. Two solar stills were fabricated, one was a modified solar still and the other was a conventional solar still. The performance of a modified solar still was compared with the conventional solar still under the same environmental conditions. At night, the top glass cover of the two stills was covered by the plywood insulation sheet to reduce the heat losses from the still to the surroundings. The water stored in the basin and evacuated tubes acted as sensible storage. The water supplied the thermal energy even after the Sun set. The stored thermal energy in water was released slowly as time changed. The still integrated with the evacuated tubes had night time productivity. The night distillation was measured the next day morning for calculating the daily productivity.

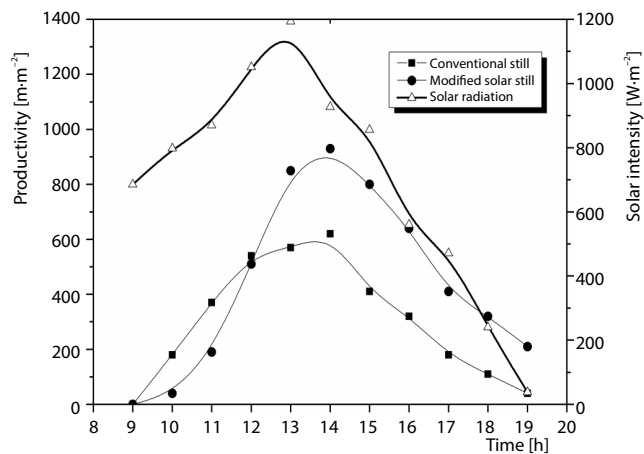
*Performance of modified solar still*

Figure 4 shows the hourly variation of the ambient temperature, basin water temperature, glass temperature of stills, and wind velocity. The water temperature of the modified solar still was higher at all times due to the fins, which increased the basin and water contact surface area. The evacuated tubes supplied more thermal energy. The glass temperature was also increased due to large condensation of water under the lower side of the glass.

Figure 5 shows the hourly variation of solar radiation and productivity. The productivity of the two solar stills was increased when the solar radiation increased because solar radiation was the



**Figure 4. Comparative analysis of conventional solar still and modified solar still**



**Figure 5. Hourly variation of distillation of conventional solar still and modified solar still**

driving force for water distillation. It can be seen that the distillate output of a modified solar still was always higher than that of the conventional solar still under the same environmental conditions, since the thin water film was maintained in the basin by forced circulation of water. The thin film of water was achieved by forced circulation only. In the conventional solar still, some area of the basin surface was exposed without water due to the irregular surface of the basin, if the water depth was very less. In addition, heat transfer rate from the basin to water was less because the area of contact between the basin and water (basin surface area  $1 \text{ m}^2$ ) was less when compared with the modified still. The five fins were welded into the modified solar still and so the basin area of modified solar still was  $1.2 \text{ m}^2$ . The fins diverted the flow of water at all the surface of the basin. The evacuated tubes were integrated into each division of the solar still to increase the water surface area exposed to solar radiation. Therefore, the productivity was increased due to additional supply of solar energy to the brine water. The heat loss from the evacuated tubes was less because the conductive and convective heat loss was negligible. The hot water film was only flown on the still basin because the higher temperature water had low density and rose up in the evacuated tubes. Therefore, it had higher evaporation rate. The vapour bubbles were easily rising up from the water due to the flow of water. The maximum hourly productivity of both the stills was at 14.00 hours. The total productivity of the conventional solar still and modified solar still was 3390 mL per day and 5300 mL per day, respectively. The modified solar still gave 56.3% higher productivity than conventional solar still.

#### Performance of modified stepped solar still

Figure 6 shows the hourly variation of atmospheric temperature, basin water temperature, glass temperature of stills, and wind velocity. The temperature of water and the glass increased as the time increased up to a maximum value of  $78 \text{ }^\circ\text{C}$  and  $54 \text{ }^\circ\text{C}$  at 13.00 hours and thereafter decreased gradually. This was due to the increase of solar radiation intensity in the morning and its decrease in the afternoon. The stepped still basin gave higher heat and mass transfer surface area ( $1.1 \text{ m}^2$ ) than the conventional still basin ( $1 \text{ m}^2$ ). Therefore, it led to increase in the basin water temperature of the stepped solar still. Due to the evacuated tubes and modified stepped arrangement, the evaporation rate was high, but condensation was reduced because the latent heat of condensation of vapour supplied more thermal energy to the glass cover. The glass temperature increased and the temperature was higher for several hours. After mid-noon

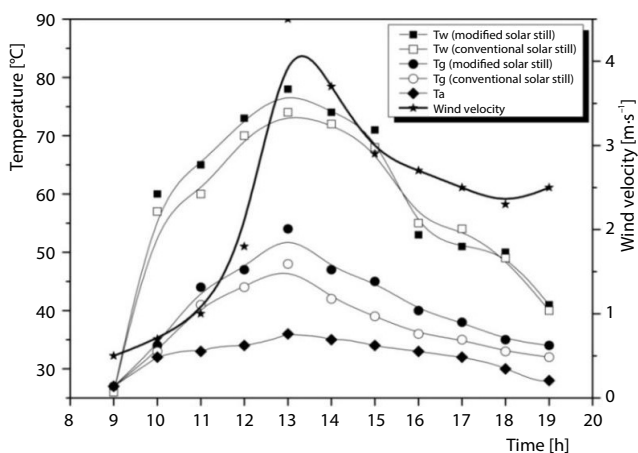


Figure 6. Comparative analysis of conventional solar still and modified stepped solar still

hour atmospheric temperature and solar intensity decreased and so all the evaporated steams began to condense. The distillation rate was high at this time. The glass temperature and basin water temperature of the modified stepped solar still is higher than that of the conventional still by about  $0\text{--}6 \text{ }^\circ\text{C}$  and  $0\text{--}4 \text{ }^\circ\text{C}$ , respectively.

Figure 7 compares the performance of the modified stepped solar still and the conventional solar still. The increase in solar radiation led to the increase in the productivity of the two solar stills.

It can be observed that the water distillation rate increased in the morning and attained peak values in the afternoon. As the gap between the basin and the glass was reduced, the volume of air trapped inside the stepped still chamber decreased. Therefore, heating up of the trapped air was faster resulting in the increase of productivity. The daily productivity was around 3120 mL and 6280 mL for the conventional still and the stepped solar still, respectively. In this case, the increase in distillate production for stepped solar still was 101.2% higher than that of the conventional still.

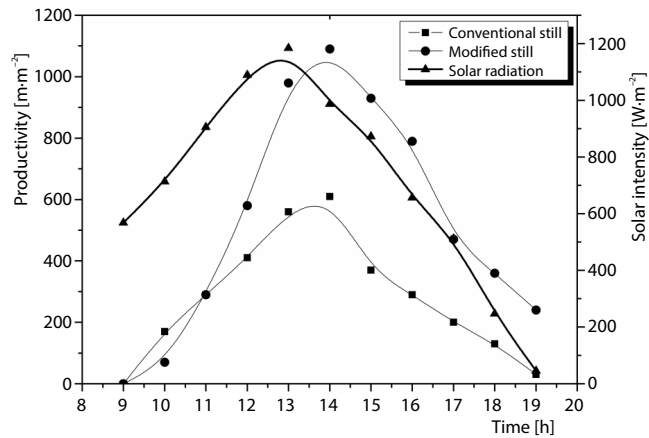


Figure 7. Hourly distillation of conventional solar still and modified stepped solar still

*Performance of modified stepped solar still with reflectors*

From fig. 8, it can be known that the glass temperature and basin water temperature of the modified stepped solar still with reflectors were higher than those of the conventional still. The mirrors were added onto the vertical sides of the steps of the stepped solar still to deflect a fraction of solar radiation on the step basin water. The top and bottom external reflectors were used to enhance energy input to the stepped still. It reflected  $1 \text{ m}^2$  surface area of solar energy into the water surface of the stepped still. As a result, the water temperature was increased. The evaporation rate was also enhanced. The evaporated steam rose up and supplied more latent heat of condensation thermal energy to the glass. Water was sprinkled continuously [9] on the glass surface to cool the glass cover. Consequently, the condensation rate was increased. The basin water temperature of stepped still was about  $25 \text{ }^\circ\text{C}$  in the morning and increased up to  $82 \text{ }^\circ\text{C}$  at mid-noon. The maximum water temperature was observed between 11 a. m. to 3 p. m. than was higher than that of the conventional solar still due to the increase in the energy absorbed by the solar still system. The increase of solar intensity enhanced the basin water temperature, which led to progress in the performance of the solar still at mid-noon.

Comparisons of the hourly variation of fresh water productivity for the modified stepped solar still with reflectors with the conventional solar stills are shown in fig. 9. It can be noticed that daily productivity reaches approximately 3480 mL and 8660 mL

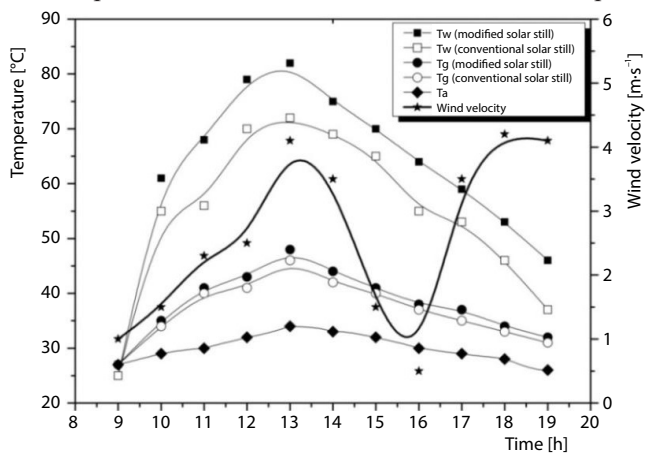
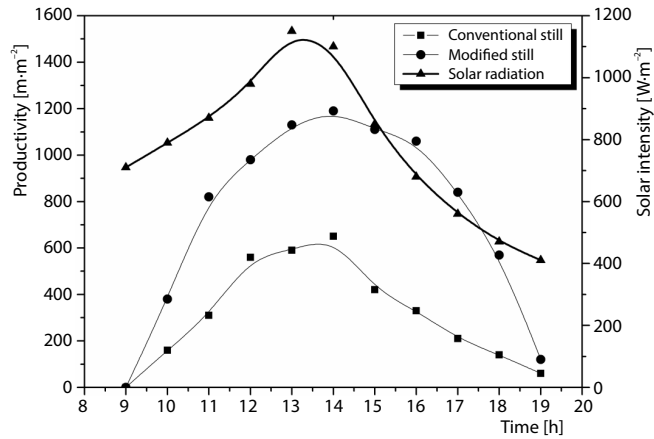


Figure 8. Comparative analysis of conventional solar still and modified stepped solar still with reflectors



**Figure 9. Hourly distilled water productivity of conventional solar still and modified stepped solar still with reflectors**

the maximum temperature of saline water. In addition, it can be observed that the fresh water productivity for the stepped still was greater than that of the conventional type at all times. The distillate production rate for each still was higher about one hour later than that of the peak solar radiation because of the heat capacity of the still.

### Error analysis

Table 1 shows the measure of error analysis for the various measuring instruments used in the experiments. The least error that occurs in any measuring instrument is equal to the ratio between its least count and minimum value of the output measured.

**Table 1. Accuracies and ranges of measuring instruments**

Instrument	Accuracy	Range	Error [%]
Anemometer	$\pm 0.1$ [ $\text{ms}^{-1}$ ]	0-15 [ $\text{ms}^{-1}$ ]	10
Kipp-Zonen solarimeter	$\pm 1$ [ $\text{Wm}^{-2}$ ]	0-5000 [ $\text{Wm}^{-2}$ ]	0.25
Measuring beaker	$\pm 10$ [mL]	0-1000 [mL]	10
Thermocouple	$\pm 1$ [ $^{\circ}\text{C}$ ]	0-100 [ $^{\circ}\text{C}$ ]	0.25

**Table 2. Cost of the units of different solar stills**

Components	Price in \$
Conventional still	80
Fins	0.8
Evacuated tubes (5 No's)	24
Pump 12 V	3.2
Solar PV panel 12 V	16
Stepped basin solar still	88
Two external mirrors and Internal mirrors	10.8

ing cost were negligible, since the overhead tank acted as reservoir to supply the brine water continuously and solar photovoltaic (PV) panel was used to run the pump. The overall total cost

for the conventional still and the stepped solar still with internal and external mirrors, respectively. In this case, the increase in distillate production for stepped solar still with mirrors was 148.8% higher than that of conventional still. It is found that there was an increase in the water productivity during the early hours of the day until it reached the maximum water productivity around midnoon at the peak solar radiation, then decreased as the Sun sets. In addition, it can be seen that the maximum productivity occurs at

### Economic analysis

The economic analysis discusses the payback period of the different solar stills. The total cost of a solar still includes fixed fabrication cost, variable maintenance cost and operating cost such as cost of feed water, throughout the year. Table 2 shows the cost of the units of the different solar stills. The maintenance cost and the operat-



and daily productivity of different solar stills were listed in tab. 3. The cost of distilled water per litre was \$ 0.16. The payback period was calculated from eq. (1) and it is mentioned in tab. 3.

$$\text{Payback period} = \frac{\text{Total cost of solar still}}{\text{Daily productivity of solar still} \times \text{Cost of distilled water per liter}} \quad (1)$$

**Table 3. Fabrication cost of different solar still per m<sup>2</sup> with its payback period**

Types of solar still	Price in \$	Productivity L per day	Payback period (No. of days)
Conventional solar still	80	3.3	152
Modified solar still	124	5.3	146
Modified stepped solar still	131.2	6.28	131
Modified stepped solar still with reflectors	142	8.6	103

### Conclusion

The performance of a stepped still with modifications on different conditions was investigated. The results show that the productivity of a modified stepped solar still with reflectors was improved through these modifications. The gap between the basin water and glass cover was less in the stepped solar still and it increased the evaporation rate. The heat transfer from the basin to water increased due to the flow of water, which enhanced the evaporation rate in the stepped still basin. Through the evacuated tubes, the water surface area exposed to solar radiation was 75% higher and solar energy input was higher. Internal reflectors reduced energy losses from the basin by deflecting a fraction of solar radiation to the stepped basin water. External reflectors supplied more solar energy to the still basin and evacuated tubes. The water depth was reduced owing to forced water circulation and so the evaporation rate was high. Sprinkled water supply removed more thermal energy from the glass cover. The productivity of the modified solar still, modified stepped solar still and the modified stepped solar still with reflectors and sprinkled glass cover cooling was 5300 mL per day, 6280 mL per day, and 8660 mL per day, respectively, in summer weather condition.

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