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Comparative analysis on the proposed novel absorber configuration in a solar still

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ABSTRACT

Two solar stills were investigated by different absorbers under the same operating condition. A conventional flat basin absorber where the water is a single pool in a basin area of 0.5 m^2 and a modified solar still with a chess board type absorber (CBTA) are investigated. CBTA has divided compartments in which water fills alternatively in the boxes of an area of 0.02 m^2 each. This research mainly focuses on the increasing solar still's evaporation rate by CBTA at varying water depths of 2.5, 5, and 7.5 cm, respectively. Maximum productivity was obtained for the modified solar still with the proposed CBTA compared with the conventional basin absorber for all the variations in the depth of water maintained in both cases. The modified SS yields 3,086 mL/d of water for an absorber area of 0.5 m^2, whereas the conventional still yields 2,456 mL/d for a depth of 2.5 cm. The thermal efficiency of modified and traditional SS is 42.75% and 24.63%, respectively. The future scope of this CBTA can be varying the shapes of the absorbers like triangular, cylindrical, conical, star pattern, rhombic, and other possible forms. The limitation of the proposed system is that filling the water in the absorber is the major problem incurred.

Keywords: Chess board type absorber; Water depth; Evaporative heat transfer; Thermal efficiency; Water yield

1. Introduction

The desalination process using solar still is environmentally friendly, as it does not consume any electricity for its operation. The use of solar stills can be dated back to ancient civilizations. Based on the evolution of technology, various modifications in solar stills, from energy storage and reflectors to augmenting the absorber with solar collectors, solar ponds, waste heat recovery units, or internal changes such as fins, wick materials, etc.

Panchal et al. [1] performed the experimental analysis on a single basin solar still with the insertion of porous fins on the absorber plate; the distillate output of the solar still with fins had a 3.8-L rise than the conventional solar still, which had a 2.67-L yield. An overall increment in the efficiency of 42.3% using porous fins in the solar still. Sathish et al. [2] studied the modified solar still in which metal matrix structures acted as a sensible heat storage material and observed some improvements in the yield. Kabeel and Abdelgaied [3] experimented with a solar still with multi-groups of two coaxial pipes in the basin. The modified solar still with multi-groups of two coaxial tubes in the basin enhanced the distillate water productivity by 97.8%, 77.4%, 63.6%, and 52.7%.

Panchal et al. [4] tried different energy storage materials marble pieces and sandstones. The sandstone energy

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storage in the SS is more productive than marble pieces and ordinary SS. Nougriaya et al. [5] conducted a comparative review by focusing on the effects of different water depths (1–15 cm) and distillate yield is maximum at low basin water depths (1–2 cm). Selvaraj and Natarajan [6] reviewed several factors that induce the evaporation in the solar still such as solar radiation intensity, temperature difference, collector area, basin water depth, insulation, angle of inclination, the thickness of glazing, wind speed, and a few methods. Ali et al. [7] experimented with thermal behavior (evolutions of absorber and glass temperatures) and the water production performance of the modified SS with pin fins absorber and condenser. They compared the results with the conventional setup. The effect observed was the SS with simple pin fins absorber, which had a water production gain of 14.53% compared to the traditional still. Agrawal et al. [8] compared the theoretical and experimental results for single-sloped basin-type SS. For solar stills, daily distillate output decreased with an increase in basin water depth. The theoretical value of daily efficiency for 2 and 10 cm basin water depths was around 52.83% and 41.75%, respectively. The experimental daily efficiency for the same basin water depth was around 41.49% and 32.42%, respectively. Tuly et al. [9] provide extensive reviews on some essential designing and operating factors, including distinct and combined parameters suitable for solar desalination systems and increasing SS productivity. The optimum yield is from a single slope, single basin SS, in summer and winter when the glass cover inclination angles are 15° and 45°, respectively. Bhargva and Yadav [11], in their review of various parameters affecting the productivity of a SS and yield improvement methods. Hollow fins offer a larger surface area for absorbing solar radiation and transferring heat from the absorber plate to water than solid fins. Furthermore, unlike concrete fins, hollow fins lighten the absorber plate [12], and yield increases for the smaller water depth because of maximum heat captivation and quick evaporation rate at minimum water depths.

The quantity of water at 1 cm depth is smaller than water at other depths, implying that heating and evaporation will take less time. Another crucial factor is that more heat is transferred from the liner with connected fins to the water than at other depths [13]. Younes et al. [14] used half-barrel and corrugated absorbers in their experimental work to improve the wick-type SS performance. Corrugated wick SS gives the best productivity compared with conventional SS, because of the high evaporation area and minimum mass of water in the basin. Dhivagar [15], in their review on productivity maximum nocturnal productivity, observed in solar pond-assisted stepped SS; focusing on separating water into several steps and improving the yield. Arunkumar et al. [16], in their review on an effectively combined passive SS setup, mentioned that tubular SS integrated with SiO_2-NPs blended with black paint and fins on the tubular basin produced 6.4 L/m^{2}d with an evaporation efficiency of 53%. The concept of tubular SS comes closer to the motive mentioned in this research to split the water into compartments. Modi and Nayi [17] in the experimental work on the effectiveness of enforced condensation and imposed evaporation with heat energy storage material on square pyramidal condenser type SS. In solar stills with pushed evaporation, the fan makes the nonstop motion of the air-water vapor mixture. The induced flow of the air-water vapor mixture grounds the forced convective heat transfer. It raises the heat transfer coefficient at the condensing surface, which reciprocates as a higher condensation rate. Modi and Modi [18] in the research on the effect of the wick heap of jute fabric on the distillate yield of double basin single slope SS, higher production was achieved for the SS and the wick pile of jute fabric. Wick heaps in the SS act as a region for enhancing the film evaporation of the water fraction rather than allowing the pool evaporation of water ultimately.

Dumka et al. [19], in the experimental research on the SS, with sand-filled glass bottles as the sensible heat storage materials, the setup yield increased by 21.32% compared to the conventional design. Jathar et al. [20] A marginal increase in the output was observed in the probe of the concave-type stepped SS because of the concave curvature in the steps. Essa et al. [21]. The least amount of water absorbed in the wick. Additionally, the rotation of the wick belt influences the transition from free to forced evaporation, increasing the evaporation rate. Palanikumar et al. [22], in the research of a solar box-type cooker, solar energy is captured by the absorber surface, which heats the vessel in the solar box, and the concentrated power from the solar box transfers to the pot for the cooking purpose. Abd Elaziz et al. [23] their research suction fan and an external condensation system are integrated with the SS and observed an increase in the yield of SS. Li et al. [24] In the balanced thermal evaporator, the areas of S_{ab} and S_{ev} are roughly equal, and the distribution of heat energy in sensible and latent heat is roughly equated. This category includes 2D evaporators with absorbent materials modified on the surface of porous materials, which have a higher evaporation efficiency (70%–80%). This research focuses on the performance of SS using the absorber above the design. It includes a detailed comparison of modified and conventional stills and the effect of water depth in both stills.

A new CBTA is proposed in the scope of this investigation to improve the basin-type SS daily productivity. The solar still basin has various rectangular compartments, and water fills into the alternative boxes, that is, one water-filled container, the next empty container, and so on. The advantage of this kind of water arrangement is that water evaporation is faster when compared to conventional basins in the SS. The empty compartment gets heated faster when compared to the water-filled box and continuously transfers the stored heat to the water-filled box to attain thermal equilibrium. So, it acts as an augmented heat source in the still and enhances evaporation. Even though the mass of water stored is less than conventional stills, less water's evaporation occurs faster. A mass pool of water requires more heat for its evaporation because the specific heat of water is high, but the smaller the quantity of water, the less heat is necessary for its evaporation.

2. Experimental methodology

The experiment was set up at SSM Institute of Engineering and Technology, Dindigul, India (10° 21′ 56.0916″ N). The basin size is 1 m × 0.5 m × 0.02 m. The basin had been coated with suitable black paint of high absorptive nature

(Absorptivity α = 0.96) (Thurmalox 250) and acted as a black body. The solar still is insulated with foam sheets to minimize the heat loss to the surroundings. This setup is covered on the top with 4 mm thick glass with a 25° inclination [11]. The glazing consisting of glass with a maximum transmissivity (>90%) is selected to produce a greenhouse effect in the SS. The material used for the basin is galvanised iron. Fig. 1 shows the schematic diagram of the modified SS.

In solar applications, the factors considered are the absorptivity of the basin material [10] and the life cycle of the absorber surface (15 y in the case of solar water heating applications) while choosing the material (Table 1). The absorber surfaces are subjected to continuous thermal loads diurnally, so the optimum materials are selected to sustain the thermal efficiency in the process.

The absorber basin has divisions, so the same design acts as augmented energy storage. The initial heating time required for a single pool of water is a maximum since the specific heat of water is high. Suppose the same basin has several alternatively filled compartments with only a tiny quantity of water in the still. In that case, it requires less heat to raise the water's temperature [13]. The rectangular absorber of dimensions 1 m × 0.5 m has five divisions (0.2 m² × 0.1 m²) into the long and the broader sides (Fig. 2). The basin has 25 compartments, 13 compartments are water-filled, and 12 containers are empty to enhance the evaporation in the setup. The area proportion of the compartment is 51% area of water-filled bins and 49% of empty boxes.

Using Dunkle's mathematical model calculates evaporative heat transfer (Q_{ewg}) from basin water to glass cover (W/m²) for both the conventional and modified SS.

Evaporative heat transfer is maximum for all the water depths in the modified stills because the internal heat generation in the 12 empty compartments adds heat to evaporate the still water in the remaining 13 compartments (Fig. 3).

Table 1
Absorptance of various metals

Metal	Normal solar absorptance
Aluminum	0.09–0.10
Aluminum anodized	0.12–0.16
Chromium	0.42
Copper polished	0.35
Iron	0.44
Nickel	0.34–0.43

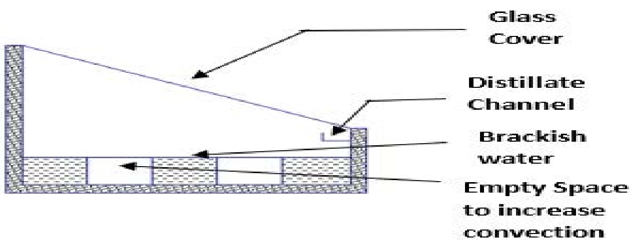

Fig. 1. Schematic diagram of the modified solar still.

Fig. 3. Photographic view rectangular box of modified solar still.

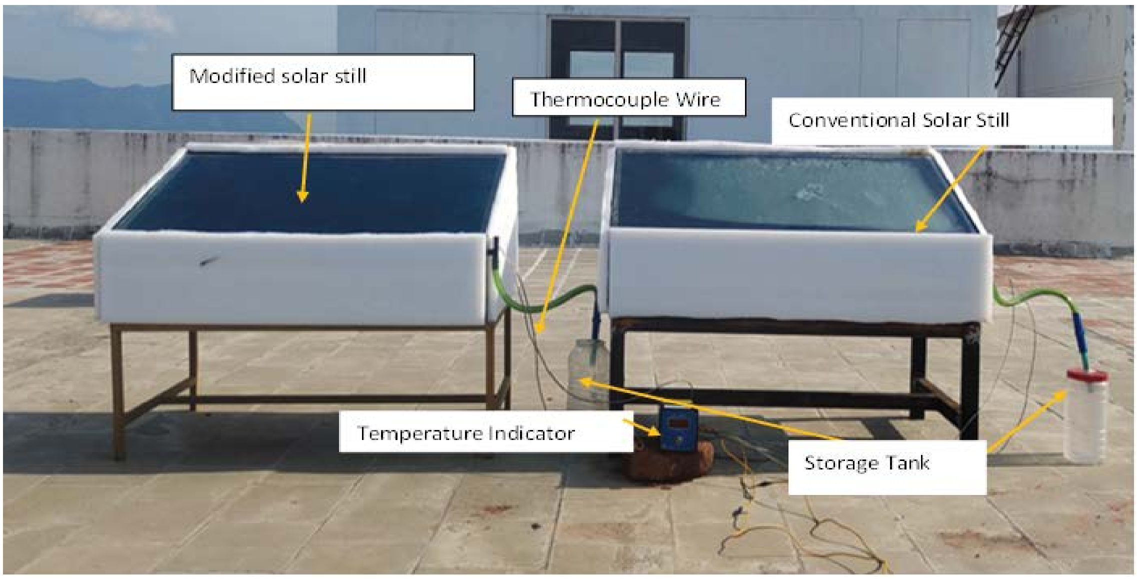

Fig. 2. Photographic view of conventional and modified solar still.

$$Q_{ewg} = h_{ewg}\left[T_w - T_G\right] \text{ [8] Abhay Agarwal et.al} \quad (1)$$

The evaporative heat transfer (Q_{ewg}) is maximum for the modified SS with CBTA configuration-water depth of 2.5 as shown in Table 2.

Mu et al. [25] mentioned the context of thermal resistances happening in the solar desalination process and made future recommendations to make a less resistive path between water and the condensing surface of the glass. So, to make the least resistive, the water is split into the number of compartments as per the proportions (51% water surface and 49% empty surface).

3. Experimental procedure

The experimentation of the solar stills was performed at SSM Institute of Engineering and Technology, Dindigul, India (10° 21′ 56.0916″ N) in April-May 2021.

The primary goal of the experiments was to evaluate and forecast SS performance. Every hour, various parameters such as irradiance, water temperature, ambient temperature, glass temperature, basin temperature, exergy analysis, and water productivity of the experimental setup get noted.

When water stagnates in a conventional passive SS, the large pool of water takes much time to get heated if the same water splits several discrete pockets/boxes—the stored heat by leaving some boxes empty in the basin for a CBTA enhances the evaporation. Alternative boxes fill with water, and in-between containers are vacant to create a local high-temperature region inside the SS. Heat flux inside the modified SS is highly increased, confirmed by the basin water temperature reading (Fig. 5). A thermal balance evaporator [24] uses the sensible heat produced in the absorber to augment the latent heat of the evaporator so that evaporative heat transfer escalates.

Brackish water is filled manually by pouring water into the boxes and maintaining the water level at a certain depth. The basin's water depth also affects water evaporation [6], so different depth levels (2.5 cm, 5 cm, 7.5 cm) are tested on both the conventional and modified SS. The solar still yield is always high for the minimum water depth level, along with changed conditions, which gives a very high yield. Incoming solar radiation [$I(t)$] and its variation with time are in Fig. 4. These data are constant for the specific location.

The instruments used in the research are thermocouples with a digital indicator for temperature measurements—a pyranometer for measuring solar irradiation.

Table 2
Accuracy, a range for different measuring instruments

S. No.	Instrument	Accuracy	Range
1	Pyranometer	±5 W/m²	0–2,000 W/m²
2	Thermocouple	±1°C	−100°C–500°C
3	Measuring flask	±1 mL	0–250 mL

4. Uncertainty analysis

The uncertainty analysis identifies incongruity between the real and the computed values as an error. Type A and type B are two types of ambiguity errors. Random errors are Type A errors with a mathematical and repeated series of readings. Systematic errors are Type B errors measured by calibration reports of the instruments.

The operating range and correctness of the equipment used are in Table 2.

Standard uncertainty inference from the following mathematical equations.

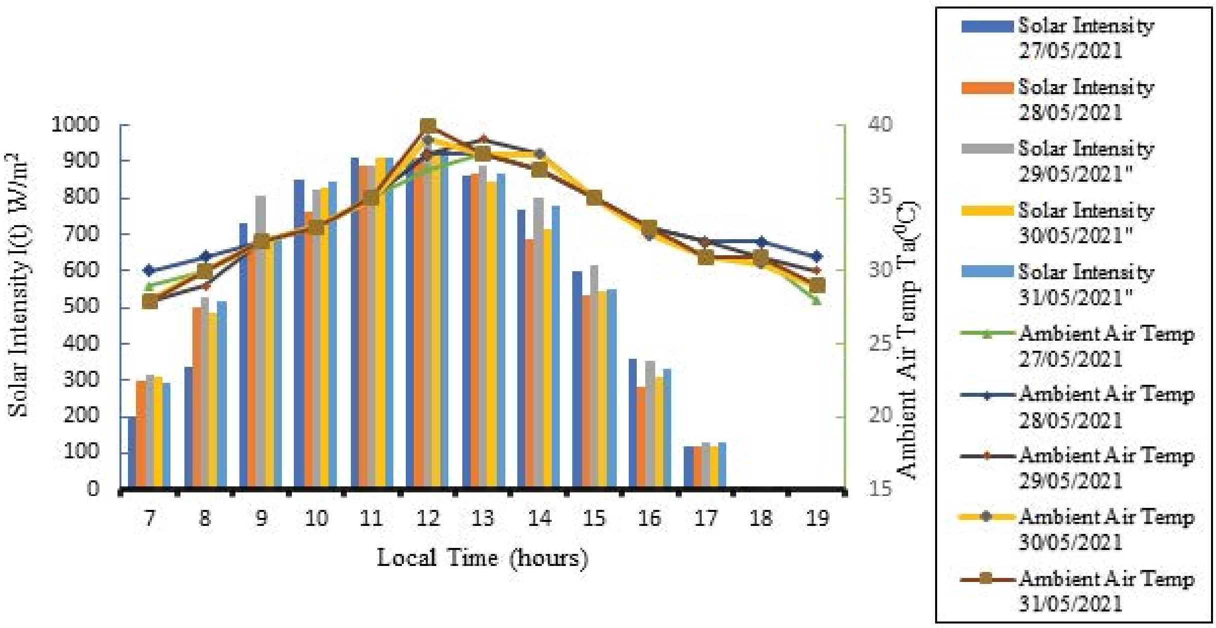

Fig. 4. Hourly variation in solar radiation Intensity.

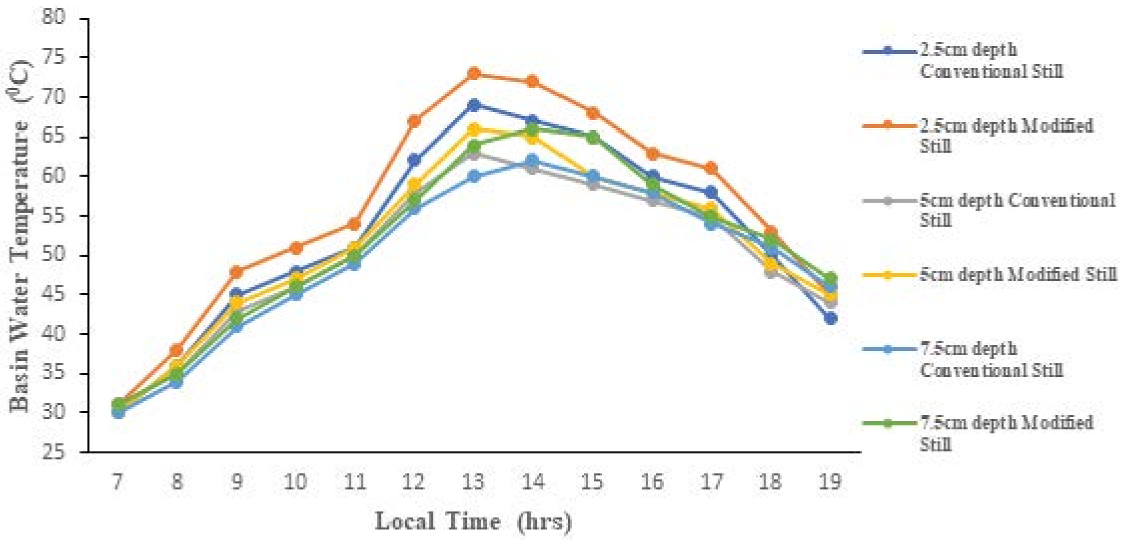

Fig. 5. Hourly variation of basin water temperature.

$$u = \frac{a}{\sqrt{3}} \tag{2}$$

where u is the standard uncertainty and a is the measuring device accuracy.

5. Energy and exergy analysis

The exergy of a solar still at a given state is the maximum freshwater yield extracted from it till it reaches the state of thermodynamic equilibrium with its surroundings. Exergy input from the solar radiation that evaporates the water, exergy output of the solar still freshwater condensate.

Heat balance equations for a single slope- single basin solar still for energy and exergy analysis. The following assumptions simplify the analysis.

- The thermal capacity and thermal resistance of the glazing are negligible.
- SS is tightly sealed.
- Heat loss from the basin bottom and side walls of SS is assumed to be negligible.
- A steady state condition is assumed for heat transfer in SS.

The evaporative and convective heat transfer between basin water and the beneath the glass cover of SS. Calculated from the Eqs. (3) and (4) [8],

$$q_{\text{ewg}} = h_{\text{ewg}}\left[T_w - T_G\right] \tag{3}$$

$$q_{\text{cwg}} = h_{\text{cwg}}\left[T_w - T_G\right] \tag{4}$$

where heat transfer coefficients for evaporation and convection by Dunkle's empirical relations [29],

$$h_{\text{ewg}} = \left(16.28\times10^{-3}\right)h_{\text{cwg}}\frac{\left(P_w - P_g\right)}{\left(T_w - T_g\right)} \tag{5}$$

$$h_{\text{cwg}} = 0.884\left[\left(T_w - T_g\right) + \frac{\left(P_w - P_g\right)\left(T_w + 273\right)}{\left(268.9\times10^{3} - P_w\right)}\right]^{1/3} \tag{6}$$

The following equation can calculate the hourly mass of water evaporated per unit basin area. [8],

$$M_w = \frac{\left(h_{\text{ewg}}\left(T_w - T_g\right)\times 3{,}600\right)}{\left(L_{\text{ev}}\right)} \tag{7}$$

The total daily mass of water evaporated from the SS is calculated using the relationship [8],

$$M'_w = \sum_{i=1}^{24} M_w \tag{8}$$

The daily thermal efficiency (η_d) of the SS is given by the relation:

$$\eta_d = \frac{M'_w \times L_{\text{ev}}}{A_b \times \sum I(t)\times 3{,}600} \tag{9}$$

Exergy input expression of SS is given by Petela [26],

$$\text{Ex}_{\text{in}} = \text{Ex}_{\text{sun}} = A_g \times I(t)\times\left[1 - \frac{4}{3}\times\left(\frac{T_a}{T_s}\right) + \frac{1}{3}\times\left(\frac{T_a}{T_s}\right)^4\right] \tag{10}$$

The exergy output of SS is obtained as [27]:

$$\mathrm{Ex}_{\mathrm{in}} = \mathrm{Ex}_{\mathrm{out}} = \mathrm{Ex}_{\mathrm{evp}} = h_{\mathrm{ewg}} \times A_b \times \left(T_w - T_g\right)\left(1 - \frac{T_a}{T_w}\right) \tag{11}$$

The hourly exergy solar efficiency of the SS is expressed as [28]:

$$\eta_{\mathrm{ex}} = \frac{\text{Energy output of solar still}\left(\mathrm{Ex}_{\mathrm{evp}}\right)}{\text{Energy input of solar still}\left(\mathrm{Ex}_{\mathrm{sun}}\right)} \tag{12}$$

6. Results and discussion

From the experimental research, Basin water temperature plays an essential role in the condensate yield, and the efforts to increase the basin water temperature in the modified SS were fruitful. The modification proposed in this research is optimum way to increase the freshwater yield and it can be replicated to other types of SS. From Fig. 5 the curves of the modified still show that the water temperature for the modified still is greater than the conventional stills for the various depth levels of water tested in this research.

The evaporative heat transfer for the modified SS is more than the conventional SS [Fig. 6], which proves more convection and evaporation takes place in the modified SS, and it is reciprocated as the freshwater yield.

The efficiency calculation from the above equation and from the calculated values bar chart is prepared (Fig. 7). We can infer that modified SS with lower water depth of 2.5 cm are good (42.75% efficiency) compared with conventional SS (24.63% efficiency). The continuous colossal volume of water will not give the maximum yield for the passive heating, from the calculate values (13.99%) for the basin water depth of 7.5 cm and for modified SS about (21.25%).

The after-effect of modification that the study proposed is inferred from the above bar charts (Fig. 8). The experimental productivity of the solar still also confirms that the change proposed is a significant one. The productivity of the modified is more than the conventional still for all three cases. Due to enhancement in the evaporative heat transfer, the mass transfer also gets increased. Heat and mass transfer complement each other; the temperature difference between the water and glass cover is the driving factor for heat transfer, achieved through our proposed CBTA configuration. The attained heat transfer complemented the required mass transfer and increased the condensate.

From Fig. 9 we can observe that during the peak hours (1.00 p.m., 2.00 p.m. and 3.00 p.m.) of sunshine during the daytime, the yield of fresh water from the still is maximum. Because of the increase in the intensity of solar insolation in the peak hours, the basin temperature increases, and the rate of evaporation increases. Again, for the modified SS, the yield is maximum for all the depths of water levels when compared with conventional SS.

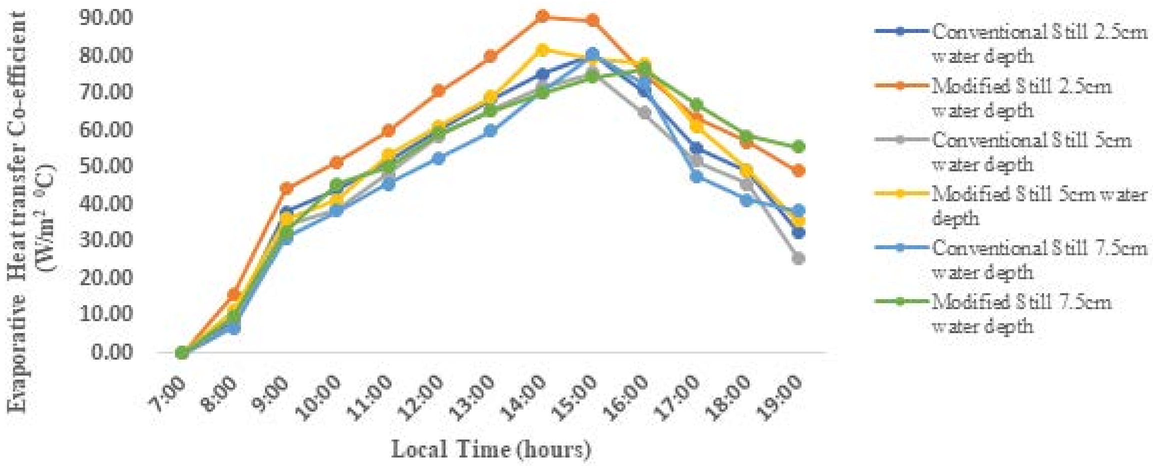

Fig. 6. Evaporative heat transfer in solar still.

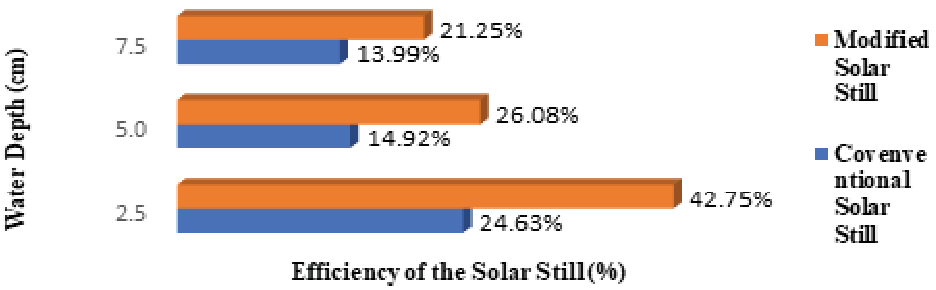

Fig. 7. Efficiency of the solar still for various depths.

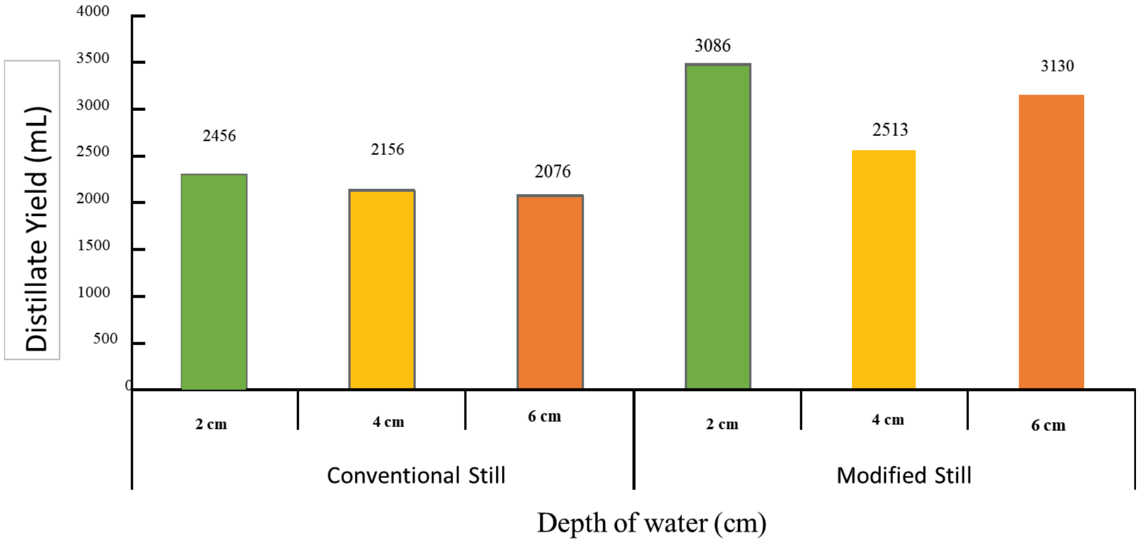

Fig. 8. Experimental mass yield (mL/m^2) of solar still at various water depth conditions.

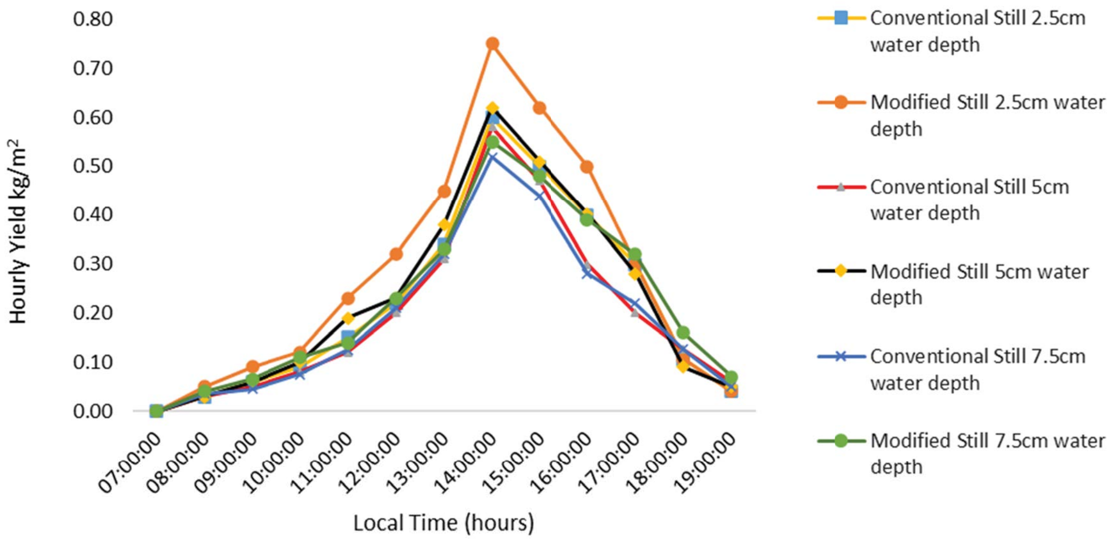

Fig. 9. Variation of hourly yield with respect to time in the solar still.

Fig. 10 depicts the hourly variation of exergy input and exergy output for a solar still with a 2.5 cm basin water depth. The exergy input gradually increases and reaches a maximum of 442.64 W at noon, after which it decreases until the evening hours. Exergy output gradually increases till 1:00 p.m. for modified SS, getting a maximum value of 74.04 W. Following that, the value of exergy output gradually decreases until sunset in the evening hours. Because of exergy destruction at various components of the solar still, the importance of exergy output is much lower than those of exergy input.

Fig. 11 indicates that the exergy efficiency rapidly rises from 12:00 p.m. to 1:00 p.m. After that, it gradually decreases with decreasing solar radiation intensity starting at 1:00 p.m. Even though solar radiation decreases from 12:00 p.m., hourly exergy efficiency increases and achieves the maximum value at 1:00 p.m. Maximum exergy efficiency is attributable to the heat stored within the basin water from 7:00 a.m. to 12:00 p.m. As a result, the basin water temperature remains high despite the low solar radiation during the afternoon. The maximum hourly exergy efficiency is 13% for 2.5 cm at 1.00 p.m. As a result, the evaporated mass of water produced by the solar still at that time is more significant.

7. Conclusion

Many researchers concluded the fact that the depth of basin water makes an impact on the productivity of the SS. However, it is evident that even though the water depth is made lesser in the SS, the continuous volume of water exists in the SS; hence, it cannot be considered the optimum solution. The optimum way is to divide water into several

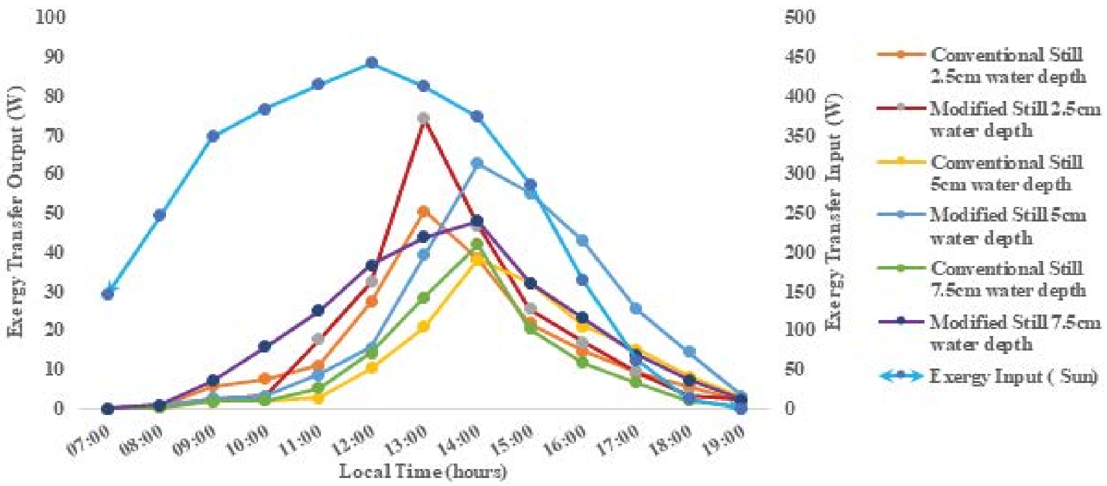

Fig. 10. Variation of hourly exergy transfer in the SS of area 0.5 m².

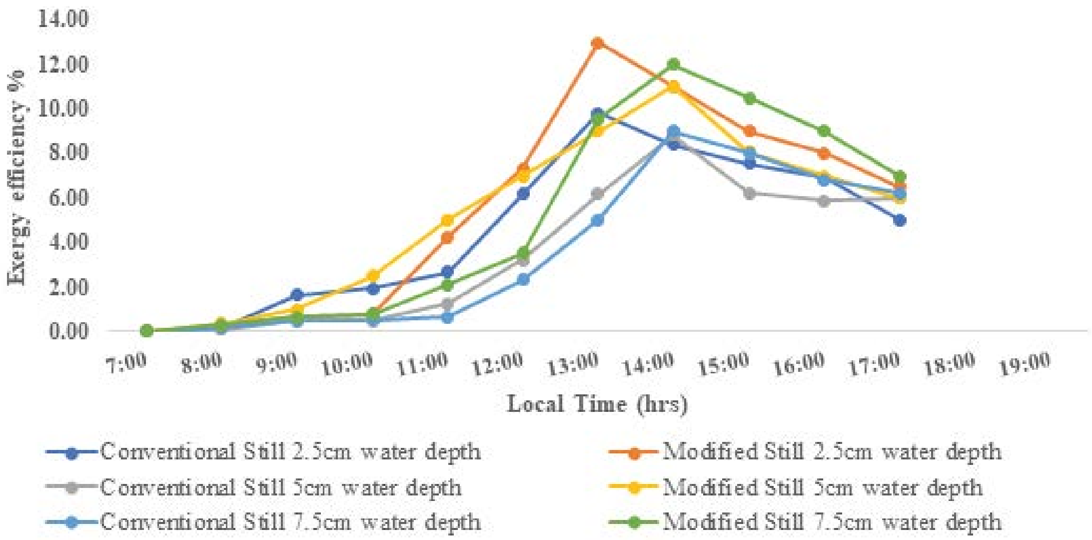

Fig. 11. Variation of hourly exergy efficiency in the SS of area 0.5 m².

compartments and give enough empty boxes to augment the convection and evaporation for the same lower water depths. From the experimental research, we can conclude the following facts.

- The experimental yield is maximum (3,086 mL/d) for the modified SS whereas the conventional SS yields 2,456 mL/d there is an increase of 25.6% freshwater yield in Modified SS for the water depth of 2.5 cm and 0.5 m² area.
- The improved distillate yield attributes to CBTA in the modified SS, which has a higher evaporative heat transfer coefficient of 110.91 W/m². In contrast, the conventional SS has an evaporative heat transfer coefficient of 63.98 W/m² for a depth of 2.5 cm.
- The maximum thermal efficiency of modified SS is 42.75%, while conventional SS is 24.63% for a 2.5 cm water depth.
- The Exergy for the modified SS is a maximum of 74.1 W and for the conventional SS is 50.4 W. The available energy for the modified SS is higher because of the proposed CBTA.
- The exergy efficiency for various water depths of modified SS is higher when compared to conventional SS. The maximum exergy efficiency is 13% for the modified SS with a 2.5 cm water depth at 1.00 p.m.
- The proposed modification in this research integrated to solar ponds, SS with energy storage, reflectors, solar collectors, and Photovoltaic thermal systems. CBTA configuration can act as a basis for efficiency improvisation in SS and pave the way for future research.
- Filling the water in the absorber is the major problem incurred, but this could have been rectified by providing ducts between the compartments to ease the water flow.

Symbols

a	—	Measuring device accuracy
A_b	—	Area of basin, m^2
A_g	—	Glass cover area of solar still, m^2
$\mathrm{Ex}_{\mathrm{in}}$	—	Exergy input of solar still, W
$\mathrm{Ex}_{\mathrm{out}}$	—	Exergy output of solar still, W
h_{cwg}	—	Convective heat transfer coefficients
h_{ewg}	—	Evaporation heat transfer coefficients
$I(t)$	—	Insolation with respect to time, h
L_{ev}	—	Latent heat of vaporization of water, J/kg
M'_w	—	Daily mass of water evaporated per unit basin area, kg/m^2·d
M_w	—	Hourly mass of water evaporated per unit basin area, kg/m^2·h
P_G	—	Partial saturated vapor pressures at glass cover temperature, N/m^2
P_w	—	Partial saturated vapor pressure at a basin water temperature, N/m^2
q_{cwg}	—	Convective heat transfer from basin water to glass cover, W/m^2
q_{ewg}	—	Evaporative heat transfer from basin water to glass cover, W/m^2
T_a	—	Ambient temperature, °C
T_G	—	Glass cover temperature, °C
T_s	—	Sun temperature, °C
T_w	—	Basin water temperature, °C
u	—	Standard uncertainty
η_d	—	Total daily energy efficiency of solar still
η_{ex}	—	Hourly exergy efficiency of solar still

Conflict of interests

No conflict of interest for this research.

Appendix A

For numerical calculation, we have used the following formula:

$$P_w = \mathrm{EXP}\left\{25.317 - \frac{5,144}{T_w + 273}\right\}$$

$$P_g = \mathrm{EXP}\left\{25.317 - \frac{5,144}{T_g + 273}\right\}$$

To calculate the latent heat of vaporization:

$$L_{\mathrm{ev}} = \left(2501.67 - 2.389T_w\right)103\frac{\mathrm{J}}{\mathrm{kg}}$$

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