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Investigation on evacuated tubes coupled solar still with condenser and fins: Experimental, exergo-economic and exergo-environment analysis

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ABSTRACT

The present experimental work was done to check the performance enhancement in distillate productivity between CSS and MSS in climatic conditions of Gandhinagar, Gujarat, India (23.21° N, 72.63° E). In modified solar still (MSS) fins, evacuated tubes and newly designed zig-zag shape air-cooled condenser were attached. An MSS was prepared to achieve the higher temperature in water inside the basin and maintain a lower temperature of glass cover than CSS. The highest obtained water temperature and temperature of inner glass cover for CSS and MSS were 63.75 °C & 69.21 °C and 54.37 °C & 54.93 °C separately. Modified solar still gives around 6 °C higher water temperature by maintaining the same inner glass cover temperature as CSS. The maximum distillate output for CSS and MSS was 2.26 kg/m^2 and 3.92 kg/m^2, respectively. It gives 73.45% of higher productivity than CSS. In a thermal analysis of a system, higher fractional exergy evaporation could be achieved for MSS. Also, in the still with different modifications, higher thermal efficiency was obtained. In cost analysis, the water achieved for CSS and MSS were 0.013 and 0.015 USD/L, respectively. Exergo-economic and exergo-environmental analysis for MSS shows that the modified system was highly beneficial from economic point of view and generation of less carbon value by CO2 mitigation.

1. Introduction

Clean water is a major requirement for all human being's lives on the earth. The sources of pure water on the earth are very limited; also, these sources are not equally distributed according to the country-wise population. Many countries of the world, like Africa, people suffer from clean water for drinking purposes. Another side in America compares to its population the sources of clean water are too much [1–5]. Impure or dirty water creates many diseases and problems in the human body; according to medical science, 5 L of clean water require only for drinking per person [6–10]. Also, clean water demands in many other sectors like agriculture, industrial, household, etc. So to fulfill the demand for clean water for drinking and another purpose, it is necessary to move towards the other available sources like seawater. But it is not directly useful for drinking and another purpose. To use seawater directly, it is necessary to remove the saltiness of the water. The method which removes the salinity is known as desalination [11–15].

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Abbreviations

Subscripts

SBSSSS	Single basin single slope solar still
CSS	Conventional solar still
MSS	Modified solar still
SSSS	Single slope solar still
SSS	Stepped solar still
DSSS	Double slope solar still
SS	Solar still
V1	Valve 1
V2	Valve 2
V3	Valve 3
PTC	Parabolic trough collector
PAC	Primary annual charge
CRA	Capital recovery aspect
YSV	Yearly salvage value
SC	Salvage cost
SFA	Sinking fund aspect
YUC	Yearly upholding cost
OAC	Overall annual cost
CPL	Cost of water per liter
CCP	Value of carbon credit generation
gi	inner surface of the glass cover

Variable

a	area, m^2
C	heat capacity, J/kg °C
I_t	total solar radiation, W/m2
k	thermal conductivity, W/m K
l	latent heat, J/kg
T_a	Ambient temp. (°C)
T_w	Basin water temp. (°C)
T_{gi}	Inner glass cover temp. (°C)
T_{cond}	Condenser temp. (°C)
I	Solar intensity (W/m^2)
A_{bw}	Basin area of water (m^2)
A_g	Inner glass cover surface (m^2)
$h_{e,bw\text{-}ig}$	Coefficient of evaporative heat transfer (W/m^2 K)
$h_{c,bw\text{-}ig}$	Coefficient of convective heat transfer (W/m^2 K)
$E_{xc,bw\text{-}ig}$	Convection exergy value for water and glass cover (W/m^2 K)
$E_{xe,bw\text{-}ig}$	Evaporation exergy value for water and glass cover (W/m^2 K)
%	Percentage in distillate output
η_{exe}	Exergy efficiency
$\varphi ex,co2$	Value of environmental exergy
R_{ex}	Value of economic exergy
C	Capital cost
m	mass, kg
n	constant
P	partial vapor pressure, N/m2
Pr	Prandtl number
Q	Heat flux, W/m2
R	Thermal resistance, m^2 K/W
t	passed time from starting the operation, s
T	temperature, °C
V	average of wind velocity, m/s
x_{ins}	thickness of insulation, m

Greek letters

η	thermal efficiency, %
φ	latitude

In the desalination method, there are many techniques available, but that solar desalination is one of the simple and economically feasible. With the help of solar energy, this technique could work, so it is renewable. Solar desalination is an easily accessible and non-polluting method. It is useful for the reason where the problem of electricity occurs [16–21]. Solar still (SS) is a device that works on solar desalination systems. On that top side is covered with glass, which passes solar radiation to basin water; after receiving solar radiation, the basin water is evaporated. Due to evaporation and condensation, the distilled water could be achieved from solar still [22–26]. In solar still, there are two types: active and passive. In the active method, some additional mechanical devices are attached with solar still, which work with electricity. In the passive method, no additional device is attached, so it could work without electricity [27–30]. In a passive solar still, the distillate output remains very low, around 1.5 to 1.7 L per day, which does not satisfy the daily drinking water demand of one person [31–34].

Many researchers have used different methods to enhance the daily distillate output of solar still. The performance of solar still is affected by the intensity of solar radiation, atmospheric temperature, basin water depth, differences in temperature, inclination angle, the thickness of insulation, glass cover thickness, basin area, the latitude of the city [35]. Prasad et al., 2021 [36] experimentally investigated that by changing the design of basin area of still from square to triangular, around 12% of higher distillate could be achieved compared to square basin solar still. A review is done by Panchal and Mohan 2017 [37] that attachment of fins, energy storage materials, and modifying the solar still with multi-basin area increase the efficiency of solar still. The shape of the absorber area also affects the performance of solar still. Compare to a flat surface, the convex and concave surface of the absorber gives around 57% and 30% of higher distillate productivity; Gawande and Bhayur 2013 [38]. Nougriaya et al., 2021 [39] found that solar still with a water depth of 1–2 cm gives the optimum performance with other water depth, also; by the addition of energy storage materials like paraffin and PCM, the day and night productivity could also be increased. Double slope solar still gives a better distillate output than single slope. The addition of energy storage materials within solar still improves its performance; Rajamanickam et al., 2021 [40]. Vigneswaran et al., 2021 [41] done experimental work using different absorbing material with basin and check the effect of phase change material. They found that low thermal conductivity material gives higher efficiency than galvanized material. Kamal et al., 2020 [42] used a heater as an external device to preheat the water and added energy storage materials to increase the heat storage capacity of water. With this modification, a 15% higher water temperature is achieved. Elfasakhany A 2016 [43] have used a copper-paraffin wax as a nanomaterial with basin water. It gives around 125% of higher distillate than conventional solar still. To increase the absorber surface area, fins are attached in a basin of solar still by Kateshia and Lakhera 2021 [44]. Attachment of fins increases the productivity up to 125%. Kaviti et al., 2021 [45] conduct an experiment on double basin solar still with different depths of water using truncated conic shape fins to improve the distillate yield. They have achieved a maximum distillate at 1 cm depth of water. Abdelgaied et al., 2021 [46] done the experiment with SS using square and circular fins. Panchal et al., 2020 [47] done experimental and water quality analysis of solar still using vertical and inclined fins. They found that both vertical and inclined fins have a higher effect on the performance of solar still compare to conventional solar still. Sathyamurthy et al., 2020 [48] conducted a study that by increasing the surface area of still with fins, higher thermal performance could be achieved. Abu-Arabi et al., 2020 [49] have used a flat plate collector as an external collector to increase the distillate productivity. Madiouli et al., 2020 [50] used a flat plate collector, parabolic concentrator, and packaged glass ball layer as an absorbing material with solar still and achieved 203% of higher distillate yield than conventional solar still. Subramanian et al., 2021 [51] prepared a pyramid tray-shaped absorber surface to reduce the gap between glass cover to absorber area in pyramid shape type solar still. A flat plate collector was also attached to preheat the basin water of still. To improve the thermal efficiency and reduce the problem of stagnant in ordinary flat plate collectors, a new spiral shape collector was designed by Verma et al., 2020 [52]. Choudhary et al., 2020 [53] used nanomaterials and FPC with SS to check thermal performance. Mohamed et al., 2020 [54] used an evacuated tube in a parabolic trough concentrator area and achieved 28% higher performance than CSS. Panchal et al., 2020 [55] placed a vacuum tube to preheat the water and calcium stone as a heat storage material with single basin solar still. They have used fourteen evacuated tubes and achieved 5.31 L of daily distillate. Abu El-Maaty et al., 2021 [56] have used evacuated tubes in solar water systems for fog desalination. Dubey et al., 2021 [57] coupled evacuated tubes with double slope solar still operated by pump to check energy and exergy analysis of a system. They achieved around 33.8% and 4.9% of energy and exergy efficiency. To increase the delay period of heat release, Papadimitratos et al., 2016 [58] used a vacuum tube and energy storage material to desalinate the water. This system could work improvably in the absence of solar radiation. Tuly et al.,

Table 1
Comparison of previous researchers work attachment with fins, energy storage materials, evacuated tubes and condenser.

Sr.	Author	Type of solar still	Work done	Productivity Enhancement (%)
1	Panchal and Mohan [13]	SSSS	Hollow triangular fins attached	34.2
2	Vigneswaran et al. [41]	SSSS	Phase changing materials used	19.1
3	Elfasakhany A [43]	SSSS	Copper- paraffin wax nano materials used	125
4	Kaviti et al. [45]	DSSS	Conic shape fins with 1 cm of constant water depth	44
5	Panchal et al. [47]	DSSS	Vertical and inclined fins were used	24
6	Madiouli et al. [50]	SSSS	FPC, PTC and Packaged glass ball layer as energy storage material	203
7	Panchal et al. [55]	SSSS	Evacuated tubes with energy storage materials	113
8	Dubey et al. [57]	DSSS	Attached evacuated tubes	33.8
9	Tuly et al. [59]	DSSS	Attached fins, energy storage materials and external condenser	24.7
10	Rahmani et al. [61]	SSSS	Used an external condenser	29
11	Patel et al. [62]	DSS	Used an external helical cooling coil condenser	20
12	Hassan et al. [63]	SSSS	Aluminum finned heat sink condenser	41.95

2021 [59] checked the performance of double slope solar still with the attachment of fins, energy storage materials, condenser, and without it. They found that attachment of condenser increases 10% more distillate productivity of SS. Toosi et al. [60] observed, attaching condenser with SS maintains the difference of temperature between water and glass covers and gives a significant improvement in daily yield. Rahmani et al., 2021 [61] check the effect of solar still with the condenser in all seasons and found that the performance of the condenser is varied with a season by season. Patel et al., 2021 [62] conducted an experiment with the attachment of a condenser for the cooling effect of vapor. They observed that the condenser reduces the pressure of vapor inside the basin area and increases evaporation, which gives a higher distillate output. Hassan et al., 2020 [63] checked the performance of solar still with glass type condenser and aluminum pin fin condenser. They achieved higher performance in aluminum fin condenser compare to glass condenser. Table 1 summary shows the work carried by different researchers on SS with fins, condenser, evacuated tubes, and energy storage materials.

In the above section, the discussion was made on enhancing the performance of CSS with the attachment of energy storage materials, nano materials, flat plate collector, parabolic trough collector (PTC), fins, evacuated tubes, and condenser and by changing the design/configuration parameter.

2. Objective of present research work

The objective of the present experimental work was to increase the distillate output of SS. In CSS, heat losses are a major problem that reduces the efficiency of solar still. So it is necessary to reduce it. The lower difference in water and inner glass cover temperature significantly affects on distillate output of SS [64]. In the present experimental work, a comparison was made between CSS and solar still with the attachment of fins, zig-zag shape air-cooled condenser, and evacuated tubes. To preheat the water inside the basin and lowers the temperature of the glass cover, evacuated tubes and condensers were used. In a previous study, it is not found that any researchers have conducted an experiment on single basin single slope solar still coupled with fins, zig-zag shape air-cooled condenser, and evacuated tubes at once. The design of the condenser is a zig-zag shape, which gives more volume and space to condense the vapor.

3. Experimental set up

The experiment was conducted in month of February 2021 to March 2021 in Gandhinagar city to compare in distillate productivity between CSS and MSS.

3.1. Construction and design of solar still

In the present experimental work, two SS were prepared from a wooden box. One conventional and other modified solar still. MSS was coupled with fins, evacuated tubes, and condenser. In Fig. 1, the 3D view of MSS is shown. The dimension of both the stills is the same, having a basin area of 1 m × 1 m. The absorbing surface was prepared from Galvanized iron material and painted with black color to absorb more solar radiation. To reduce the leakage of heat, a silica gel was used. The top surface of solar still is covered with 4 mm thickness of glass. To pass the solar radiation on basin water, transparent glass was used. It was placed at an angle of 23.7° latitude of Gandhinagar city. In MSS, the fins were attached to increase the surface area of the absorber. In this vertical fins were attached, which was made from aluminum material having dimensions of 3 mm diameter and 60 mm height [65]. To preheat the basin water, six

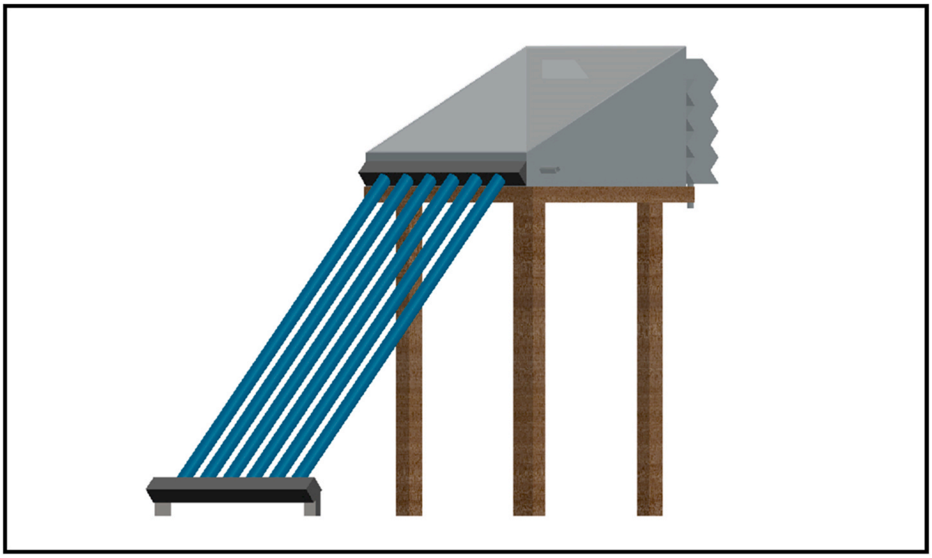

Fig. 1. Modified solar still.

evacuated tubes were attached with solar still. The dimensions of the evacuated tube were: 58 mm outside diameter, 1800 mm length. It is made from borosilicate glass material. In the solar still, the difference of temperature between glass cover and water plays an important role. To maintain this difference of temperature, a zig-zag shape air-cooled condenser was used. To give more space for condensation of vapor zig-zag shape condenser was used. A condenser was made from galvanized iron material. The dimensions of the condenser are 80 cm × 20 cm × 50 cm (l × b × h). In Fig. 2, the 3D view of the zig-zag shape air-cooled condenser is shown.

3.2. Experimental procedure

The experiment was conducted to check the performance enhancement of SBSSSS with the attachment of fins, evacuated tubes, and condenser under the circumference of Gandhinagar, Gujarat, India (23.21° N, 72.63° E). Here an experimental comparison was made between CSS and MSS. To achieve more solar radiation, the direction of glass cover for both the solar still was concerned with easy-west direction [66–69]. Figs. 3 and 4 shows the schematic and real view of the experimental setup. The experiment was conducted by maintaining a constant water depth of 3 cm for both solar stills. The reason for lower water depth is that Failizadeh et al., 2016 [70] have made an experimental study that with a lower depth of basin water, a higher evaporation rate could be achieved due to the lower volumetric heat capacity of water. A solenoid valve was attached, which keep the constant level of water and compensate for the water evaporated. The fins, evacuated tubes, and condenser were attached with MSS. The reason behind the attachment of evacuated tubes and condenser is that evacuated tubes increase the evaporation rate, and the condenser lowers the temperature of the glass cover. During experimental work, distilled water was collected from the distillate trough of CSS, MSS, and condenser area. The collected distillate water was measured in a measuring jar on an hourly basis. To avoid the leakage of vapor and re-evaporation of collected water, the distillate trough was kept covered.

During experimental work, the different parameters like atmospheric temp. (Ta,°C), The intensity of solar radiation (I, W/m2), Water temp. (Tw,°C) and Glass cover temp (Tgi,°C) for both solar still, condenser temperature (Tcond.,°C) for MSS, and wind speed were measured. The temperatures at different intervals of solar still were measure using k-type thermocouples. Here solarimeter and anemometer were used to measure solar radiation and the speed of the wind. The experimental readings for both CSS and MSS were taken from morning 7:00 a.m. to next day morning 6:00 a.m. (24 h) for all experimental days. The measured readings were recorded using ARDUINO based data logger for 24 h on all days.

3.3. Thermal analysis

To calculate daily efficiency of solar still following equation was used [71]:

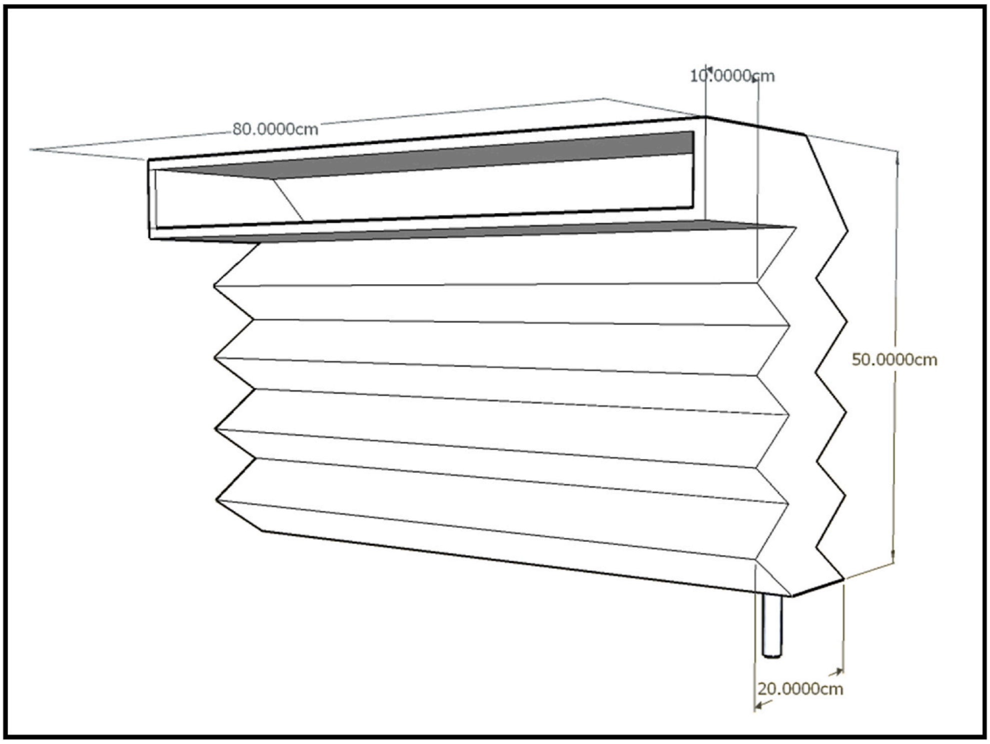

Fig. 2. Zig zag shape air cooled condenser.

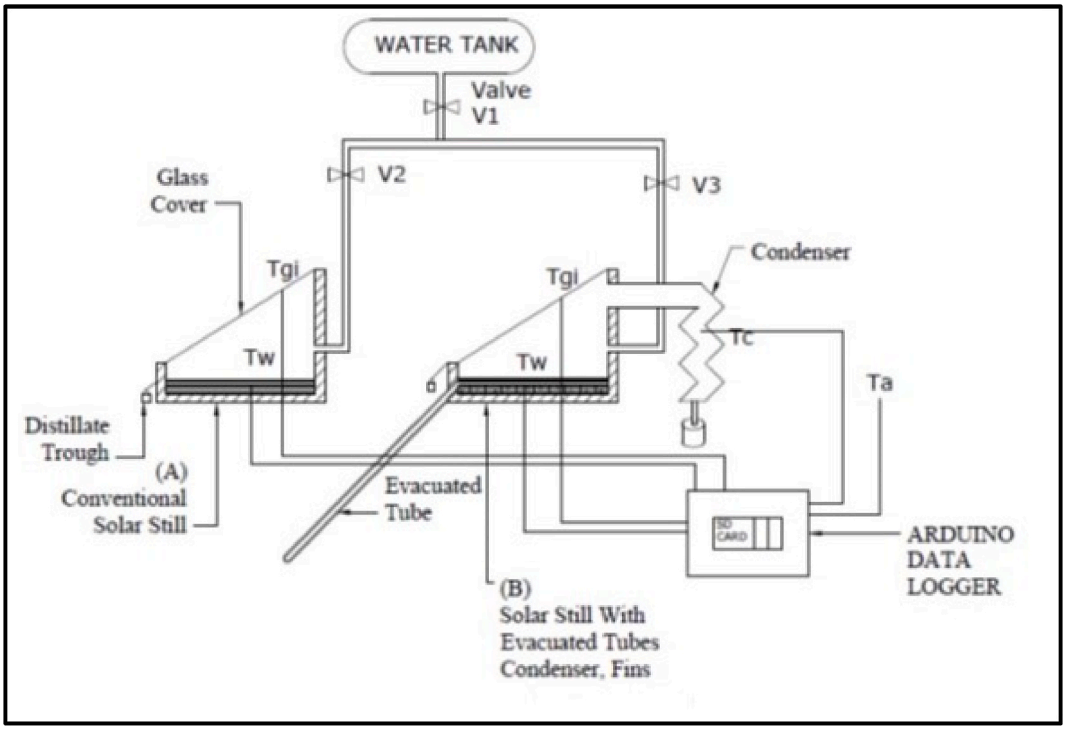

Fig. 3. Schematic diagram of (A) conventional and (B) modified solar still.

Fig. 4. Experimental set up.

$$nD = \frac{\sum mD \times hlg}{\sum Ag \times It} \tag{1}$$

Here, m_D = total sum of hourly distillate yield in day (kg), h_{lg} = latent heat of evaporation (J/kg), it can be calculated using equation (3) [71,72]], A_g = Surface area of glass cover (m^2), I_t = Average value of daily solar radiation (W/m^2)

$$h_{ig} = \left[2501.9 - 2.40706T_{bw} + 1.192217 \times 10^{-3} \times T^2{}_{bw} - 1.5863 \times T^3{}_{bw}\right] \tag{2}$$

Here, T_{bw} = Average value of basin water (°C).

Using following equation the convection exergy value for basin water and glass cover ($Ex_{c,bw\text{-}ig}$)was calculated [73].

$$Exc,bw\text{-}ig = hcbw\text{-}ig \times \times Abw \times (Tw - Tig) \times \left(1 - \frac{Ta}{Tbw}\right) \tag{3}$$

Here $h_{c,bw\text{-}ig}$ = Convective heat transfer coefficient (W/m^2 K), which can be found by Eq (4), A_{bw} = Basin area (m^2), T_{ig} = Temp. of glass cover and Ta = Atmospheric Temp.

$$hc,bw\text{-}ig = 0.884 \left\{ (\mathrm{Tbw} - \mathrm{Tig}) + \frac{(Pbw - Pig)(Tbw + 273.15)}{268900 - Pbw} \right\}^{1/3} \tag{4}$$

Where, P_{bw} = Partial pressure of basin water vapor and P_{ig} = Partial pressure glass cover surface (N/m^2), It can be calculated by following equations [73].

$$Pbw = \exp\left(25.317 - \frac{5144}{Tbs + 273}\right. \tag{5}$$

$$Pig = \exp\left(25.317 - \frac{5144}{Tig + 273}\right. \tag{6}$$

The evaporation exergy value for basin water and glass cover surface ($Exe, bw\text{-}ig$) can be found using following equation [73].

$$Exe,bw\text{-}ig = he,bw\text{-}ig \times Abw \times (Tbw - Tig) \times \left(1 - \frac{Ta}{Tbw}\right) \tag{7}$$

Where $h_{e,bw\text{-}ig}$ = Evaporative heat transfer coefficient between water basin and glass cover (W/m^2 K), it can be calculated using equation (8).

$$h(e,bw\text{-}ig) = 16.273 \times 103 \times hc,bw\text{-}ig \times \left[\frac{Pbw - Pig}{Tbw - Tig}\right. \tag{8}$$

The total value of exergy heat transfer for basin water and glass cover can be calculated done using Eq. (9) [73].

$$Exti = ht \times Ag \times (Tbw - Tig)\left(1 - \frac{Ta}{Tbw}\right. \tag{9}$$

Where h_t = Total heat transfer coefficient for basin water and glass cover surface (W/m^2 K), It could be using following Eq. (10)

$$h_t = h_{e,bw-ig} + h_{c,bw-ig} \tag{10}$$

The evaporation and convection fractional exergy value could be found by Eq. (11) and Eq. (12) [73].

$$Fe,bw\text{-}ig = \frac{Exe,bw\text{-}ig}{Exti} \tag{11}$$

$$Fc,bw\text{-}ig = \frac{Exc,bw\text{-}ig}{Exti} \tag{12}$$

To find out exergy efficiency (η_{exergy}) following Eq. can be used

$$\eta exer = \frac{Exout}{Exinp} \tag{13}$$

Here, Ex_{out} = $Ex_{e,bw\text{-}ig}$ and Ex_{inp} = Exergy for absorbed solar radiation, which can be determined using Eq. (14)

$$Ex_{inp} = Ex_{sun} = Abw \times It \times 1 - \frac{4}{3} \times \left(\frac{Ta + 273.15}{Ts}\right) + \frac{1}{3}\left(\frac{Ta + 273.15}{Ts}\right)4 \tag{14}$$

Where, Ts = temperature of sun ⁅ 6000 K).

4. Results and discussion

The experimental set up was prepared as shown in Figs. 8 and 9, and readings were taken from morning 7:00 a.m. to morning 6:00 a.m. for all experimental days in Gandhinagar's climatic conditions. CSS and solar still measurements were taken with fins, vacuum tubes, and a zig-zag shape air cooled condenser.

4.1. Atmospheric temperature (T_a) vs solar intensity (I)

The different parameters like the temperature of ambient, solar radiation, and wind speed have a variable effect on the distillate output of SS. With the higher value of ambient temperature and solar intensity, higher distillate can be achieved. In Fig. 5, the variation between atmospheric temperature and solar intensity is shown. It can be noticed that ambient temperature and solar intensity varied with time. The maximum obtained value for the intensity of solar radiation and the atmospheric temperature was 40.87 °C and 830 W/m2, respectively. From the figure, it is found the value of atmospheric temperature becomes maximum at 15:00 p.m. At 13:00 p.m., the highest value of solar intensity could be achieved. Atmospheric temperature becomes lower in the afternoon and night hours due to lower solar radiation. The lower atmospheric temperature after evening hours affects on nocturnal productivity of solar still.

4.2. Temperature of basin water (T_w) vs atmospheric (T_a)

In a solar still, with a higher temperature of basin water, maximum evaporation rate could be achieved, which gives the more distillate of water [53]. Here in Fig. 6, a comparison is made for a basin water temperature between CSS and MSS with ambient temperature. Water temperature for both solar still is varied with atmospheric temperature. Basin water temperature and atmospheric temperature becomes maximum at 15:00 p.m. During a period of 13:00 to 17:00, the basin water temperature shows in maximum value because of higher solar intensity and atmospheric temp. They received the highest value of water temp, for CSS and MSS were 63.75 °C and 69.21 °C, respectively. For MSS, around 6 °C of higher water temperature could be achieved than CSS. With the attachment of evacuated tubes and fins with MSS, this could be possible. Evacuated tubes preheat the water inside the basin of a solar still, which increases the evaporation rate of water and generates more vapor inside the still. Fins increase the absorbing surface area of a solar still, which generates more heat inside the basin of solar still. In the nocturnal period, the graph of water temperature shows lower for both solar still, but compared to CSS, the MSS shows a higher value of temperature. The reason behind this is the attachment of the condenser. The heat stored inside the condenser was liberated during the night period also and gave distillate. So in night time, higher distillate could be achieved than CSS.

4.3. Inner glass cover temperature vs ambient temperature

The higher value of inner glass cover temperature creates higher heat loss of glass cover to ambient, which leads to a decrease in the productivity of solar still. So, to increase the performance of solar still, it is necessary to decrease the temperature of the glass cover. Fig. 7 shows the variation of glass cover temperature for CSS and MSS. The inner glass cover temperature is also varied with atmospheric temperature. From the figure, it is found that glass cover temperature increases from morning hours, reaches a maximum at noontime, and then after it decreases. In the morning hours, it shows lower than atmospheric temperature. The glass cover temperature

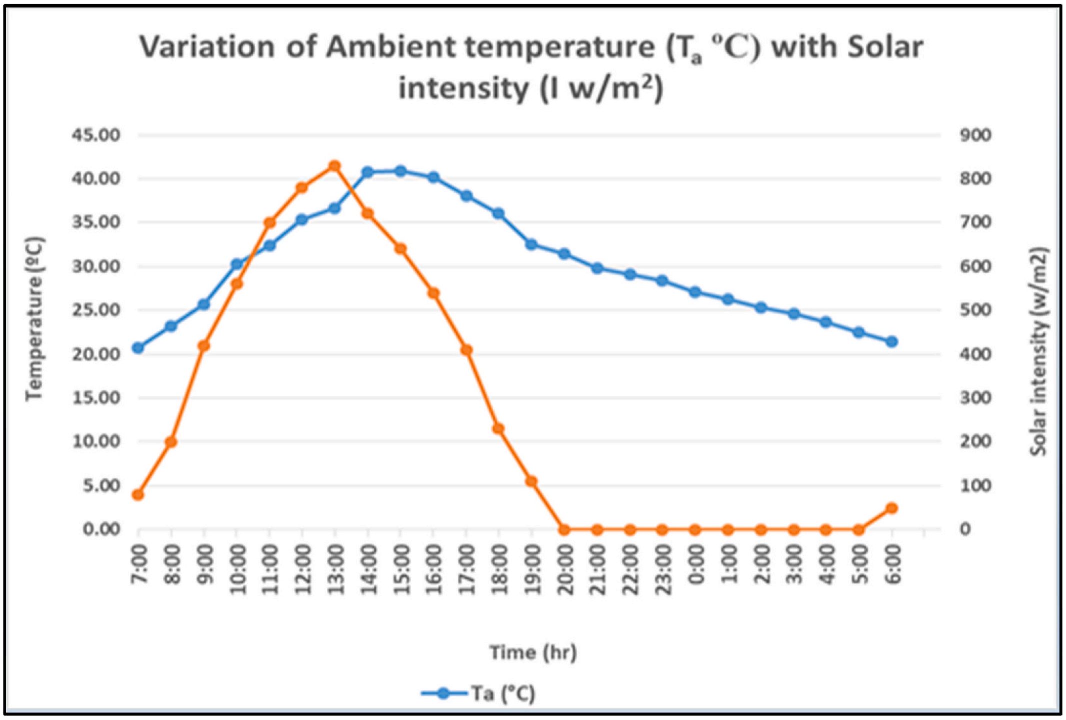

Fig. 5. Variations in solar intensity and ambient temp.

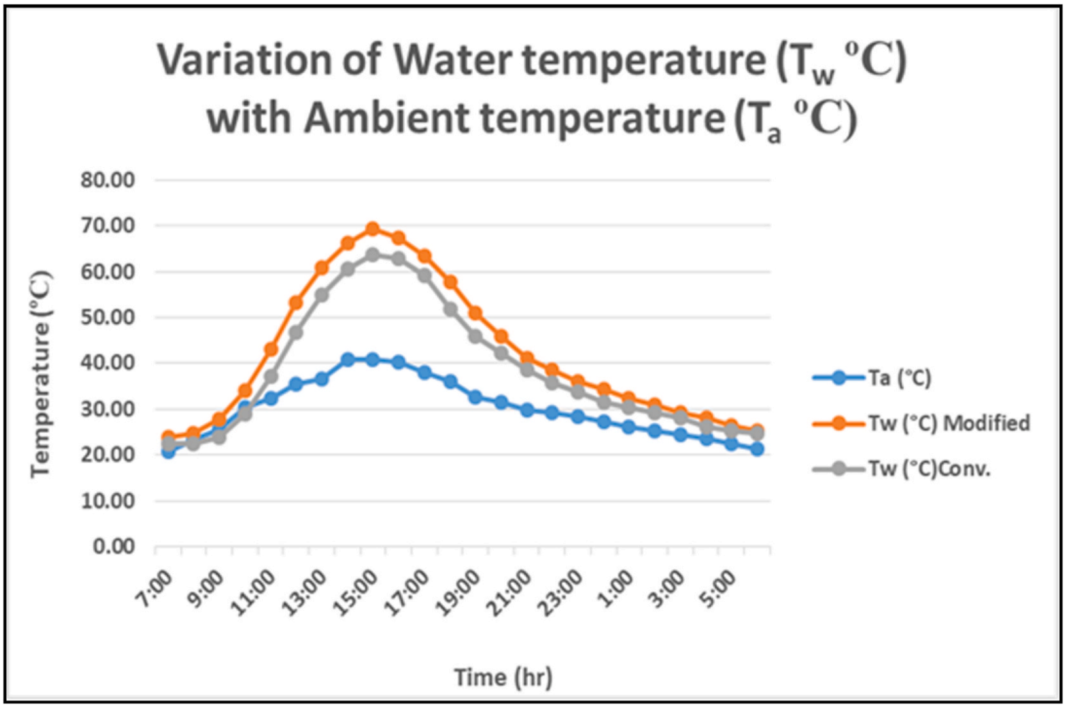

Fig. 6. Comparison of water temperature between two solar stills.

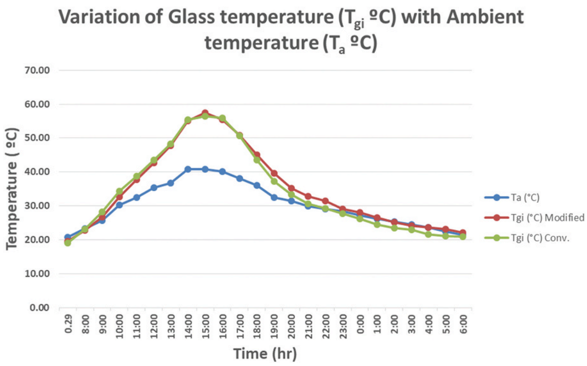

Fig. 7. Changes in temperature of glass cover between two solar stills.

at the maximum level for CSS and MSS were 54.37 °C and 54.93 °C, respectively. The value of inner glass cover temp. For CSS and MSS were very closed. The lines of a graph of temperature for both stills show nearer to each other. In MSS with a lesser value of glass cover temp., the higher water temperature may be achieved than CSS. The reason behind this is the attachment of the condenser, which lowers the temperature of the glass cover. The vapor generated inside the SS moves toward the condenser area and condenses inside it. The vapor pressure inside the SS could also be decreased by a condenser.

4.4. Variation of water temperature, inner glass cover temperature and condenser temperature of MSS

In Fig. 8, changes in water temperature, the temperature of the glass cover, and condenser temperature in MSS are shown. All the temperatures were varied with atmospheric temperature. The lines of the graph for different temperature increases reach on maximum position and then after it decreases. The obtained maximum value for water temperature, inner glass cover temperature, and condenser temperature in MSS was 69.21 °C, 54.93 °C, and 56.5 °C separately. Here, the water temperature of the basin shows the highest value, and the inner glass cover shows a lower. The value of temperature for inner glass cover and condenser varied with each other up to afternoon, and after that, it shows very near to each other. In night hours, the lines of the graph for atmospheric temperature, the temperature of condenser, and the temperature of glass cover were aligned to each other. It means in night hours, this value of temperature does not show much difference. In MSS, with the attachment of fins, evacuated tubes, a higher temperature of basin water

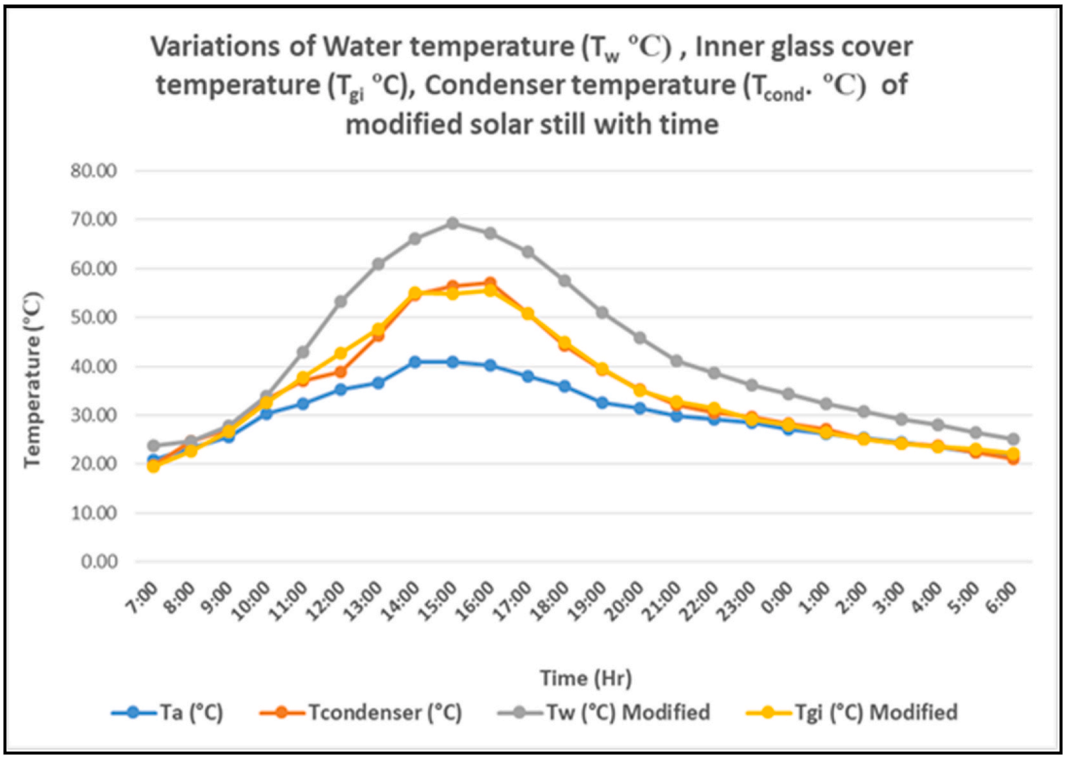

Fig. 8. Comparison of various temperature of modified solar still.

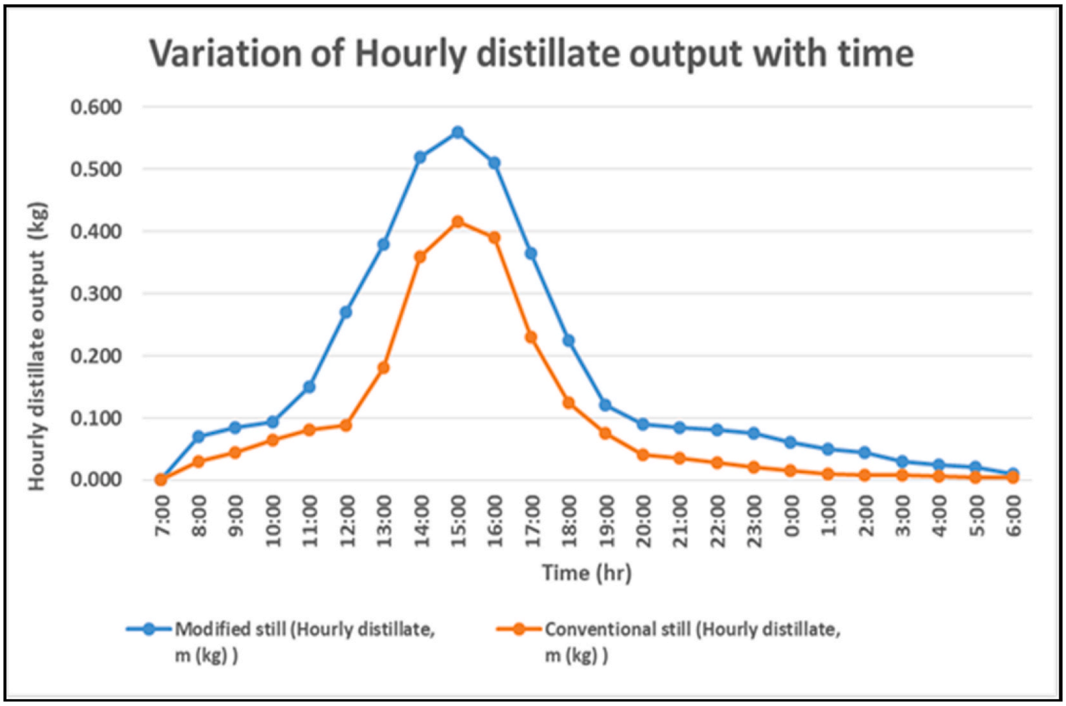

Fig. 9. Hourly distillate productivity for CSS and MSS.

could be achieved in both day and night time compared to CSS. Also, it shows a lower inner glass cover temperature than CSS. In MSS, the condenser temperature does not exceed than glass cover temperature because the outer surface of the condenser remains in direct contact with air, which does not exceed its temperature and maintains lower in night hours than atmospheric temperature.

4.5. Hourly variation in distillate output between two solar stills

Fig. 9 shows the 24 h of distillate variation for CSS and MSS. From the figure, it could be found that in morning and night hours, the lines of the graph are tilted, and in afternoon hours, it shows vertically. It is discussed in sections 4.2 & 4.3 that the Tw and Tgi become maximum at 15:00 p.m.; because of higher atmospheric temperature. In MSS, the higher value Tw and lower Tgi leads to maximum distillate than CSS. So, the hourly distillate shows highest at 15:00 p.m. The achieved maximum value for CSS and MSS were 0.415 kg/m2 and 0.56 kg/m2 separately. In MSS, a higher distillate could be achieved than CSS. This could be achieved in modified solar still due to attachment of fins and condenser. Attachment of zig-zag-shaped condenser with solar still increases the volumetric heat capacity of solar still. The vapor stored inside the condenser condenses inside it and gives distillate output in the nighttime also. Compare to CSS; the MSS gives higher nocturnal productivity.

4.6. Variation of cumulative distillate with time

In Fig. 10, a comparison in total distillate output between CSS and MSS is shown. The graph for total distillate output in conventional and modified solar still starts to increase from morning hours and reaches its maximum position up to next day morning. From the figure, it is found MSS gives higher distillate productivity than CSS. The total distillate yield achieved for CSS and MSS were 2.26 kg/m2 and 3.92 kg/m2. In MSS, better performance could be achieved with fins, evacuated tubes, and condenser compare to CSS. It gives around 73.45% of higher distillate productivity than conventional solar still. During night time the CSS gives lower distillate productivity than MSS. Attachment of condenser with MSS plays an important role in increasing the night distillate output in MSS.

4.7. Thermal behavior in SS

A variation of fractional exergy of convection and evaporation for CSS and MSS was done using Eqs. (11) and (12). The value of fractional exergy of evaporation remains in the range of 0.72–0.85. It could be found that for MSS, the value of fractional exergy shows substantial improvement after peak hours to the completion of the experiment. The fractional exergy of convection decreased from 0.11 to 0.03 between morning to noontime. Using Eq. (1), the full day efficiency of solar still can be achieved using experimental readings. The value of efficiency for CSS and MSS were 24.5% and 35.2%, respectively. The thermal efficiency of MSS solar still could

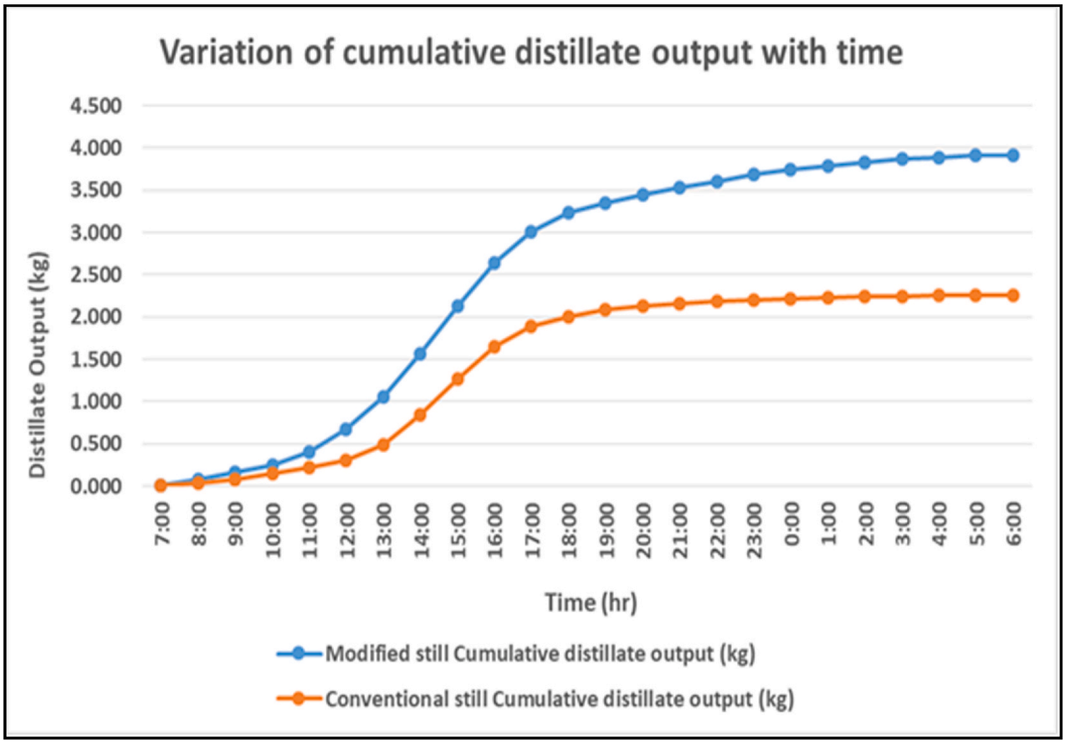

Fig. 10. Comparison in distillate productivity between CSS and MSS.

be achieved higher compared to CSS because of the attachment of fins, evacuated tubes, and condenser within it.

The exergy efficiency for CSS and MSS was found using Eq. (13). The obtained values of exergy efficiency for CSS and MSS were 1.7% and 3.5%, respectively. In MSS, due to the attachment of fins and evacuated tubes, a higher evaporative coefficient could be achieved in the afternoon time, also in CSS solar still the evaporation rate of water remains lower, which reduces its efficiency.

4.8. Economic analysis

This section shows the economic analysis for CSS and MSS. The obtained total distillate for CSS and MSS were 2.26 L/m^2 and 3.92 L/m^2 in day respectively. The experimental was done in climatic condition of, Gandhinagar, Gujarat, India (More than 300 sunny days throughout the year) [74]. Here to determine the total water cost per liter for CSS and MSS Eq. (15)–(22) used [78]. By Eq. (15) the *PAC* for SS was found, also to determine *CRA*, Eq. (16) was used. The *YSV* could be found by Eq. (17) [74].

$$\mathrm{PAC} = \mathrm{C}\ (\mathrm{CRA}) \tag{15}$$

$$CRA = \frac{i \times (1+i)\, i}{(1+i)i - 1} \tag{16}$$

$$\mathrm{YSV} = (\mathrm{SFA}) \times \mathrm{SC} \tag{17}$$

In above equations, C = Capital cost of SS, i = rate of interest, l = life of the SS. Here for calculation the rate of interest was considered as 0.05% [73,74]. To determine Salvage cost (SC) and Sinking fund Aspect (SFA) Eqs. (18) and (19) were used.

$$\mathrm{SC} = 0.2 \times \mathrm{C} \tag{18}$$

$$SFA = \frac{i}{(i+1)i - 1} \tag{19}$$

The value of YUC, OAC and CPL were determined using Eq. (20)–(22)

$$\mathrm{YUC} = 0.15 \times (\mathrm{PAC}) \tag{20}$$

$$\mathrm{OAC} = \mathrm{PAC} + \mathrm{YUC} - \mathrm{YSV} \tag{21}$$

$$CPL = \frac{OAC}{M} \tag{22}$$

Here, M shows the mean yearly distillate.

Table 2 shows the comparison between the MSS and CSS. In Table 3 the total manufacturing cost, PAC, and liter per water cost for CSS and MSS are shown. The total cost for CSS and MSS was 75 and 136 USD/m^2. The distillate yield for CSS and MSS was 2.26 and 3.92 L/m^2. day, whereas the cost of water per liter was 0.013 and 0.015 USD/L.

The total payback period for modified solar still was calculated using following data.

Capital cost of MSS = 136 USD.

Basic price of water in market = 0.26 USD/L.

Distillate yield of MSS = 3.92 L/day.

Price of water produced per day = 1.02.

Total payback period $= \frac{Capital\ cost}{Net\ earning}$

$= \frac{136}{1.02} = 4.4\ month$

4.9. Analysis of exergo economic, environmental and CCP

To enhance the performance of solar still exergy and economic analysis was done carried out [47]. To check the economic performance of system the optimum cost value was found. The aim of exergo-economic analysis was to check the exergy loss of system, because the solar radiations are in fluctuating manner and it's not available constant throughout the days. The exergo-economic analysis parameters (R_{ex}) are shown in Table 3. The R_{ex} could be found by Eq. (23)

$$Rex = \frac{Exout}{PAC} \tag{23}$$

Here, Ex_{out} = output exergy.

The exergy output value of for CSS and MSS were 10.22 W and 20.16 W respectively. From Table 3 it can be found that exergy-economic parameter value for MSS is higher than CSS, because of addition of fins and evacuated tubes within it. So the MSS gives the better performance to generate the exergy output.

For environmental prospect, the emissions of carbon into the environment from solar still were done in exergo-environmental analysis. In calculation, the cost of carbon emission was considered 2 kg/kWh. The CO_2 production mitigation/year was calculated using following equation:

Table 2
Analysis of cost for CSS and MSS.

Sr.	Instrument	CSS (USD $/m^2)	MSS (USD $/m^2)
1.	Absorber surface area of M.S Plate	32	32
2.	Insulating Material and Plywood	23	23
3.	Transparent Glass cover	9	9
4.	Paint of Black color	7	7
5.	Distilled water collector	1.5	1.5
6.	Sealant	2.5	2.5
7.	Evacuated tubes (6 nos.)	–	55
8.	Fins	–	3
9.	Condenser	–	3
10.	Total cost	75	136
11.	Primary Annual Charge (PAC)	9.67	17.5
12.	Full day distillate (L/m^2)	2.26	3.92
13.	Yearly distilled water generation (L/m^2)	678	1176
14.	Cost of Water/L (USD $)	0.013	0.015

Table 3
Economic analysis for CSS and MSS.

Sr.	Parameters	CSS	MSS
1.	Yearly total life of SS In years	10	10
2.	Yearly distillate yield (L/m^2)	678	1176
3.	PAC (In USD)	9.67	17.5
4.	Ex_{out}, (W)	10.22	20.16
5.	Rex (W/USD)	1.056	1.152
6.	$\varphi_{ex,\ CO2}$ (t CO_2/year)	0.20	0.40
7.	CCP (USD/year)	2.9	5.8

$$\varphi ex, co2 = \frac{(Exout \ \times l) \times 2}{1000} \tag{24}$$

Here, $\varphi ex, co2$ = exergo-environemmtal value, Exout=exergy output and l=Life of SS.

The CCP by the entire system was calculated by using Eq. (25). In that the average price of carbon (Z_{CO2}) was considered as 14.5 USD.

$$CCP = \varphi ex, co2 \ \times Zco2 \tag{25}$$

From Table 3 it could be found that the exergo-environmental value for CSS and MSS are 0.20 t CO_2/year and 0.40 t CO_2/year. This value remains higher in MSS because of higher value of exergy output, which enhances the exergo-environemmtal value in case of MSS. With concern to exergo-environemmtal, the MSS and CSS are economic and reduce the emission of CO_2. The value obtained for production of carbon credit (CCP) for CSS and MSS were 2.9 USD and 5.8 USD respectively.

5. Conclusion

In the present experimental work, a comparison was made to check performance enrichment in distillate output of between MSS and CSS. MSS was coupled with fins, evacuated tube, and condenser for experimental work. After completing the experimental work, thermal, economic, environmental analysis for CSS and MSS, the following points were summarized:

- In MSS higher distillate in productivity could be achieved compare to CSS due to the use of evacuated tubes, condenser and fins.
- The achieved maximum temperature in CSS and MSS for basin of water and glass cover were 63.75 °C & 69.21 °C and 54.37 °C & 54.93 °C separately.
- Distillate productivity achieved for CSS and MSS remains 2.26 kg/m^2 and 3.92 kg/m^2 individually. It was found that MSS gives 73.45% of higher distillate output than CSS. The maximum hourly distillate could be achieved at 15:00 p.m. for CSS and MSS were 0.415 kg/m^2 and 0.56 kg/m^2 respectively.
- With attachment of fins and evacuated tubes higher water temperature of basin in MSS could be achieved compare to CSS. A novel zig zag shape condenser maintains temperature of inner glass cover lower in MSS than CSS. It also decreases the pressure of vapor inside basin of still and increases its volumetric heat capacity.
- The nocturnal distillate output of MSS could also be achieved higher compare to CSS, because of attachment of condenser. It condenses the vapor stored inside it during the night time.
- It was also observed that, with attachment of fins and evacuated tubes higher temperature of basin water could be achieved, whereas zig-zag shape air cooled condenser maintains the lower inner glass cover temperature in MSS compare to CSS.

- In MSS, higher convective and evaporative coefficient can be achieved, which gives higher fractional value of exergy evaporation compare to CSS. In exergy efficacy for MSS and CSS were 3.5% and 1.75%respectively.
- The annual cost of water production per liter for CSS and MSS were 0.013 and 0.015, where the payback time for MSS was 4.4 month which was lower than CSS.
- In exergy-economic point of view the exergy output value for CSS and MSS were 10.22 W and 20.16 W respectively. The exergo-economic parameter for CSS and MSS were 1.056 W/USD and 1.152 W/USD respectively.
- For environmental aspect the generation of CO2 for MSS is higher compare to CSS. The value of CO2 emission for CSS and MSS were 0.2 USD/t $_{CO2}$ and 0.4 USD/t $_{CO2}$. MSS generated higher carbon value because of attachment with fins, condenser and evacuated tubes. The carbon credit value for CSS and MSS were 2.9 USD/year and 5.8 USD/year respectively.

Author statement

Dinesh Mevada: Conceptualization, Methodology, Software, Investigation, Data curation, Writing- Original draft preparation.
Hitesh Panchal: Writing- Reviewing and Editing.
Kishor Kumar Sadasivuni: Supervision, Project administration, Acquisition of the financial support for the project leading to this publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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