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ORIGINAL RESEARCH ARTICLE

Performance analysis of triple basin solar still with energy-exergy analysis approach

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ABSTRACT

An experimental investigation was conducted on novel design of triple basin solar still with different modification in the climatic conditions of India. The triple basin solar still was modified with attachments of evacuated tubes (ETCs), heat pipes (HP), corrugated surfaces and energy storage materials called modified triple basin solar still (MTBSS). To get the more water in distillate output and higher water temperature solar still was designed with three basin area. From experimental results it was found that the total distillate output obtained by MTBSS during day and night was 16.46 l/m^2 and 7.40 l/m^2, respectively. The performance of MTBSS was also check by 4E (Energy, Exergy, Exergo-Economic, Exergo-Environmental) analysis for economical and environmental point of view. The generation of exergy for evaporation (Exe,bw-ig) and convection (Exc,bw-ig) for MTBSS (Modified triple basin solar still) were 24.03 & 1.30 (joule) respectively. The values of energy efficiency (η_{energy}) and exergy efficiency (η_{exergy}) obtained for MTBSS were 31.89% & 3.04% respectively. An economic point of view, the CPL of water remains higher in MTBSS. The NPBT for MTBSS was 2.5 months. For environmental assessment, the CO_2 mitigation for MTBSS was 0.48 t/year, based on the exergy approach. The additions of ETCs, H.P, corrugated surface, and ESMs with MTBSS are effective from an exergo-economic and carbon credit point of view.

Keywords: Solar still (SS); Triple basin solar still (TBSS); Energy; Efficiency; Productivity; Distillate output

Abbreviations & Nomenclatures:

SS	Solar still
CSS	Conventional solar still
DBSS	Double basin solar still
TBSS	Triple basin solar still
ETCs	Evacuated tubes
MTBSS	Modified Triple basin solar still
ESMs	Energy storage materials
PAC	Primary annual cost.
CPL	Cost of water per litre
FPCs	Flat plate collectors
CCP	Carbon credit
NPBT	Net payback time
Ta	Atmospheric Temperature (°C)
T_w	Basin Water Temperature (°C)
I	Solar intensity (W/m^2)
Tgi	Inner glass cover temperature (°C)
$he,bw\text{-}ig$	Evaporative heat transfer coefficient (W/m^2 K)
$hc,bw\text{-}ig$	Convective heat transfer coefficient (W/m^2 K)
$Exc,bw\text{-}ig$	Convection exergy value for water and glass cover (W/m^2 K)
$Exe,bw\text{-}ig$	Evaporation exergy value for water and glass cover (W/m^2 K)
η_{ener}	Energy efficiency
η_{exe}	Exergy efficiency
$\phi_{ex,\ CO2}$	Value of environmental exergy
R_{ex}	Value of economic exergy
C	Capital cost

1. Introduction

India has the second largest population in the world. In many remote areas people do not get pure drinkable water. The sources of pure water are very less on the earth. According to World health organization majority of diseases are occurs due to impure water and in future the requirement of clean water will be increase[1]. The major portion of water on earth is salty or impure water, there is very little source of clean water. So it is necessary to create the sources which convert the impure water into the pure form. The non-renewable sources are decreasing day by day and they are highly polluting[2-3]. So the better option is to use a renewable sources of energy to convert the salty water into clean water. Solar still is a device which work with the help of solar energy and convert the salty water into pure water. It is a simple and non- polluting device and also useful on the areas where supply of electricity is not available. The process of converting salty water into pure form with the help of solar still is known as solar distillation[4-5].

The distillate production of a conventional solar still remains quite low, thus many researchers have utilized various approaches to improve the distillate output of solar stills, with improvements in the design of solar stills. Many researches have been conducted experiments with new designs in single basin solar still such as, solar still with evacuated tubes, flat plate collector, solar still with water heating techniques, solar still with multi basins, etc. within solar still[6-8]. To get the better performance in water heating system Allouhi et al.2019[9] integrate a heat pipe with flat plat collector and get 33% more efficiency than previous one. Dondapati et. al.2018[10] found the effect of various parameters like glazing material, solar irradiance, heat transfer coefficient etc. to check the effectiveness of FPCs in heating application. Varma et al.2019[11] replaced a FPC with spiral tube collector to heat the water and achieved 22% higher efficiency. The hybrid system developed by Ananno et.al.2020[12] using FPC for drying application gives 20% higher efficiency than conventional solar still (CSS). Iqbal et al.2020[13] tested the efficiency of SS using a solar air heater and base coating. The solar air heater was introduced to increase the evaporation rate of water by delivering hot air and covering the SS base. The porous fins used in the SS to increase their surface area by Panchal and Sathyamurthy 2020[14] and compared them to Traditional SS. From their experiment, the experiments found that the average SS yield with and without the use of porous fins was 3.8 and 2.67 liters/day. To increase the evaporative and absorber area solar still is modified with attachment of trays and mirror inside still by Abdullah et al.2020[15]. By changing the configuration of solar still with increasing basin stages, changes in height and width etc. the more productivity was achieved by Zhang et al.2020[16]. Madiouli et al.2020[17] used a parabolic trough collector and flat plate collector to achieve and concentrate the more solar radiation with conventional solar still, also it gives maximum efficiency in summer and winter. Abu-Arabi et al.2020[18] used a different absorbing material within still to increase its performance. Kumar et al.2021[19] have used a different type of nano material and compare it with two conventional solar still. They found that solar still with nano material increase the distillate output of solar still. Alqsair et al.2022[20] have used a parabolic trough collector and absorbing material with single basin solar still and get 72% higher in efficiency than conventional solar still. El-Sebaey et al.2023[21] conducted an experiment on cylindrical and double slope type solar still with addition of different heat storage materials and fins etc. The experimental study reveals that the performance of cylindrical solar still was 16.01% higher in daily efficiency than double slope type solar still. Gnanaraj et al.2017[22] make a comparative study between single basin solar still and double basin solar still. They recommended with experimental study that by increment in basin of solar still the higher performance in distillate output could be achieved. In experimental investigation for novel tubular stepped type solar still by El-Sebaey et al.2024[23] reveals that stepped solar still gives higher thermal efficiency in both energy and exergy compared to conventional type solar still. Kamal et al.2021[24] used an electric heater in double basin solar still to increase the temperature of water. The performance of DBSS with electric heater increased the temperature of water in upper basin also. It gives around 15% higher productivity than single basin solar still. Davani et al.2023[25] checked the performance of solar still by increasing the stages of basin and varying the depth of water. Author found that with more number of stages in the basin 94% of maximum distilled yield could be achieved than single basin solar still. Also it was found that with minimum depth of water maximum productivity could be achieved. Sharma et al.2021[29]. checked the performance of pyramid solar still with attachments of copper fins and improved the future performance. Naveen et al.2012[30] used an optimization technique to reduce the cost and increased the life and efficiency of solar still. To enhance the performance in solar still Dumka et al.2024[31] used a wax-material rod to increase the performance of solar still, hence performance was increased. Abed et al.2024[32] phase changing material and nano material with solar still to improve the performance of solar still and achieved 117% more efficiency than conventional solar still. Mahala and Sharma 2024[33] used a fins, energy storage materials with pyramid type solar still. They also done a energy-exergy analysis to check the thermal behavior of it. Bady et al.2024[34] conducted an experiment with conventional conical solar still and modified conventional solar still. They used hollow copper tubes and check the performance. The modified solar still gave 20% higher distillate output than conventional type. Jeyaraj et al.2024[35] used a trapezoidal channel in double slope solar still. It increases the water heating and evaporation rate in solar still, which increase the efficiency of solar still. Aghakhani et al.2024[36] conducted a numerical study on solar still with effect of photovoltaic- thermal collector and evacuated heat pipe tube collector. The results of study reveals that modification in solar still gives higher performance in distillate output than previous one. Aghakhani et al.2023[37] applied a thermal approach on heating and cooling on basin water in solar still. The novel method increase the evaporation rate of water and reduces the heat losses inside basin area. Metal oxides thin films may be the very important technology for the future of the solar desalination too[38].

From the above literature review it was clear that the solar still with multi basin increases the distillate output in efficiency of solar still. However many researchers have not conducted an experimental study on triple basin type solar still with different modifications on it.

In present research work a novel design of triple basin type solar still was prepared and its performance was checked with different modifications. The objective behind this study was to improve the distillate of solar still with triple basin type and different attachments like heat pipes, evacuated tubes & energy storage materials. The different modifications in triple basin solar still increase the heat transfer coefficient of water and gives improvement in productivity.

2. Experimental set up

The water inside the basin of solar still (SS) received solar energy and evaporated. Higher temperature of basin water, gives the higher distillate output due to higher evaporative heat transfer coefficient. Higher the area of basin collects the more water inside SS, which comes in contact with solar energy and evaporative heat transfer coefficient could be increased.

Here in present experimental work triple basin solar still was manufactured using mild steel material. The basin area of TBSS was 1m^2. Also to enhance the latent heat storage capacity of modified triple basin solar still (MTBSS) pebbles, black gravels and white granite marbles were used as heat storage materials. These heat storage materials store the heat during day time and release it on night period, which increases the nocturnal productivity of TBSS. The experimental work was performed during September 2019 to December 2020 in climatic conditions of Gandhingar, Gujarat, India (23.0337° N, 72.4634° E). To prepare experimental set up different modification were done with TBSS like i) evacuated tubes, ii) evacuated tubes with heat pipe and iii) evacuated tubes with heat pipe & corrugated surfaces were attached with TBSS. The material of basin area was mild steel which was covered with glass cover. In MTBSS, total twenty-five numbers of evacuated glass tubes were attached to enhance the temperature of basin water. The experimental readings were taken from morning 8:00 to evening 19:00. During the experimental work the different parameters like ambient temperature (Ta), solar intensity (I), water temperature for basin 1, basin 2 and basin 3 (Tw), glass cover temperature (Tc), hourly distillate output. After the experimental work the life cost analysis of the system was found.

In below **Table 1** shows the different instruments used during experimental work with accuracy and range.

Table 1. Uncertainty analysis of instruments.

Sr.	Instrument	Accuracy	Range	% of error
1.	Copper Constantan Thermocouple	±0.1°C	-55°C to +125°C	0.5
2.	Solarimeter	±1W/m^2	0-1400 W/m^2	2.5
3.	Measuring Jar	±10 ml	0-1000 ml	10
4.	Temperature indicator	±0.1°C	-55°C to +125°C	1

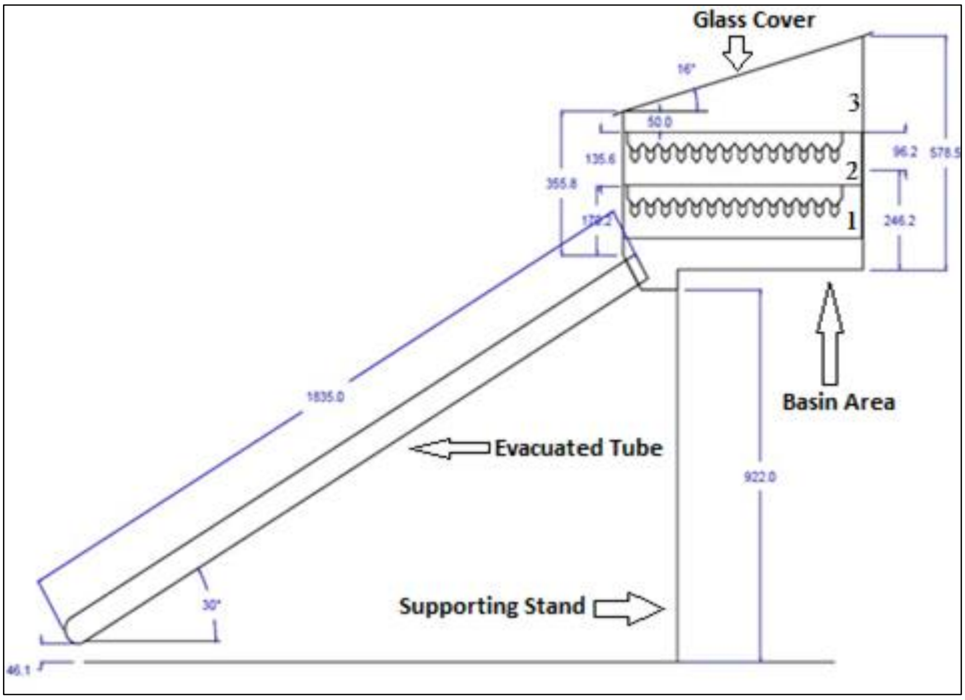

Figure. 1 (a) Schematic of experimental set up

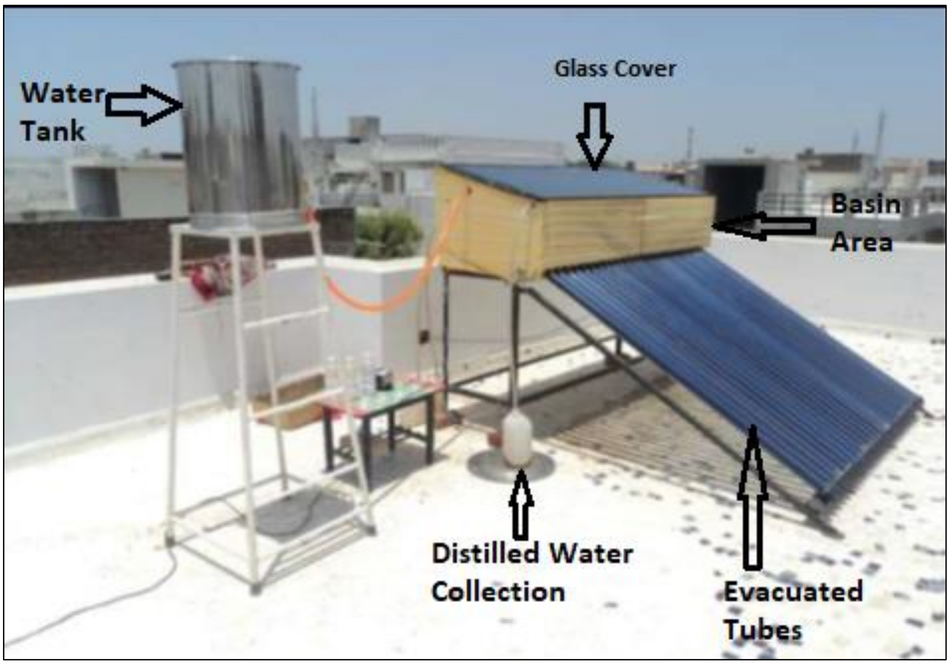

Figure.1 (b) Photograph of experimental work

3. Results & Discussion

3.1. Hourly variation in ambient temperature (°C) and solar intensity (W/m^2)

In below **Figure 2 and 3** the hourly variations in atmospheric temperature (Ta) and solar intensity (I) are shown for day 1 (12/10/2021), day 2 (13/10/2021) and day 3 (14/10/2021). The higher atmospheric temperature and solar intensity gives increases the basin water temperature of SS, hence higher distillate output could be obtained. Here the atmospheric temperature and solar intensity were measured for all the working days. In below **Figure 2 and 3** a comparison of atmospheric temperature and solar intensity is shown for three days. From figure it was found that the atmospheric temperature and solar intensity increases from morning time, reaches maximum at noon time and then after it decreases. The obtained maximum value of ambient temperature and solar intensity for day 1, day 2 and day3 were 39°C, 40°C, 39°C and 790 W/m^2, 820 W/m^2, 810 W/m^2 respectively. The maximum values of ambient temperature and solar intensity was found for day 2 having 40°C and 820 W/m^2. Also there is not much variations was found in ambient temperature and solar intensity for day 1, day 2 and day 3.

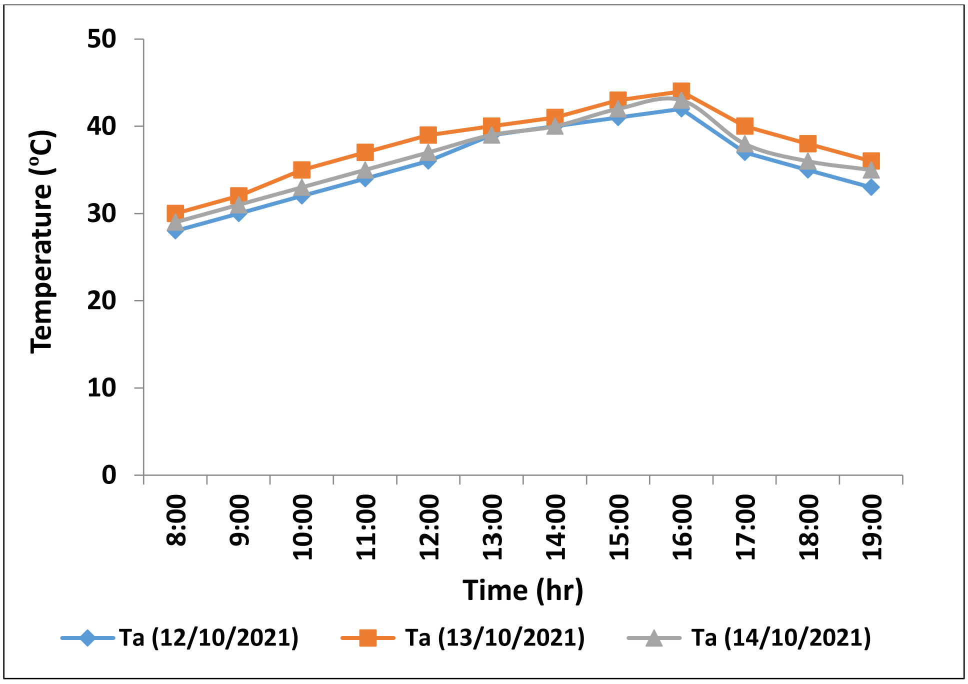

Figure 2. Hourly variations of ambient temperature (°C).

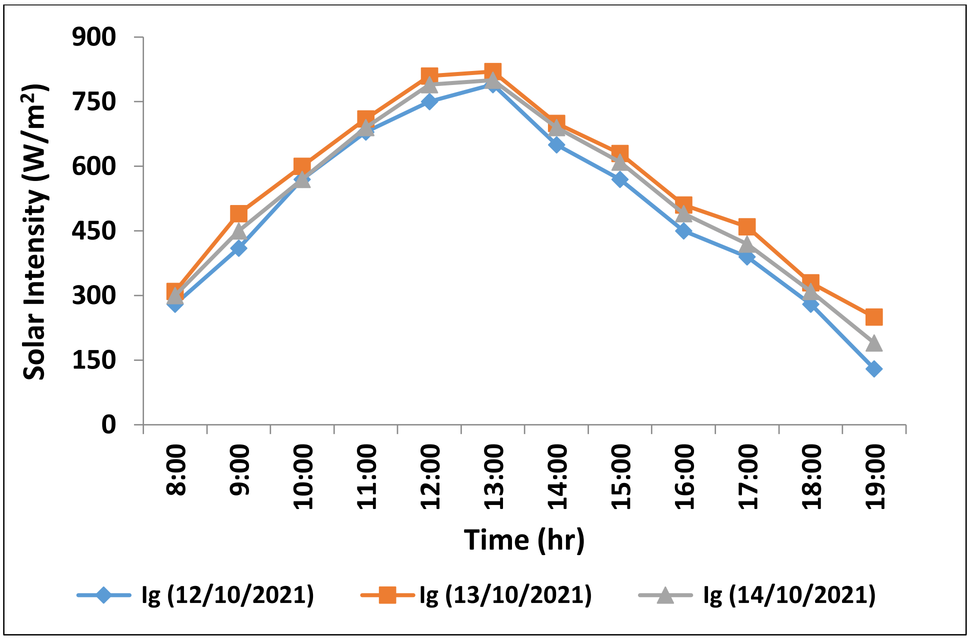

Figure 3. Hourly variations of solar intensity (W/m^2).

3.2. Variations in water temperature (T_w) with ambient temperature (T_a)

In triple basin solar still different modification were done to get the higher distillate output. To increase the basin water temperature and heat transfer rate an evacuated tube with heat pipes were attached with TBSS. Here in below **Figure 4, 5 and 6** a comparison of basin water temperature with ambient temperature is shown for day 1, day 2 and day 3. From figure it clearly found that basin water temperature (Tw) shows lower in morning time due to lower atmospheric temperature becomes maximum during noon time around 15:00 and then after that it decreases. The lower basin water temperature (Tw1) shows maximum for all three days than basin 2 (Tw2) and basin 3 (Tw3). The maximum value of basin water temperature obtained for Tw1 for day 1, day 2 and day 3 were 87 ℃, 90 ℃. 88 ℃ respectively. The maximum values of atmospheric temperature for day 1, day 2 and day 3 were 39 ℃, 40 ℃, 39 ℃ respectively. On 13/10/2021 the value of basin temperature shows maximum due to higher value of atmospheric temperature, hence higher evaporation rate could be achieved, which gives higher distillate output. Basin 1 gives higher performance in temperature than basin 2 and 3. From the data of Tw and Ta for various days it clearly shows that the basin water temperature values increase more compared to ambient temperature. Also during the night time, the basin water temperature shows higher because of latent heat releases by the energy storage materials. The higher value of basin water temperature increases the distillate output of TBSS.

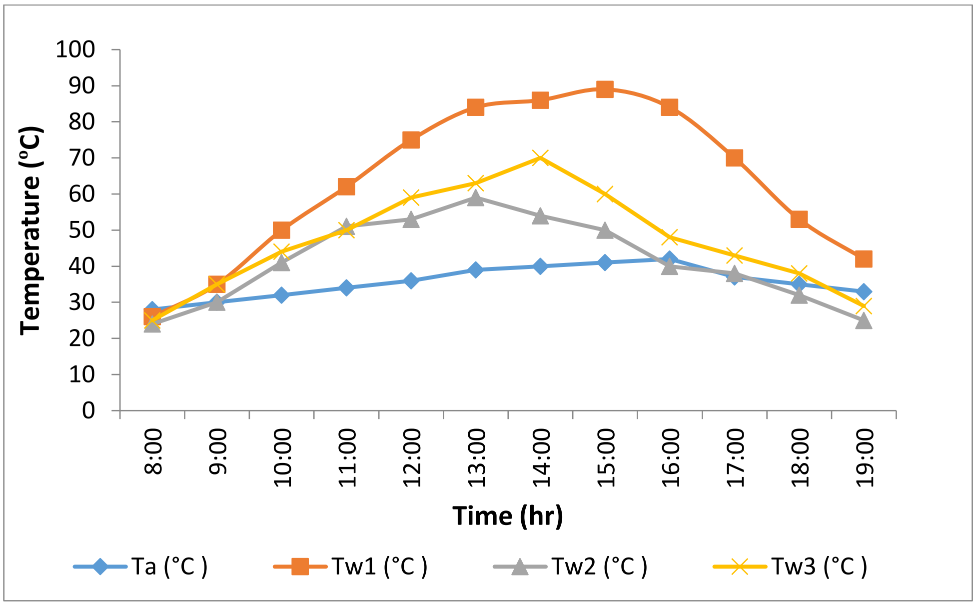

Figure 4. Hourly variation in water temperature (12/10/2021).

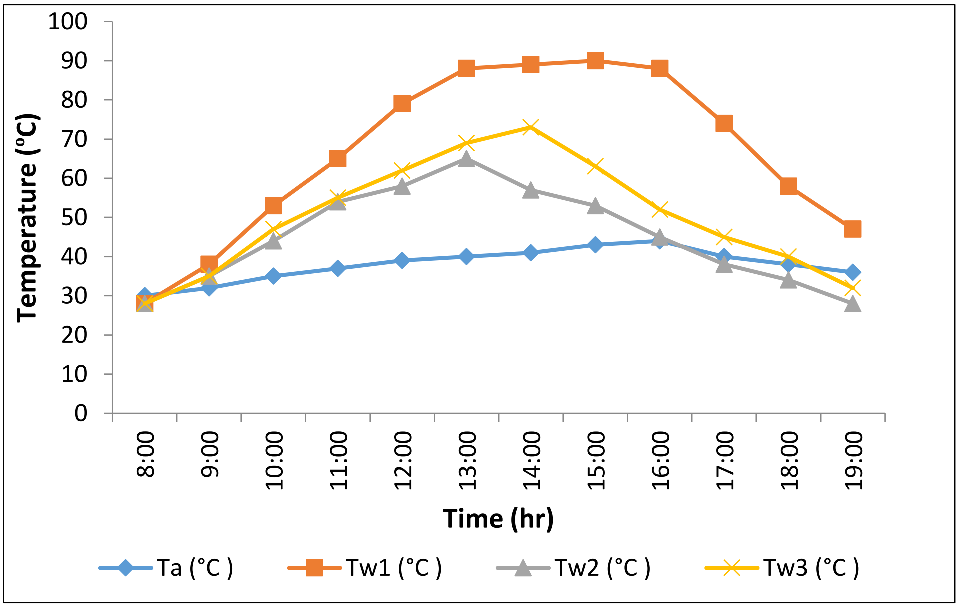

Figure 5. Hourly variation in water temperature (13/10/2021).

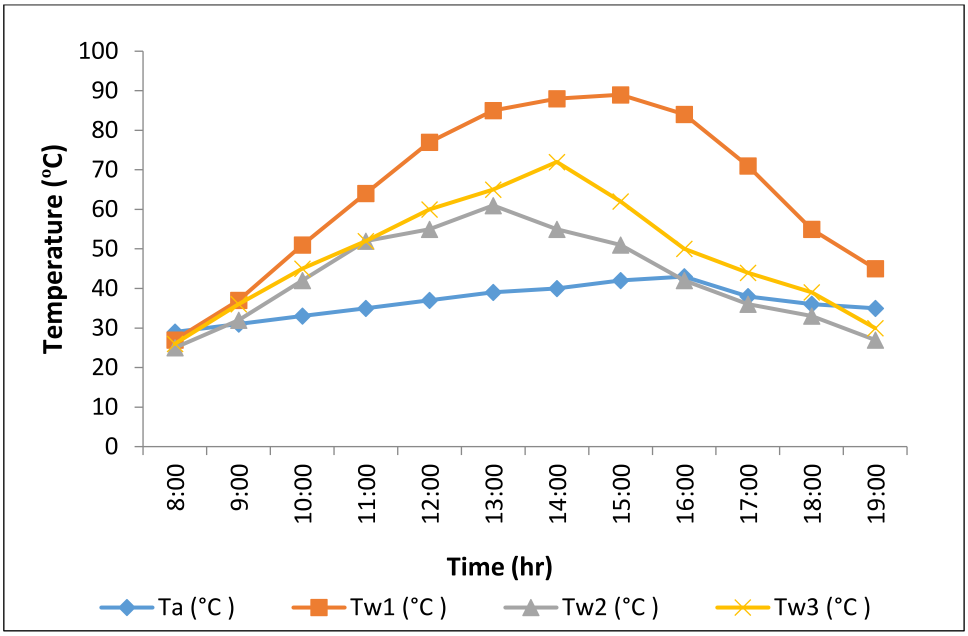

Figure 6. Hourly variation in water temperature (14/10/2021).

3.3. Hourly variations in distillate output (l/m^2)

Figure 7, 8 and 9 shows the hourly variations in distillate water of basin 1, 2 and 3 for all three working days. The higher value of basin water temperature (Tw) leads to the higher distillate output. In below figure it clearly shows that the distillate output for basin area 1 remains higher than basin 2 and 3. This happens because of higher temperature of basin water in basin 1 compared to basin 2 and 3. The maximum value of hourly distillate obtained in basin 1(Mw1) for day 1, day 2 and day 3 were 1.39 (l/m^2), 1.45 (l/m^2) and 1.4 (l/m^2) respectively. In day 2 the maximum distillate output was obtained than other days. It shows maximum during the noon time due to higher atmospheric temperature and solar intensity. In morning and evening time the atmospheric temperature and solar intensity remains lower, which gives lower basin water temperature, hence lower distillate output was obtained during the morning and evening time. From the figure it was found that, there is huge difference in the distillate of water between basin 1, basin 2 and basin 3 during the afternoon time because of higher basin water temperature.

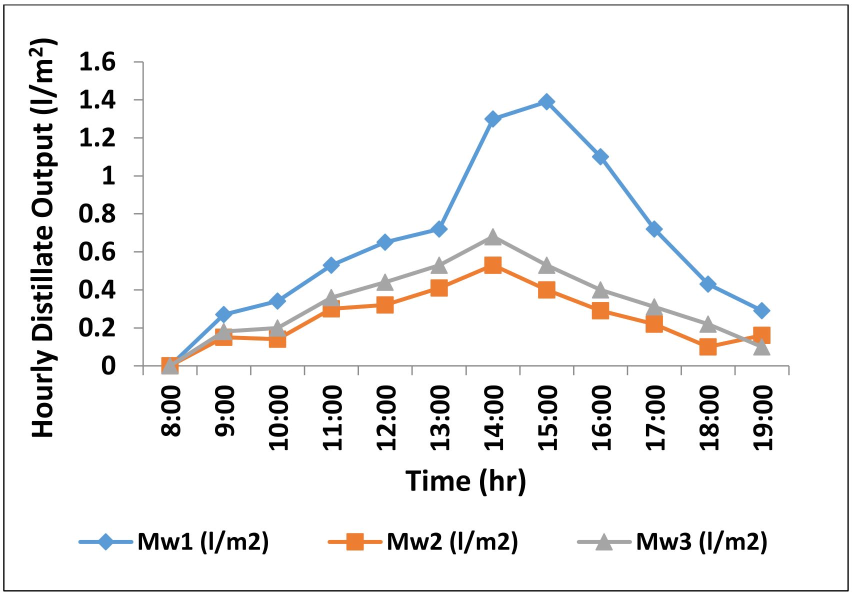

Figure 7. Hourly variations in distillate output (12/10/2021).

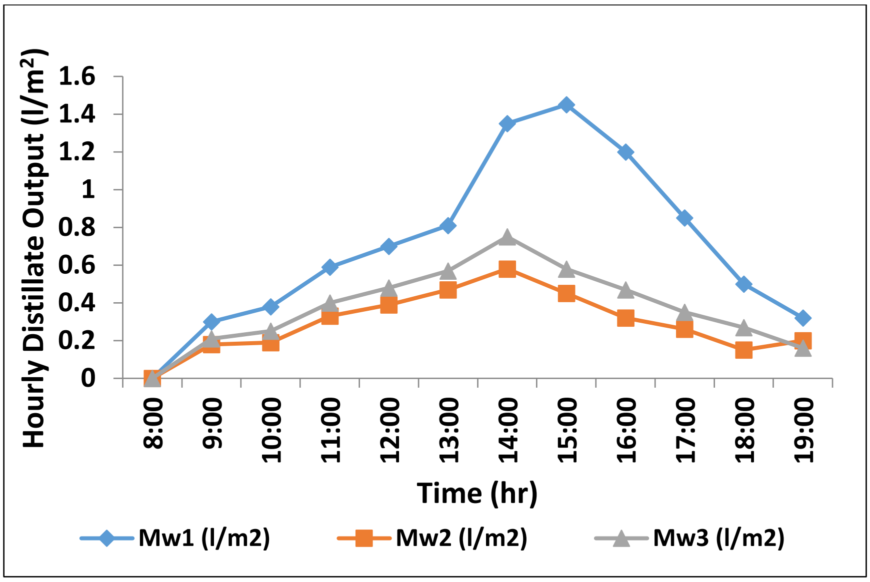

Figure 8. Hourly variations in distillate output (13/10/2021).

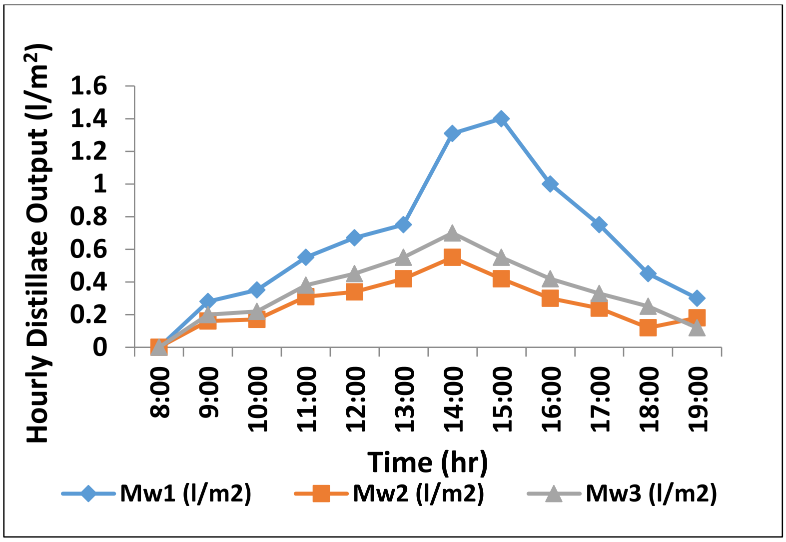

Figure 9. Hourly variations in distillate output (14/10/2021).

3.4. Variations in hourly and cumulative distillate output (l/m^2)

The higher basin water temperature leads to the higher value of distillate output. **Figure 10-11** shows the total hourly and cumulative distillate output for different days. From figure 5.42 it was found that at 14:00 the maximum distillate output was obtained for all three days. The trend of the graph shows maximum during the noon time. The value of maximum distillate obtained for day 1, day 2 and day 3 were 2.51 (l/m^2), 2.68 (l/m^2) and 2.56 (l/m^2) respectively. Figure 10 shows the comparison of cumulative distillate output for different days. The distillate output continuously increases from the morning time to evening hours. The cumulative distillate output obtained for day 1, day 2 and day 3 were 14.71 (l/m^2), 16.46 (l/m^2) and 15.19 (l/m^2) respectively. The results obtained in MTBSS gives higher performance in distillate output and efficiency than other single basin solar still[23]. From the figure it was found that for day 2 (13/10/2021) the maximum hourly and cumulative distillate output was obtained because of higher basin water temperature in that day compared to other days. Attachment of evacuated tubes, heat pipe and energy storage materials increases the basin water temperature in solar still which leads to the higher distillate output during day and night time.

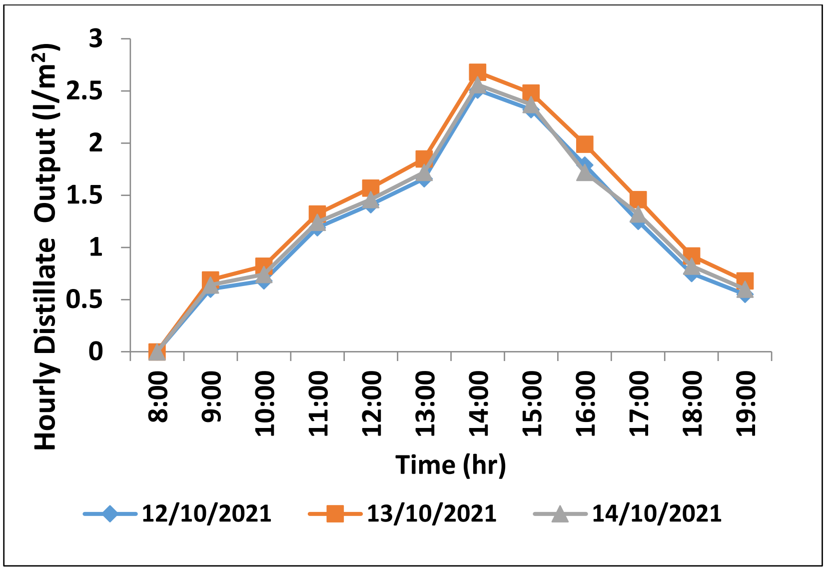

Figure 10. Hourly distillate output for all three days.

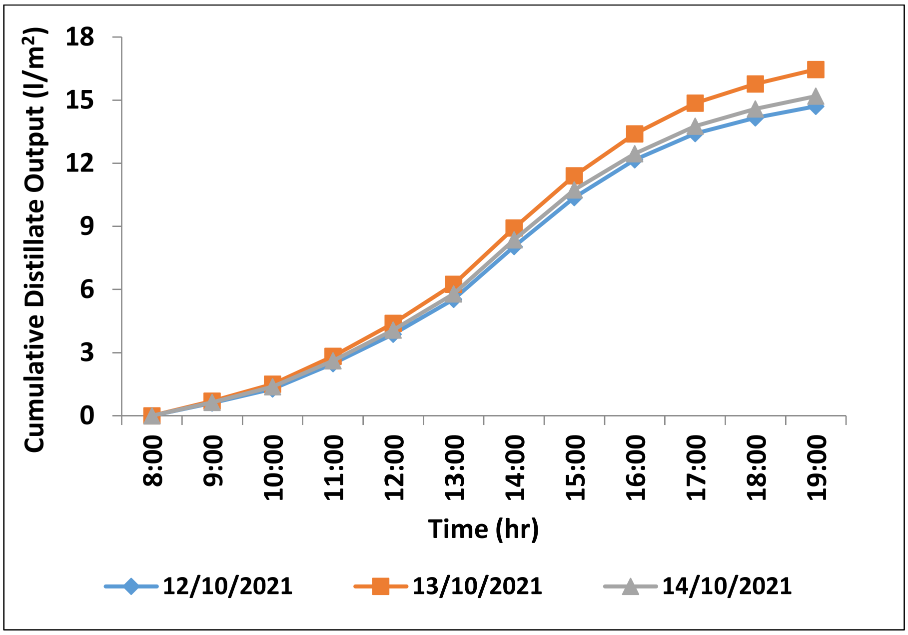

Figure 11. Cumulative distillate output for all three days.

3.5. Comparison of day and night distillate output

In below **Figure 12**, a comparison of day and night distillate output for all three days is shown. The total distillate output obtained during day hours for day 1, day 2 and day 3 were 14.71 (l/m^2), 16.46 (l/m^2), 15.19 (l/m^2) respectively. Also during the night time, the distillate output obtained for day 1, day 2 and day 3 were 6.3 (l/m^2), 7.4 (l/m^2), 6.9 (l/m^2) respectively. Here in this experimental work the TBSS was modified with attachment of evacuated tubes, heat pipes, corrugated surfaces and energy storage materials. During the day time the higher distillate output was obtained due to higher values of basin water temperature, but in night time due to absence of solar intensity, the ambient temperature remains lower, which decreases the temperature of basin water, hence lower distillate output could be obtained. The energy storage materials store the heat during daytime and releases it on night time, hence higher night distillate productivity was obtained. There is much difference shows in the distillate output of day and night time. The total distillate output (day and night) obtained by MTBSS in day 1, day 2 and day 3 were 21.01 (l/m^2), 23.86 (l/m^2) and 22.09 (l/m^2) respectively.

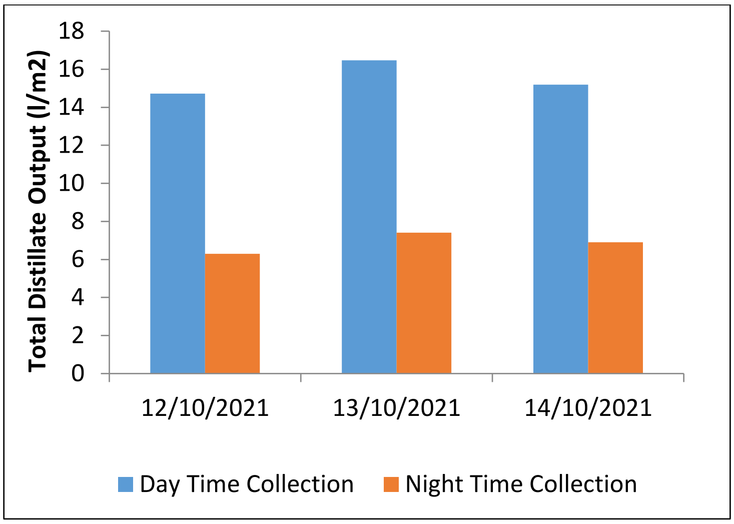

Figure 12. Comparison of day and night distillate output.

Table 2. Thermo-physical property of energy storage materials.

Sr.	**Materials**	**Operating temperature (°C)**	**Density (Kg/m^3)**	**Thermal Conductivity (W/mK)**
1.	Sand stone	Up to 160	2200	2327
2.	Graphite stone	Up to 160	2640	2.12-112
3.	Brick	20-70	1600	0.15-0.6

4. Life cycle cost analysis of system

Life cycle cost analysis is very important to check the performance of any solar still for commercial and economical point of view. Here after the experimental work, the life cost analysis was done MTBSS (Modified triple basin solar still). The objective of life cycle cost analysis was to check economical and efficiency performance of MTBSS for point of view. During the experimental work the MTBSS was modified with attachments of evacuated tubes, heat pipes, corrugated surfaces and energy storage materials. The life of the solar still and its annual cost of water are very important parameters for economical point of view. Here the economic analysis and energy- exergy efficiency analysis was done for MTBSS. The energy- exergy are very important parameters to check the energy and efficiency behavior of solar still. Also it becomes necessary to find out the exergo-economic and exergo-environmental parameters to identity the carbon credit generated by SS.

4.1.Energy- exergy efficiency analysis

This section shows the energy-exergy efficiency analysis for modified triple basin solar still (MTBSS). In energy- exergy efficiency analysis the different parameters like pressure of basin water vapor (P_{bw}), inner glass surface (P_{ig}), evaporative ($h_{e,bw-ig}$) and convective ($h_{c,bw-ig}$) heat transfer coefficient, exergy for evaporation ($Ex_{e,bw-ig}$) and convection ($Ex_{c,bw-ig}$), latent heat of vaporization (L), exergy (η_{exe})and energy (η_{energy}) efficiency were measured[21].

The value of energy and exergy efficiency were measured by calculation. To find out the energy efficiency equation (1) was used.

$$n_D = \frac{\sum m_D \times L}{\sum A_g \times It} \tag{1}$$

In above equation,

m_D = Total freshwater yield during the day (kg),

L = latent heat of evaporation (J/kg),

A_g = Glass cover surface area (m^2),

I_t = Total solar radiation (W/m^2)

Also to find out the latent heat of evaporation equation (2) was used.

$$L = 3.1615 \times 10^{6} \times [1 - (7.616 \times 10^{-4} \times T_W)] \quad (2)$$

In above equation,

L = latent heat of evaporation (J/kg),

Tw= Temperature of basin water (℃)

- To find out the exergy efficiency following equation no. (3) was used.

$$\eta_{exer} = \frac{Ex_{out}}{Ex_{inp}} \quad (3)$$

Here,

Ex_{out}= Exergy output value is equal to value of exergy generation ($Ex_{e,bw\text{-}ig}$)

Ex_{inp} = Exergy input value,

- To calculate the value of evaporative exergy value ($Ex_{e,bw\text{-}ig}$) equation (4) can be used.

$$Ex_{e,\,bw\text{-}ig} = he_{,bw\text{-}ig} \times Ab_W \times (T_{bw} - Tig) \times \left(1 - \frac{T_a}{T_{bw}}\right) \quad (4)$$

In above equation,

$h_{e,bw\text{-}ig}$ = Evaporative heat transfer coefficient (W/m^2 K), which was found using equation (5).

$$h_{(e,bw\text{-}ig)} = 16.273 \times 10^{-3} \times hc_{,bw\text{-}ig} \times \left[\frac{P_{bw} - Pig}{T_{bw} - Tig}\right] \quad (5)$$

$$P_{bw} = \exp\left(25.317 - \frac{5144}{T_{bs} + 273}\right) \quad (6)$$

$$P_{ig} = \exp\left(25.317 - \frac{5144}{T_{ig} + 273}\right) \quad (7)$$

In equation (5) to calculate the value of convective heat transfer coefficient ($h_{c,bw\text{-}ig}$) equation no. (8) was used

$$h_{c,bw\text{-}ig} = 0.884 \left\{(T_{bw} - T_{ig}) + \frac{(P_{bw} - Pig)(Tbw + 273.15)}{268900 - Pbw}\right\}^{1/3} \quad (8)$$

- Exergy input value = Ex_{sun}, (exergy input value is equal to absorbed solar radiation) could be found using equation (9).

$$Ex_{sun} = Abw \times It \times \left[1 - \frac{4}{3} \times \left(\frac{T_a + 273.15}{T_s}\right) + \frac{1}{3}\left(\frac{T_a + 273.15}{T_s}\right)^{4}\right] \quad (9)$$

Where Ts= temperature of sun (~6000 K).

- The value of fractional exergy for evaporation ($F_{e,bw\text{-}ig}$)and convection ($F_{c,bw\text{-}ig}$) were calculated using equations (10 & 11)

$$Fe{,}bw\text{-}ig = \frac{E_{xe,bw\text{-}ig}}{Exti} \quad (10)$$

$$F_{c,bw\text{-}ig} = \frac{E_{xc,bw\text{-}ig}}{E_{xti}} \quad (11)$$

Where E_{xti} = the total heat transfer, which was found using following equation no. (12)

$$Ex_{ti} = ht \times Ag \times (T_{bw} - Tig)(1 - \frac{T_a}{T_{bw}}) \tag{12}$$

Where

$$h_t = h_{e,bw\text{-}ig} + h_{c,bw\text{-}ig} \tag{13}$$

All the measured parameters are shown in **Table 3**.

Table 3. Measured parameters of energy-exergy analysis for CSS and MTBSS.

Sr	Parameter	Unit	MTBSS
1	Partial pressure of basin water vapor (P_{bw})	N/m^2	26385.9
2	Partial pressure of inner glass surface (P_{ig})	N/m^2	24126.47
3	Evaporative heat transfer coefficient ($h_{e,bw\text{-}ig}$)	W/m^2 K	26.84
4	Convective heat transfer coefficient ($h_{c,bw\text{-}ig}$)	W/m^2 K	1.46
5	Exergy for evaporation ($Ex_{e,bw\text{-}ig}$)	Joule	24.03
6	Exergy for convection ($Ex_{c,bw\text{-}ig}$)	Joule	1.307
7	Fraction exergy for evaporation ($F_{e,bw\text{-}ig}$)	%	2.07
8	Fraction exergy for convection ($F_{c,bw\text{-}ig}$)	%	0.05
9	Latent heat of vaporization (L)	J/kg	3000.17
10	Exergy Efficiency (η_{exe})	%	3.04
11	Energy Efficiency (η_{energy})	%	31.89

i. Fractional exergy variations for evaporation ($F_{e,bw\text{-}ig}$) and convection ($F_{c,bw\text{-}ig}$)

In below **Figure 13 and 14**, the fractional exergy variations for evaporation and convection is shown for MTBSS. In **Figure 13** the value of evaporation of exergy remains in the range of 0.94 % to 2.04%. This was happened due to the attachments of evacuated tubes, heat pipes, corrugated surfaces and energy storage materials with modified triple basin solar still. The exergy value increases from the morning time and reaches maximum in noon time and after that it decreases. This also happen due to the higher value of basin water temperature during that time. In **Figure 14** the variations of convection of exergy for MTBSS is shown. The values of convection of exergy remains in the range of 0.31% to 0.05 %

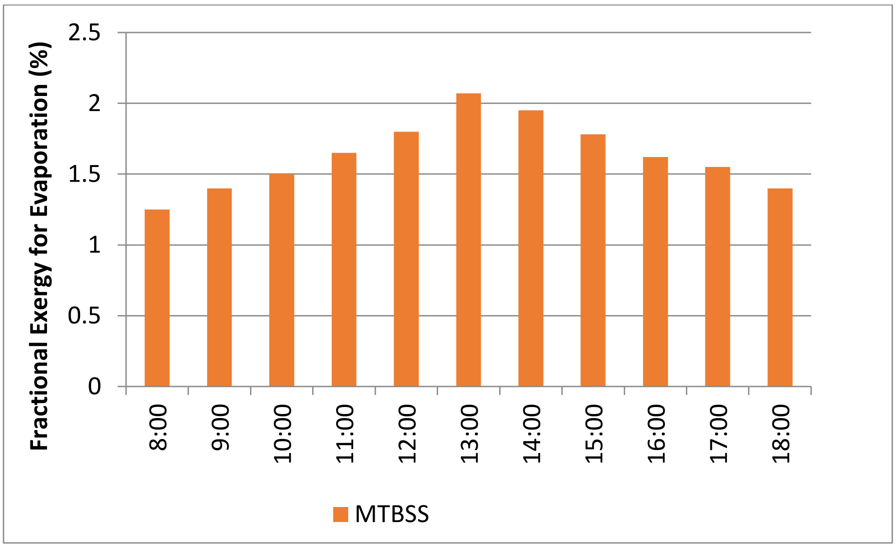

Figure 13. Fractional exergy for evaporation.

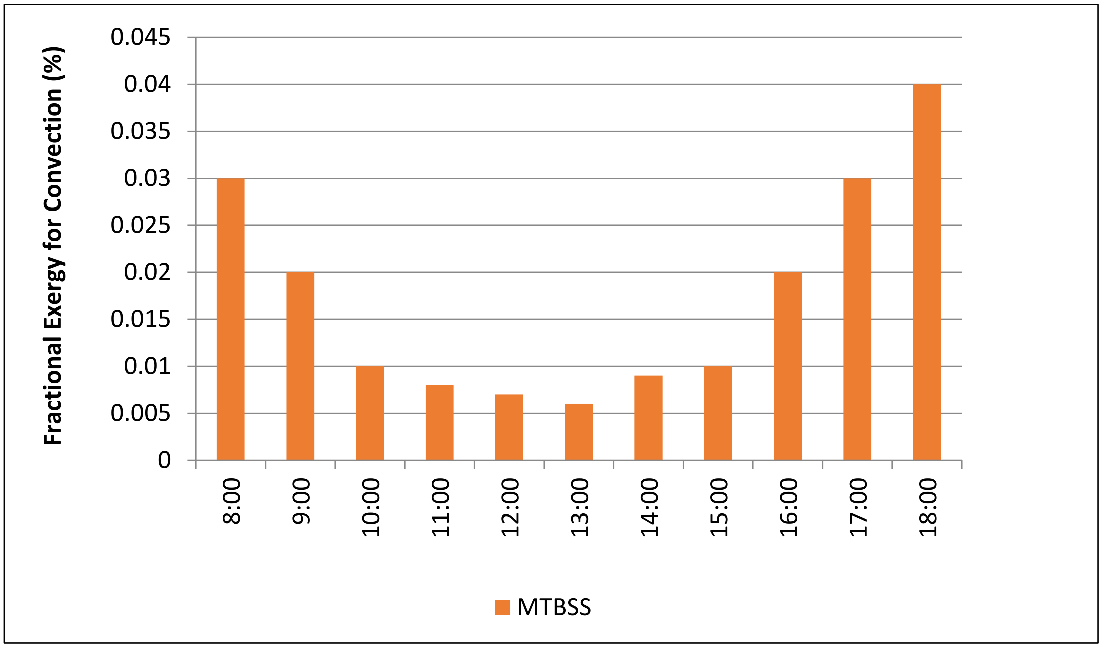

Figure 14. Fractional exergy for convection.

ii. Comparison of full-day energy (η_{energy}) and exergy (η_{exe}) efficiency

Here in below **Figure 15** the comparison of energy and exergy efficiency is shown for MTBSS. The value of energy and exergy efficiency for MTBSS is shown in **Table 3**. The energy and exergy efficiency for MTBSS remains than the work done by Thakur et al.2021[26], because in MTBSS the value of exergy generation remains higher. Also it has lower value of latent heat of vaporization (L). In MTBSS the partial pressure generated for basin water vapor remains higher. Due to higher pressure of water inside the basin, gives higher heat transfer coefficient of water for MTBSS. Hence higher energy and exergy efficiency of 72.12% and 87.12% was obtained for MTBSS than Thakur et al.2021[26].

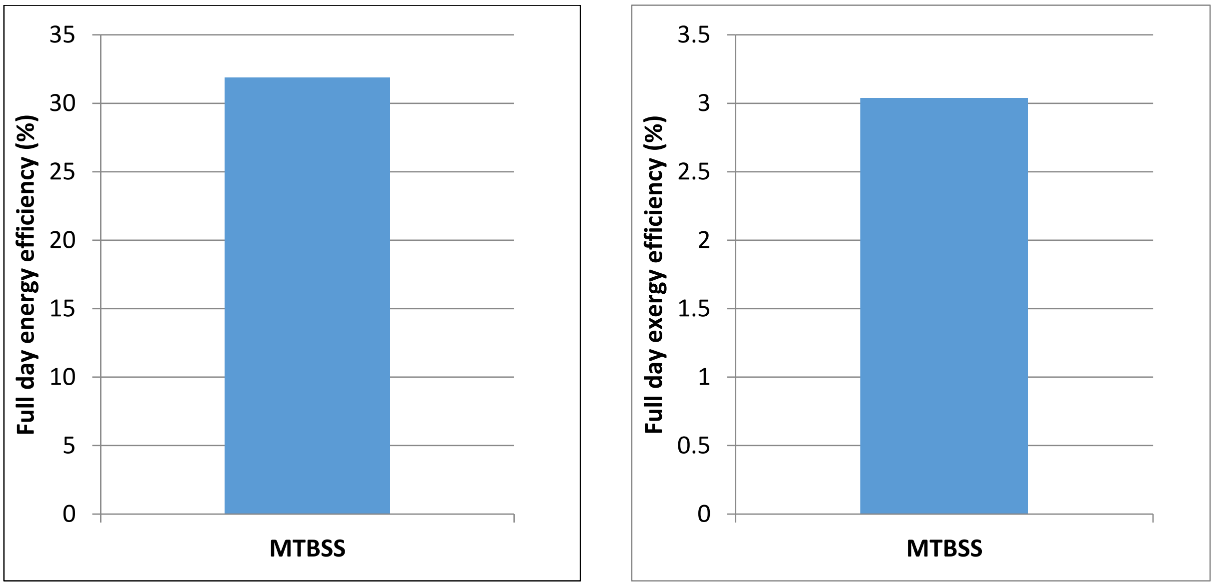

Figure 15. Comparison of full day energy and exergy efficiency.

4.2. Exergo-economic and exergo-environmental analysis of MTBSS

i. Economic analysis of MTBSS

To check the performance of any solar still for commercial point of view, it is necessary to determine its economics analysis. To calculate the economics analysis, it becomes necessary to consider the material cost, cost of different instruments used, distillate water production cost (CPL)[27]. The different economic and environmental parameters were found during calculation.

To determine the total water cost per liter for MTBSS Eq. (14) to (21) were used. Primary annual cost (PAC) and Yearly salvage value was found using eq. no (14) and (16)

$$PAC = C\,(CRA) \tag{14}$$

$$CRA = \frac{i \times (1+i)^{l}}{(1+i)^{l}-1} \tag{15}$$

$$YSV = (SFA) \times SC \tag{16}$$

Here

C = Capital cost of TBSS,

i = rate of interest,

l = life of the SS.

The rate of interest was considered as 0.05%. Salvage cost (SC) and Sinking Fund Aspect (SFA) was found using Eq. (17) & (18).

$$SC = 0.2 \times C \tag{17}$$

$$SFA = \frac{i}{(i+1)^{l}-1} \tag{18}$$

The value of YUC, OAC and CPL were determined using Eq. (19) to (21)

$$YUC = 0.15 \times (PAC) \tag{19}$$

$$OAC = PAC + YUC - YSV \tag{20}$$

$$CPL = \frac{OAC}{M} \tag{21}$$

Here, M shows the mean yearly distillate.

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

$$\text{Total payback period} = \frac{Capital\ cost}{Net\ earning} \tag{22}$$

In below **Table 4** the different parameters calculated for economic analysis of MTBSS is shown.

Table 4. Economic analysis of MTBSS.

Sr.	Material	Quantity	MTBSS (USD)
1	Evacuated Tube	25	100
2	EGT Cap	25	8
3	Glass Cover	2	13
4	Iron Stand	10 kg	107
5	Mild Steel Sheet	120 kg	128
6	PUF Sheet	6	6
7	Tar Seal	2	4
8	Silicon Ring	15	6
9	Silicon Seal	2	3
10	Fevicol S.R	1	3
11	Thermocouple	10	13
12	Measuring Jar & Pipe	6	4
13	Fabrication Cost	–	80
14	Total cost	–	475
15	Primary Annual Cost (PAC)	–	60.8
16	Full day distillate (L/m^2)	–	23.86
17	Yearly distilled water generation (L/m^2)	–	7158
18	Cost of Water/L (USD ȸ)	–	0.0087
19	Net pay back time (NPBT) in Month	–	2.5

ii. Environmental analysis of MTBSS

Exergy generation and carbon credit production (CCP) are very important parameters considered for environmental analysis. Here in below **Table 5** the different calculated parameters of environmental analysis for MTBSS is shown. Also the net pay back time of water was found. For the generation of (CO_2) the carbon credit should also be considered, which is very important parameter for environmental aspect[28]. The different exergo-economic and exergo-environmental analysis parameters (R_{ex}) are shown in below table. The R_{ex} could be found by Eq. (23)

$$R_{ex} = \frac{Ex_{out}}{PAC} \tag{23}$$

where, Ex_{out} = output exergy

Table 5. Environmental analysis of MTBSS.

r.	Parameters	MTBSS
1	Yearly total life of SS (In years)	10
2	Yearly distillate yield (L/m^2)	7158
3	PAC (In USD)	60.8
4	Ex_{out}, (W)	24.03
5	Rex (W/USD)	0.40
6	$\phi_{ex,\,CO2}$ (t CO_2/year)	0.48
7	CCP (USD/year)	8.99
8	Net pay back time (NPBT) in Month	2.5

In respect of environmental parameters, the value of carbon credit generated were calculated and mentioned in **Table 5**.

The CO_2 production mitigation/year was calculated using following equation:

$$\phi_{ex_{,}co2} = \frac{(Ex_{out} \times l) \times 2}{1000} \tag{24}$$

Where, $\phi_{ex_{,}co}2$ = exergo-environemmtal value,

Ex_{out} = exergy output and

l = Life of solar still.

The generation of carbon credit (CCP) was found by Eq. (25).

$$CCP = \phi_{ex_{,}co2} \times Zco_2 \tag{25}$$

5. Conclusion

After conducting experimental work on Modified Triple basin solar still the following points were summarized.

a) Solar still having more number of basins and area gives higher performance in distillate output.

b) Triple basin solar still was modified with attachments of ETCs, ETCs with H.P, corrugated surfaces, and energy storage materials (ESMs). With corrugated surfaces the basin area of basin was increased, which absorbs the maximum solar radiations; hence higher evaporative and convective coefficient could be achieved.

c) Pebbles, black gravel and white granite marbles were used as energy storage materials (ESMs). It the heat during the day time and release it on night; hence, higher nocturnal productivity could be obtained. The total distillate output obtained by MTBSS during day and night was 16.46 l/m^2 and 7.40 l/m^{2,} respectively.

d) The MTBSS give higher pressure of basin water and inner glass cover. Also, it generates a higher value of exergy. The generation of exergy for evaporation ($Ex_{e,bw-ig}$) and convection ($Ex_{c,bw-ig}$) for MTBSS were 24.03 & 1.30 (joule) respectively.

e) The ETCs, heat pipes, and ESMs increase water's evaporative heat transfer coefficient and latent heat of evaporation in MTBSS. It also gives a higher efficiency of energy and exergy. The values of energy efficiency (η_{energy}) and exergy efficiency (η_{exergy}) obtained for MTBSS were 0.39% & 3.04% respectively.

f) From economic point of view, the CPL of water remains higher in MTBSS. The NPBT for MTBSS was 2.5 months.

g) For an environmental assessment, the CO_2 mitigation for MTBSS was 0.48 t/year, respectively, based on the exergy approach. The additions of ETCs, H.P, corrugated surface, and ESMs with MTBSS are effective from an exergo-economic and carbon credit point of view.

The following points are considered for future scope:

a) The different modifications were done on TBSS to enhance the distillate output during the day and night. It can also be extended with attachments of fins and nanomaterial.

b) To reduce top heat losses, the experiment can be conducted with an attachment of a condenser.

c) A comparison is possible by adding different sensible and latent heat storage materials with TBSS.

References

1. Tripathi, Abhishek & Aruna, Mangalpady & Pv, Elumalai & Karthik, Krishnasamy & Khan, Sher & Asif, Mohammad & Rao, Koppula. (2024). Advancing Solar PV Panel Power Prediction: A Comparative Machine Learning Approach in Fluctuating Environmental Conditions. Case Studies in Thermal Engineering. 59. 104459. 10.1016/j.csite.2024.104459.
2. Panchal, H. N. (2016). Life cycle cost analysis of a double-effect solar still. International Journal of Ambient Energy, 38(4), 395–399. https://doi.org/10.1080/01430750.2015.1132767
3. D. Mevada, H. Panchal, and K. K. Sadasivuni, "Investigation on evacuated tubes coupled solar still with condenser and fins: Experimental, exergo-economic and exergo-environment analysis," Case Stud. Therm. Eng., vol. 27, no. June, p. 101217, 2021, doi: 10.1016/j.csite.2021.101217.
4. H. N. Panchal and P. K. Shah, "Enhancement of upper basin distillate output by attachment of vacuum tubes with double-basin solar still," Desalin. Water Treat., vol. 55, no. 3, pp. 587–595, 2015, doi: 10.1080/19443994.2014.913997.
5. H. N. Panchal and S. Patel, "Effect of Various Parameters on Augmentation of Distillate Output of Solar Still: A Review," Technol. Econ. Smart Grids Sustain. Energy, vol. 1, no. 1, pp. 1–8, 2016, doi: 10.1007/s40866-016-0005-2.
6. H. Panchal, D. Mevada, and K. K. Sadasivuni, "Recent advancements in condensers to enhance the performance of solar still: A review," Heat Transf., vol. 49, no. 6, pp. 3758–3778, 2020, doi: 10.1002/htj.21799.
7. D. Mevada, H. Panchal, and K. K. Sadasivuni, "Investigation on evacuated tubes coupled solar still with condenser and fins: Experimental, exergo-economic and exergo-environment analysis," Case Stud. Therm. Eng., vol. 27, no. June, p. 101217, 2021, doi: 10.1016/j.csite.2021.101217.
8. H. Panchal, D. Mevada, and R. Sathyamurthy, "The requirement of various methods to improve distillate output of solar still: a review," Int. J. Ambient Energy, vol. 42, no. 5, pp. 597–603, 2021, doi: 10.1080/01430750.2018.1542630.
9. A. Allouhi, M. Benzakour Amine, M. S. Buker, T. Kousksou, and A. Jamil, "Forced-circulation solar water heating system using heat pipe-flat plate collectors: Energy and exergy analysis," Energy, vol. 180, pp. 429–443, 2019.
10. R. S. Dondapati, R. Agarwal, V. Saini, G. Vyas, and J. Thakur, "Effect of Glazing Materials on the Performance of Solar Flat Plate Collectors for Water Heating Applications," Mater. Today Proc., vol. 5, no. 14, pp. 27680–27689, 2018.
11. S. K. Verma, K. Sharma, N. K. Gupta, P. Soni, and N. Upadhyay, "'Performance comparison of innovative spiral shaped solar collector design with conventional flat plate solar collector,'" Energy, vol. 194, 2020.
12. A. A. Ananno, M. H. Masud, P. Dabnichki, and A. Ahmed, "Design and numerical analysis of a hybrid geothermal PCM flat plate solar collector dryer for developing countries," Sol. Energy, vol. 196, no. September 2019, pp. 270–286, 2020.
13. S. Mohamed Iqbal, K. Karthik & Jee Joe Michael (2020) Performance analysis on improved efficiency in a hybrid solar still and solar heater, International Journal of Ambient Energy, 41:13, 1516-1523, DOI: 10.1080/01430750.2018.1517685.
14. Hitesh Panchal & Ravishankar Sathyamurthy (2020) Experimental analysis of single-basin solar still with porous fins, International Journal of Ambient Energy, 41:5, 563-569, DOI: 10.1080/01430750.2017.1360206
15. A. S. Abdullah, M. M. Younes, Z. M. Omara, and F. A. Essa, "New design of trays solar still with enhanced evaporation methods – Comprehensive study," Sol. Energy, vol. 203, no. April, pp. 164–174, 2020, doi: 10.1016/j.solener.2020.04.039.
16. L. Zhang, Z. Xu, B. Bhatia, B. Li, L. Zhao, and E. N. Wang, "Modeling and performance analysis of high-efficiency thermally-localized multistage solar stills," Appl. Energy, vol. 266, no. March, p. 114864, 2020, doi: 10.1016/j.apenergy.2020.114864.
17. J. Madiouli, A. Lashin, I. Shigidi, I. A. Badruddin, and A. Kessentini, "Experimental study and evaluation of single slope solar still combined with flat plate collector, parabolic trough and packed bed," Sol. Energy, vol. 196, no. August 2019, pp. 358–366, 2020, doi: 10.1016/j.solener.2019.12.027.
18. M. Abu-Arabi, M. Al-harahsheh, M. Ahmad, and H. Mousa, "Theoretical modeling of a glass-cooled solar still incorporating PCM and coupled to flat plate solar collector," J. Energy Storage, vol. 29, no. November 2019, p. 101372, 2020, doi: 10.1016/j.est.2020.101372.
19. P.Kumar, C.Senthil kumar, K.Muralidharan, Y.Muniratnam, K.Abraham, V.Manikandan, P.Stalin, S.Prasanth, "Augmenting the performance of conventional solar still through the nano-doped black paint (NDBP) coating on absorber," Material Today, vol. 47, no. April 2021, pp. 4929-4933, 2021, doi: https://doi.org/10.1016/j.matpr.2021.03.721.
20. U.Alqsair, A.Abdullah, Z.Omara, "Enhancement the productivity of drum solar still utilizing parabolic solar concentrator, phase change material and nanoparticles' coating," J. Energy Storage, vol. 55, no. August 2022, p. 105477, 2022, doi:10.1016/j.est.2022.105477.

21. El-Sebaey , Asko Ellman , Ahmed Hegazy , Fadl A. Essa , “Experimental study with thermal and economical analysis for some modifications on cylindrical sector and double slope, single basin solar still,” Case study in Thermal Engg., vol. 49, no. July 2023, p. 103310, 2023, doi.org/10.1016/j.csite.2023.103310.
22. S.Gnanaraj, S. Ramachandran, D.Christopher, “Enhancing the design to optimize the performance of double basin solar still,” Desalination, vol. 411, no. Feb 2017, p. 112-123, 2017, doi.org/10.1016/j.desal.2017.02.011.
23. El-Sebaey, A Hegazy, F.Essa, “Performance enhancement of a tubular solar still by using stepped basins: An experimental approach,” J.Clear production, vol. 437, no. Jan 2024, p. 140746, 2024, doi.org/10.1016/j.jclepro.2024.140746.
24. M.Raj Kamal,B. Parandhaman, B. Madhu, D.Babu, R.Sathyamurthy “Experimental analysis on single and double basin single slope solar still with energy storage material and external heater,” M.Today Proceed., vol. 46, no. Feb 2021, p. 10288-10292, 2021, doi.org/10.1016/j.matpr.2020.12.444.
25. E. Davani, K. Jafarpur, M.Estahbanati “A novel analytical performance investigation of varying water depth in an active multi-stage basin solar still in addition to optimization of water depth in a single stage basin still,” E. Reports , vol. 10, no. July 2023, p. 581-590, 2023, doi.org/10.1016/j.egyr.2023.07.013.
26. A. K. Thakur et al., “Performance analysis of a modified solar still using reduced graphene oxide coated absorber plate with activated carbon pellet,” Sustain. Energy Technol. Assessments, vol. 45, no. January, p. 101046, 2021, doi: 10.1016/j.seta.2021.101046.
27. D. Mevada et al., “Investigation and performance analysis of solar still with energy storage materials: An energy-exergy efficiency analysis,” Case Stud. Therm. Eng., vol. 29, no. July 2021, p. 101687, 2022, doi: 10.1016/j.csite.2021.101687.
28. D. Mevada, H. Panchal, and K. K. Sadasivuni, “Investigation on evacuated tubes coupled solar still with condenser and fins: Experimental, exergo-economic and exergo-environment analysis,” Case Stud. Therm. Eng., vol. 27, no. June, p. 101217, 2021, doi: 10.1016/j.csite.2021.101217.
29. Sharma, N., Noushad, S., Siva Ram Kumar Reddy, G. (2022). Effect of Copper Fins on Fresh Water Productivity of Pyramid Solar Still. In: Kumar, R., Pandey, A.K., Sharma, R.K., Norkey, G. (eds) Recent Trends in Thermal Engineering. Lecture Notes in Mechanical Engineering. Springer, Singapore. https://doi.org/10.1007/978-981-16-3132-0_9.
30. N. Sharma, Varun, and Siddhartha, “Stochastic techniques used for optimization in solar systems: A review,” Renew. Sustain. Energy Rev., vol. 16, no. 3, pp. 1399–1411, 2012, doi: 10.1016/j.rser.2011.11.019.
31. P. Dumka et al., “A case study on single basin solar still augmented with wax filled metallic cylinders,” Case Stud. Therm. Eng., vol. 61, no. July, p. 104847, 2024, doi: 10.1016/j.csite.2024.104847.
32. A. F. Abed, M. J. Alshukri, and D. M. Hachim, “Improving solar still performance via the integration of nanoparticle-enhanced phase change materials: A novel pyramid-shaped design with a numerical simulation approach,” J. Energy Storage, vol. 97, no. PB, p. 112980, 2024, doi: 10.1016/j.est.2024.112980.
33. T. Mahala and N. Sharma, “Experimental investigations of a novel solar still with heat storage materials - energy, exergy, economic and environmental analyses,” Desalination, vol. 578, no. November 2023, p. 117467, 2024, doi: 10.1016/j.desal.2024.117467.
34. M. Bady, M. El Hadi Attia, and A. Elnaby Kabeel, “Performance improvement of the conical solar still using hollow copper tubes in the basin with CO2 mitigation and economic analysis,” Sol. Energy, vol. 278, no. July, p. 112797, 2024, doi: 10.1016/j.solener.2024.112797.
35. T. Jeyaraj, P. Kumar, and S. Pathak, “Experimental and computational modeling analysis of double slope solar still with a trapezoidal channel for preheating,” Appl. Therm. Eng., vol. 253, p. 123757, 2024, doi: 10.1016/j.applthermaleng.2024.123757.
36. H. Aghakhani, S. M. Ayatollahi, and M. R. Hajmohammadi, “A novel numerical model for solar still combined with collector and reflector,” Appl. Therm. Eng., vol. 248, no. PA, p. 123123, 2024, doi: 10.1016/j.applthermaleng.2024.123123.
37. H. Aghakhani, S. M. Ayatollahi, and M. R. Hajmohammadi, “Proposing novel approaches for solar still performance enhancement by basin water heating, glass cooling, and vacuum creation,” Desalination, vol. 567, no. September, p. 117011, 2023, doi: 10.1016/j.desal.2023.117011.
38. Min, Ho. (2022). A Review of Metal Oxide Thin Films in Solar Cell Applications. International Journal of Thin Films Science and Technology. 11. 37-45. 10.18576/ijtfst/110105.