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Effect of orientation on the yield of low cost solar stills with coco peat and charcoal as an absorber material

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ABSTRACT

Effect of the orientation on the yield of the stills has been discussed in this experimental work. Two identical modified stills S1 and S2 fabricated, each with 0.5 m^2 of basin area. Stills had transparent glass walls with trough to collect the condensate from the walls. Mixture of highly porous coco peat and charcoal were used as basin material. Still S1 had North-South (N-S) orientation with cover slope due south whereas still S2 had East-West (E-W) orientation with cover slope due east. Experiments were conducted by changing the water quantity in the solar stills ranging from 5 to 10 kg. Maximum distillate output of 5.67 L/m^2-d was obtained for S1, whereas it was 5.45 L/m^2-d for S2 for an average solar radiation intensity of 695 W/m^2 (25 MJ/m^2-d). The increase in the yield of S1 over S2 due to the orientation was found to be in the range of 0% to 11%.Use of transparent walls increased the condenser area by 78.4%.The distillate water cost per litre was estimated as Rs. 0.86 (0.013 US$) and Rs.0.90 (0.014 US$) for S1 and S2 respectively. Energy payback time (EPT) for stills S1 and S2 was estimated as 4 months.

Keywords: Charcoal; Coco peat; Low cost; Distillation; Solar still

1. Introduction

The drinking water scarcity is one of the major problem several countries facing along with the energy shortage. There is an increase in demand for fresh water due to population explosion and industrial growth. However, most of the available water resources are polluted and the water is not suitable for direct consumption. Distillation is one of the best method to purify the polluted water. The amount of energy required for distillation is enormous and most of it comes from the fossil fuels. Use of fossil fuels for distillation have larger carbon footprint. India is a populous country with over a billion people. However, its most of the parts are blessed with bright sunshine almost throughout the year. More than 90% of places have annual average global horizontal radiation (GHI) in the range of 4.5–6.0 kWh/m^2-d. Use of solar energy for distillation is a win-win situation to solve the drinking water issue without any adverse impact on an environment. Basin type solar still is a simple and proven technology but with a disadvantage of low yield.

Many experimental studies were performed on various design of solar stills to improve the yield [1–4]. The yield of basin type still is dependent on operational parameters, design and environmental conditions. Environmental conditions are site specific and hence cannot be changed, however design and operational parameters can be changed to obtain higher yield. Still yield is directly proportional to the solar radiation intensity [5]. Solar radiation enters the still trough transparent covers and then

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absorbed by basin material to heat the water. The vapours then get condensed on the inside of the cover as distillate. Conventional still have opaque walls which block the radiations from falling into the basin during early and late hours of the day. The fraction of incoming energy equivalent to shaded area is lost due to wall shadow. A triangular pyramid still [6] was used over conventional still to reduce loss of incoming energy due to wall shadow. The design modification reduced the wall shadow and increased the distillate.

Basin material with high absorptivity and porosity will improve the evaporation rate resulting into the increased yield. Different absorber materials used [7] coated and uncoated metallic wiry sponges and black volcanic rocks, [8] different size sponge cubes, [9] light cotton cloth, sponge sheet, coir mate and waste cotton pieces. Heat storage materials stored the energy when it is extra and give off during non-sunshine hours. A variety of sensible heat storage materials [10–12] and latent heat storage materials [13,14] used to increase the yield after sunset. Different still designs were used like Pyramid [15], conical [16] triangular pyramid [6] and hemispherical stills [17] to improve the yield. Operational parameters like depth of water in the basin has significant impact on the yield and it reduces with increase in the water depth [18]. Other parameters like surface cooling [19], still operation under vacuum, force convection inside the still [15] and feed water temperature were investigated.

A.K. Singh et al. [20] investigated the double slope solar still and the effect of orientation on the yield. They performed numerical computation and data of daily solar radiation on surfaces facing different directions to conclude that still (β < 55°) with east-west orientation will produce maximum distillate in winter period. Trad Abderachid et al. [21] used simulation program to analyse the effect of orientation on the yield of double slope symmetric still and asymmetric still with double effect. They have found that with south-north orientation asymmetric still with double effect obtained 22.57% more distillate over symmetric still. Also, there is increase in yield by 16.76% for asymmetric still with south- north orientation compared to that of east-west orientation. IbrahemAltarawneh et al. [22] investigated single slope, double slope and pyramid stills and found that double slope still (β = 35°) with south orientation performed slightly better than other stills in summer.

The novelty of this solar still design over the conventional stills is the use of transparent walls with troughs. Transparent walls allows solar radiation to fall in the basin and avoids wall shadow. These walls also act as an extra condensing surface. The use of natural, biodegradable and highly porous mixture of charcoal and coco peat as a basin material may increase the distillate output of the stills.

The objective of this experimental work is to (a) to find out the effect of orientation on the yield of stills, (b) to estimate the cost per litre of distillate (c) to estimate energy payback time (d) to compare the yield and economics with other designs.

2. Materials and method

2.1. Construction of basin type solar stills

In this work two identical basin type of solar stills (S1 and S2) were fabricated. Fig. 1 shows the schematic diagram of the still. The solar still is divided into two parts 1. Tray and 2. Cover. The tray was fabricated using stainless steel sheet (1 mm thick) having about 0.5 m^2 (0.9 m × 0.58 m × 0.05 m) basin area. The walls of cover have height of 0.04 m and 0.26 m for low and high side respectively to get an inclination of 14°. The cover of the stills was fabricated with 4 mm thick window glass. The walls of the stills were kept transparent which allows the solar radiation to fall in to the basin. The inner surface of walls for stills acts as condensing surface along with the condensing cover with glass trough to collect the condensate (Fig. 2). The basin material used for S1 and S2 was a mixture of charcoal and coco peat of 20 mm thick (Fig. 3). The bulk density and porosity of coco peat was calculated through experiments and found in the range of 110–120 kg/m^3 and 0.72–0.75, respectively. Expanded polystyrene of 20 mm thickness was used as an insulation. Stills had been provided with insulation only

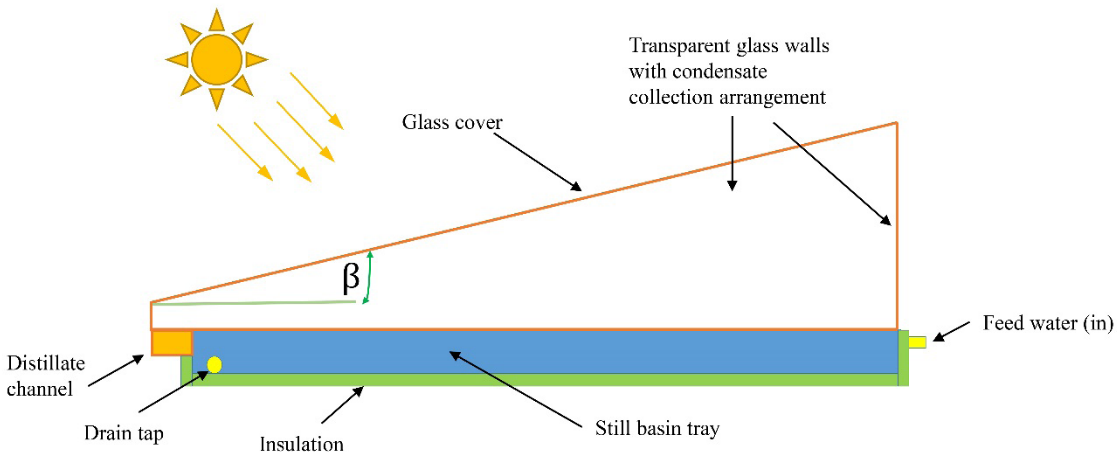

Fig. 1. Schematic diagram of solar still.

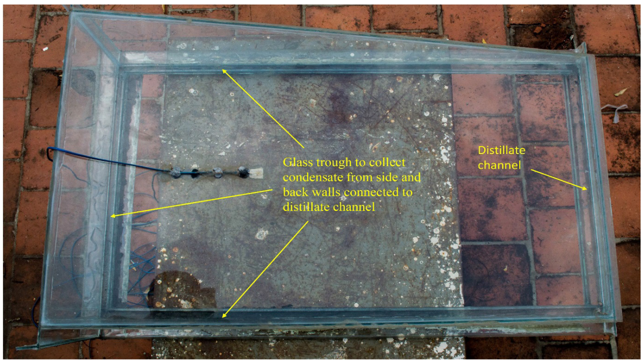

Fig. 2. Solar still with troughs to collect distillate at the walls (top view).

Fig. 3. Basin materials (a) coco peat (b) powdered charcoal.

on the tray sides and bottom. Silicone gel was used to stick glasses and glass putty was used between basin tray and cover to arrest water vapour leakage from solar still to the surroundings.

2.2 Experimental method

Experiments were carried at Solar Energy Lab, Department of Energy & Environment (DEE), NIT Trichy, Trichy (10.7589°N, 78.8132°E) during the months of February and March 2017 from 8.00 h to 18.00 h. Still S1 had North-South (N-S) orientation with cover slope due South whereas still S2 had East-West (E-W) orientation with cover slope due East. Stills were tested under similar atmospheric conditions to find out the exact improvement in their performance. Fig. 4 shows the photograph of the experimental setup. Stills were individually tested for 5 kg, 7.5 kg and 10 kg of water in the basin. Feed water was fed every morning before starting the experiment. The solar radiation intensity, basin water temperature, inner and outer glass cover temperatures and ambient temperature were recorded for every 10 s with the help of data logger. Distillate output was measured every hour using the measuring jar and recorded manually. Table 1 shows the accuracy and range of different instruments used for experimentation.

2.3 Efficiency of solar still

The hourly and overall efficiency of the solar still (η) calculated using Eq. (1):

Fig. 4. Experimental set up.

Table 1
Instrumentation details

S. No	Instruments	Accuracy	Range
1	Kipp & Zonen Pyranomter	± 1 W/m²	0–4000 W/m²
2	Thermocouple	±1 °C	0–100 °C
3	Measuring jar	± 5 ml	0–500 ml
4	Data Logger Yokogava GX20	±1 °C	0 to 100 °C
		±0.06 mV	–20 to 20 mV

Table 2
Cost breakdown of the components of stills

S. No	Components of still	Cost (Rs.)
1	SS basin tray (0.5 m²)	2000
2	Window glass cover (4 mm)	250
3	Window glass walls (4 mm)	200
4	Expanded polystyrene (20 mm)	50
5	Coco peat and charcoal	50
7	Silicone sealant tube (260 ml)	120
8	Glass putty (0.5 kg)	20
9	Labour (1 man day)	400
	Total cost in Rs. (US$)	3090 (48)

Note: 1 US$ = 64.2 INR (August 2016) (costs are based on Trichy market rates)

$$\eta = \frac{\sum m \times h_{fg}}{\sum IT \times A} \quad (1)$$

where m is the distillate collected, IT is the average solar radiation intensity, A is the basin area and h_{fg} is the latent heat of vaporization of water.

3. Results and discussion

Solar radiation intensity variation on 25th February, 25th March and 27th March, 2017 has been shown in Fig. 5. The solar radiation is at its peak value around 12.00 h

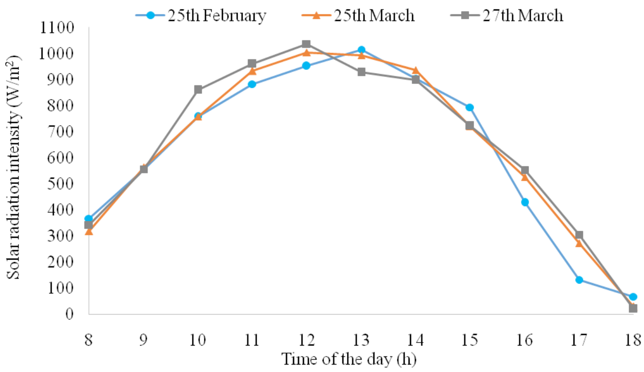

Fig. 5. Solar radiation intensity variation on 25th February, 25th and 27th March, 2017.

on 25th and 27th March whereas it was at 13.00 h on 25th February. The average solar radiation intensity during a time period of 8.00 h to 18.00 h was 671, 691 and 695 W/m^2 on 25th February, 25th March and 27th March, 2017 respectively. The relative standard deviation (RSD) value for average solar radiation intensity was 1.88%. The variation of ambient temperature with time of the day has been shown in Fig. 6. The average ambient temperature was 36.3°C, 38.0°C and 37.4°C on 25th February, 25th March and 27th March, 2017 respectively. The relative standard deviation (RSD) value for average ambient temperature was 2.32%. Ambient temperature rises steadily form 8.00 h and reaches peak value about 14.00 to 15.00 h and later decreases slowly with reduction in solar radiation intensity.

Figs. 7a,b and c represent hourly and cumulative yield of stills S1 and S2 with 5 kg, 7.5 kg and 10 kg water respectively. The hourly yield for S2 remains slightly higher than S1 during early morning hours. It remains higher up to 10.00 h, 11.00 h and 12.00 h with 5 kg, 7.5 kg and 10 kg water in the basin, respectively. This is due to the slope of still towards east and in the morning hours solar radiation is almost normal to the cover glass slope. The hourly yield reaches maximum value at 13.00 h for both S1 and S2 with all the three quantities of water in the basin due to highest solar radiation intensity value.

After 13.00 h hourly yield gradually decreases with decrease in the solar radiation intensity. The hourly yield decreases sharply with 5 kg water whereas it decreases gradually with 7.5 kg and 10 kg of water due to higher thermal mass in later. The cumulative yield for S1 and S2 was 5020 and 4640 ml/m^2, 5460 and 5240 ml/m^2, 5140 and 4990 ml/m^2 for 5 kg, 7.5 kg and 10 kg water in the basin, respectively during 8.00 h to 18.00 h. The overnight distillate output for S1 and S2 was 130 and 130 ml, 210 and 210 ml, 420 and 410 ml for 5 kg, 7.5 kg and 10 kg water in the basin, respectively.

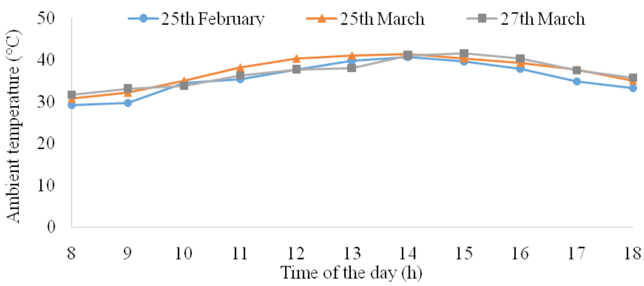

Fig. 6. Variation of ambient temperature on 25th February, 25th and 27th March, 2017.

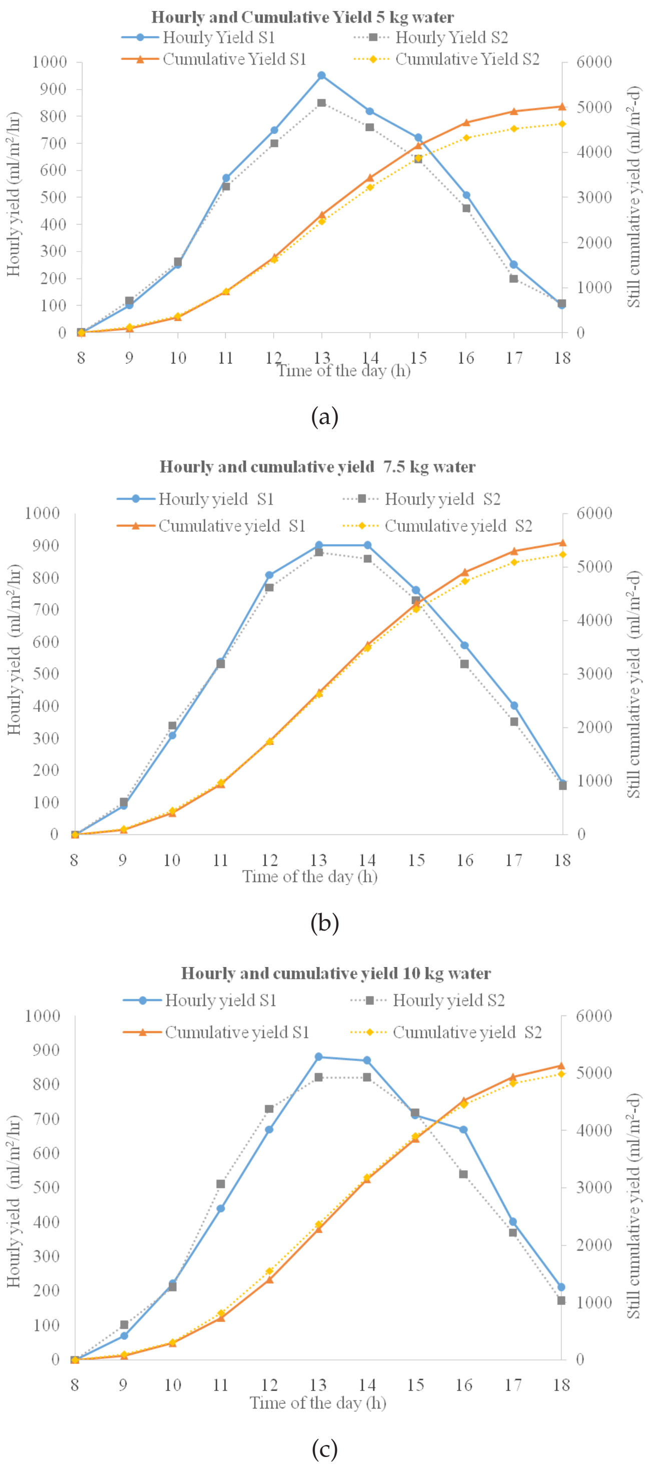

Fig. 7. Hourly and cumulative yield of S1 and S2 (a) 5 kg (b) 7.5 kg and (c) 10 kg water in the basin.

The distillate output of solar still is highly dependent on the basin temperature (Tb) and condensing cover temperature (Tg). The difference between the basin and glass temperature is the driving force for the distillation. Higher is this difference (Tb – Tg), higher will be the evaporation and ultimately more distillate output. This can be achieved by either increasing the basin temperature or by decreasing the glass temperature. The value of Tb can be increased by high absorptivity basin material like black painted basin or use of charcoal etc. The glass temperature Tg can be reduced by cooling the cover glass with water. Figs. 8a,b and c show the variation of basin and inner glass temperatures for still S1 and S2 with time of the day with 5 kg, 7.5 kg and 10 kg of water in the basin, respectively. In Fig.8a the inner glass temperatures (Tgi) is higher than that of basin temperatures (Tb) of S1 and S2. Still S2 is facing towards east direction and hence receives more morning radiation compared to the S1 which is facing south. The basin is consist of water mass with coco peat and charcoal mixture which takes time to get heated compared to that of glass cover and hence Tgi is more than Tb. As the solar radiation intensity increases with time of the day Tb slowly increases and becomes higher than Tgi around 11.00 h. After 12.00 h the difference between basin and glass temperatures (Tb – Tgi) keeps on increasing with time of the day. Fig. 8b represents the glass and basin temperatures for 7.5 kg of water in the basin. The inner glass temperatures (Tgi) are higher than basin temperatures (Tb) due to higher thermal mass to be heated. Tgi for S2 is higher than that of S1 due to the orientation of still. Tgi for both the stills remain higher than Tb approximately till 09.30 h and become lower after 10.00 h. The temperature difference (Tb – Tgi) keeps on increasing after 11.00 h throughout the day.

In Fig. 8c the glass temperatures (Tgi) are much higher than that of basin temperatures (Tb). The high thermal mass of 10 kg of water in the basin takes more time to get heated compared to the glass cover. At 11.00 h Tb and Tgi of respective stills are almost have same value. After 12.00 h the difference (Tb – Tgi) keeps on increasing due to the thermal storage effect and gradual reduction in solar radiation intensity.

Variation of the difference of the basin and glass temperature (ΔT) with time of the day has been shown in Figs. 9a and b for S1 and S2 respectively. The early solar radiation heats up the cover glass faster than basin water due to lower thermal mass. The slope of glass cover of S2 is towards east direction and hence it gets heated more compared to glass cover of S1 which oriented towards south. ΔT for S2 has higher negative value than that for S1 during morning hours. For S1 ΔT with 10 kg of water remains highest negative value up to 12.00 h due to higher thermal to heat and becomes highest positive value after 13.00 h due to the stored heat. Whereas for S2 ΔT with 10 kg of water remains highest negative value up to 13.00 h due to higher thermal to heat and becomes highest positive value after 15.00 h due to the stored heat.

Variation of the difference of the basin and glass temperature (ΔT) with time of the day has been shown in Figs. 10a, b and c for S1 and S2 with 5 kg, 7.5 kg and 10 kg water in the basin, respectively. ΔT value remains more negative for S2 during morning hours than that of S1. S2 attains higher positive value of ΔT after approximately 10.30 h, 12.15 h and 13.00 h than that of S1 for 5 kg, 7.5 kg and 10 kg of water in the basin, respectively. There is large difference between ΔT value of S1 and S2 at 5 kg compared to that of at 7.5 kg and 10 kg water in the basin. This is due to the higher thermal mass of basin water.

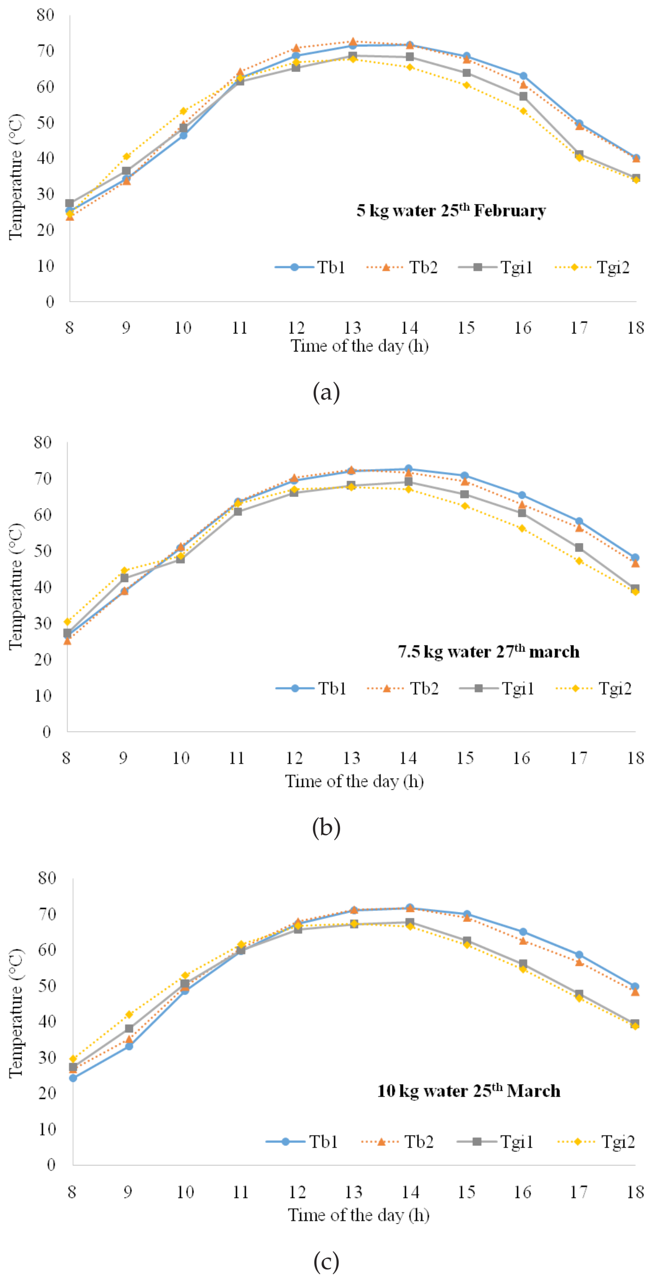

Fig. 8. Basin and inner glass temperatures for still S1 and S2 (a) 5 kg (b) 7.5 kg and (c) 10 kg water in the basin.

Yield of stills S1 and S2 on different days with 5 kg, 7.5 kg and 10 kg water in the basin with % increase in yield of S1 over S2 has been shown in Table 3. The minimum average solar radiation intensity during the experiments was 422.68 W/m^2 whereas maximum value was 695.40 W/m^2. The minimum yield was 3110 and 2900 ml/m^2-d whereas

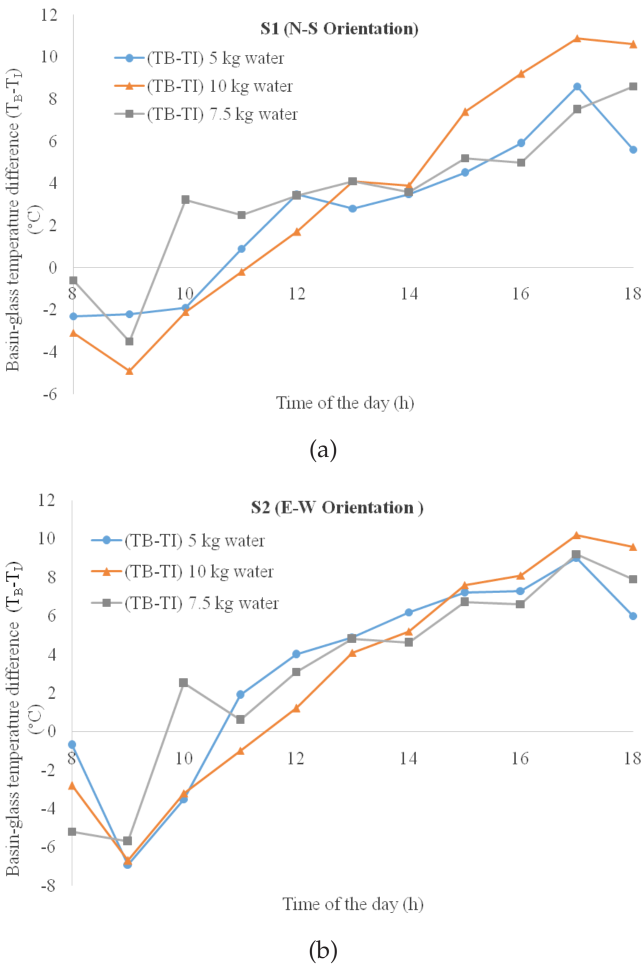

Fig. 9. Variation of difference of basin and glass temperatures with time of the day (a) S1 (N-S) (b) S2 (E-W).

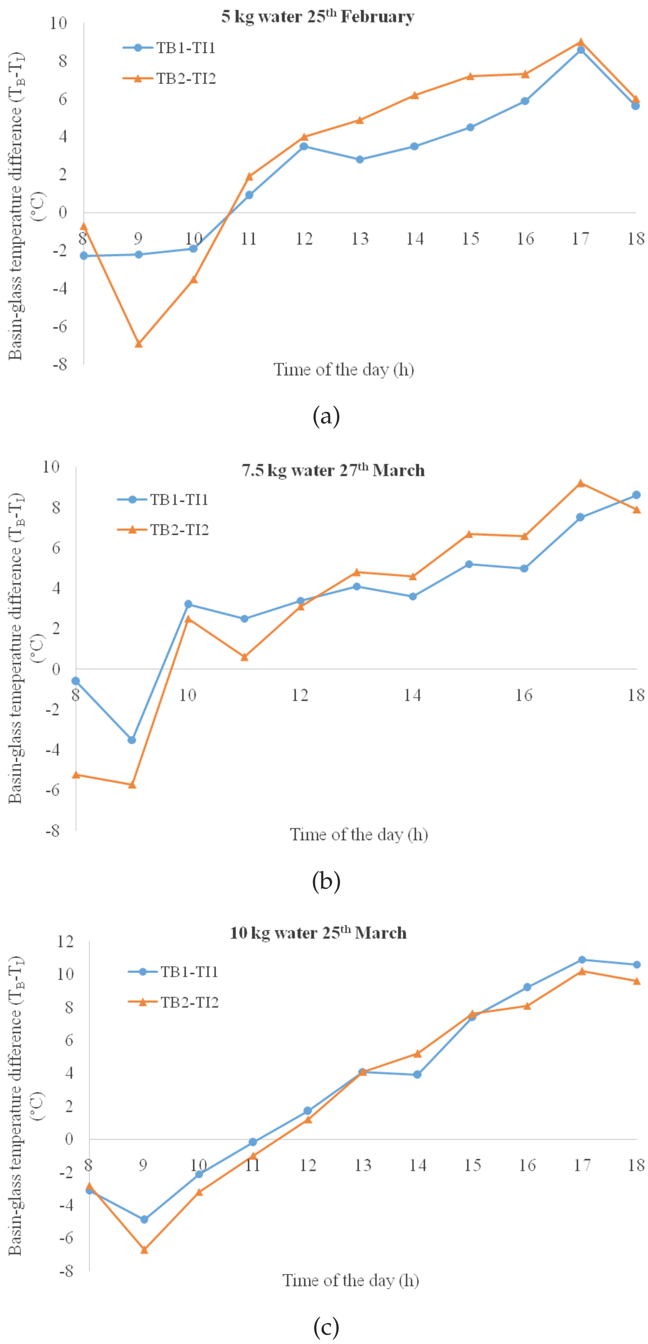

Fig. 10. Variation of difference of basin and glass temperature with time of the day (a) 5 kg water (b) 7.5 kg water and (c) 10 kg water in the basin.

maximum yield was 5670 and 5450 ml/m²-d for S1 and S2, respectively. The range of % increase in yield of S1 over S2 was from 0 to 10.9 %. The difference between the yields of S1 and S2 was higher at low water quantity (5 kg) in the basin compared to that of at higher water quantity (7.5 kg and 10 kg) in the basin.

4. Performance and enviro-economic analysis

4.1. Performance analysis

Comparison of present work with reported designs with respect to distillate output, still efficiency and cost of the still is presented in Table 4. Distillate output for the still depends on the climatic conditions and varies from place to place, however the still efficiency can be used to compare the performance of various stills form different places [23]. The present work has higher distillate output and low cost than most of the reported still designs. Also present still design has the highest still efficiency than that of the other stills (Table 4). The reason for higher yield is modified design and basin material. The basin material is biodegradable, cheap, easily available and highly porous. The glass walls avoids wall shadow by allowing the sunlight. Also the walls act as an extra condensing surface which results in increasing the distillate output.

4.2. Economic analysis

Economic analysis of stills S1 and S2 is discussed in this section. The average distillate output over the year could be estimated for S1 and S2 as 4.0 L/m²-d and 3.8 L/m²-d,

Table 3
Yield of S1 and S2 on different days with 5 kg, 7.5 kg and 10 kg water

S.No.	Date/Water quantity / Average solar radiation intensity (W/m^2)	Yield (ml/m^2-d)		% increase in yield of S1 over S2
		S1 (N-S)	S2 (E-W)	
1	23-02-2017 (5 kg) 661.18	5120	4560	10.9
2	24-02-2017 (5kg) 654.42	5120	4630	9.6
3	25-02-2017 (5 kg) 671.59	5150	4770	7.4
4	26-02-2017 (7.5 kg) 604.65	4870	4640	4.7
5	28-02-2017 (7.5 kg) 536.49	4020	3620	10.0
6	01-03-2017 (7.5 kg) 622.39	4940	4500	8.9
7	02-03-2017 (7.5 kg) 422.68	3110	2900	6.8
8	20-03-2017 (10 kg) 534.95	3970	3860	2.8
9	21-03-2017 (10 kg) 444.49	3300	3300	0.0
10	22-03-2017 (10kg) 551.89	4240	4180	1.4
11	23-03-2017 (10 kg) 620.611	4920	4850	1.4
12	24-03-2017 (10 kg) 693.73	5550	5430	2.2
13	25-03-2017 (10 kg) 690.97	5560	5400	2.9
14	27-03-2017 (7.5 kg) 695.40	5670	5450	3.9

respectively. The number of working days were taken as 330 days for Trichy, India excluding monsoon days. The cost breakdown of components and fixed cost of the still is given in Table 2. The total cost per litre of distillate is calculated using Eq. (2).

$$\text{TCPL} = \frac{\text{Total annual cost}}{\text{Total annual yield of still}} \tag{2}$$

Table 5 shows the economic analysis of the stills S1 and S2 and cost of the distillate per litre was estimated as Rs.0.86 (0.013 US$) for S1 and Rs.0.9 (0.014 US$) for S2.

4.3. Energy payback time (EPT)

Embodied energy is the total energy required to manufacture any product or services in addition to the energy consumed for transportation and other functions. This

Table 5
Comparison of economics

	S1 (N-S orientation)	S2 (E-W orientation)
Fixed cost, Rs.	6180	6180
Annual fixed cost, Rs.	1005.77	1005.77
Annual operating and maintenance cost, Rs.	201.15	201.15
Annual salvage value, Rs.	77.55	77.55
Total annual cost, Rs.	1129.37	1129.37
Total annual yield of still, L	1320	1254
Total cost per 1 litre distillate, Rs. (US$)	0.86 (0.013)	0.90 (0.014)

Table 4
Comparison of the present work with the literature reported values

S. No	Description	Location	Maximum Distillate Output	Total Cost (INR/US$ per m^2)	Overall Efficiency
1	Solar still with porous absorber and bubble wrap as an insulation [24]	India	2.9 L/m^2-d	57US$	NA
2	Variation of distillate output of the still based on specific height [25]	India	4.19L/m^2-d	9000 INR (136 US$)	39.59%
3	Inclined still with fin type absorber integrated with basin type still [2]	India	4.01 L/m^2-d	NA	40.90%
4	Still with reticular basin material [26]	Iran	3.829 L/m^2-d	61US$	37.00%
5	External condenser and agitation used in Single basin solar still [27]	India	2.67 kg/m^2-d	27400 INR	30.57%
6	Circular and square fins in the basin of solar still [28]	India	4.55 kg/m^2-d	154US$	NA
7	Single basin solar still with fins [29]	Egypt	5.07 kg/m^2-d	2764 LE (387 US$)	NA
8	Single slope solar still with heat sink as condenser [30]	Egypt	4.14 kg/m^2-d	NA	19.00 %
9	Pyramid still with absorber made from carbon fibres [31]	Jordan	3.33 kg/m^2-d	460 US$	NA
10	Single transparent walled still with integrated troughs and organic absorber material (N-S orientation) (Present work)	India	5.67 L/m^2-d	6180 INR (96 US$)	53.86%

NA- Not available

Table 6
Embodied energy of solar stills (S1 and S2)

S. No.	Materials	Weight (kg)	Embodied energy	Total embodied energy	
			(MJ/kg)	(MJ)	(kWh)
1	Window glass	10.26	15	153.9	42.75
2	SS basin tray	5.338	56.7	302.66	84.07
3	Expanded polystyrene	0.34	88.6	30.124	8.37
4	Silicone sealant	0.27	100	27	7.5
5	Glazing putty	0.5 kg	5.3	2.65	0.74

Total embodied energy (0.5 m^2 basin area) 143.43 kWh

concept can be used to find out time taken by energy saving or producing device to become CO_2 neutral. Embodied energy for the parts of the solar still has been given in Table 6.

Energy payback time (EPT) can be defined as time required to recover the energy used in the system. EPT of solar stills could be find out using the following Eq. (3) [32] :

$$EPT = \frac{\text{Embodied energy}}{\text{Yearly energy output from solar still}} \tag{3}$$

Energy payback time (EPT) has been evaluated using Eq. (3). Yearly energy output was estimated using average daily output of 4.0 kg/m^2-d for 330 working days. The EPT for S1 and S2 was found as 0.329 year (approximately 4 months).

5. Conclusion

Effect of orientation on the performance of stills S1 (N-S) and S2 (E-W) has been investigated in this work. The percentage increase in the yield of S1 over S2 due to the orientation was found to be in the range of 0% to 11%. The highest yield of 5.67 L/m^2-d and 5.45 L/m^2-d was obtained for stills S1 and S2 , respectively for an average solar radiation intensity of 695 W/m^2 (25 MJ/m^2-d). The difference between the productivities of S1 and S2 was higher at low water quantity (5 kg) in the basin compared to that of at higher water quantity (7.5 kg and 10 kg) in the basin. The energy payback time is approximately 4 months for both the stills and will further reduce with increase in the working days. Economic analysis shows that the cost of distillate per litre for 330 working days and 10 years of lifetime is about Rs.0.86 (0.013 US$) for S1 and Rs.0.9 (0.014 US$) for S2.

Nomenclature

A — Basin area (m^2)
h_{fg} — Latent heat of vaporization of water (kJ/kg)
i — Interest rate per year (%)
IT — Solar radiation intensity (W/m^2)
m — Quantity of distillate (kg)
m_w — Distillate output (mL/day)
M_y — Annual solar still distillate (kg)
n — Still life (years)
T — Temperature (°C)

Abbreviations

AFC — Annual fixed cost (Rs.)
AOMC — Annual operation and maintenance cost (Rs.)
ASV — Annual salvage value (Rs.)
EPT — Energy payback time (years)
FC — Fixed cost (Rs.)
PCM — Phase change material
RF — Recovery factor
RSD — Relative standard deviation (%)
S1, S2 — Solar still 1 and 2 respectively
TCPL — Total cost per litre (Rs. per litre)
TAC — Total annual cost (Rs.)

Subscripts

b — Basin
i — Inner glass surface
g — Glass

Greek symbol

η — Efficiency of basin type solar still (%)
β — Inclination angle (degrees)
Δ — Difference

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Appendix A

TAC = AFC + AOMC-ASV

AFC = FC × RF

$$RF = \frac{i \times (1+i)^n}{(1+i)^n - 1}$$

AOMC = 20%AFC

ASV = S × SFF

$$SFF = \frac{i}{(1+i)^n - 1}$$

Yearly energy output = $M_y \times h_{fg}$