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Research Article

Performance enhancement of stepped solar still coupled with evacuated tube collector

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ABSTRACT

The provision of fresh water is the most important problem in developing countries. With the rising need for fresh water, it is vital to look for other sources. Solar energy is still one of the most essential and technically feasible applications of the sun. There are numerous varieties of solar stills; the basin type is the most basic and well-proven. The biggest disadvantage of a traditional basin solar still is that it produces very little distilled water per unit area. Solar distillation is one of the most basic method to remove pollutants including heavy metals, dust, salts, and microorganisms from water. When compared to rainwater, it produces more clean water. Using solar distillation technology, sea water can be converted to fresh water. In this study, a solar still with a single basin is compared against a concentrator with evacuated tubes and a stepped basin solar still to see which one produces the most output with the least amount of energy. The four cases are analyzed, and it is discovered that the productivity of case 1: a solar still with a single slope with constant flow rate is 1.05kg/m^2 and the maximum temperature obtained during this case is 49.0°C at 3:00 PM. The productivity for case 2: single slope solar with secondary stepped basin is 1.32kg/m^2 while the maximum temperature is about 61.8°C at 3:00 PM. The productivity of case 3: a solar still with a single slope linked to a compound parabolic concentrator is 1.47kg/m^2 with a maximum temperature of 62.4°C at around 3:00 PM. The output of Case 4: a solar still with a single slope with secondary stepped basin and compound parabolic concentrator is 1.72kg/m^2 with a maximum temperature of 70.2°C obtained at 3:00 PM. The efficiency of a solar still with a single slope and a secondary stepped basin with a compound parabolic concentrator is 63.8 % higher than the reference case.

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INTRODUCTION

Today's human society faces two significant challenges: a lack of conventional energy and fresh water. Solar stills are the most efficient way to transform saltwater into fresh water by utilizing sunlight that is freely and abundantly available on our planet. The primary challenge of the twenty-first century is to improve use of water purification devices so that clean

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water may be provided while simultaneously safeguarding the environment in a sustainable manner. Many researchers have examined various solar still arrangements. The various factors influencing solar still production (climatic conditions, operation, and design parameters) as well as enhancement techniques (wicks, internal and external condensers, internal and external reflectors, phase change materials, stepped solar still, and a new method which improved the solar still yield by using nanoparticles) have been discussed [1]. Experiments have been conducted on night distillation, which accounts for the majority of the production of deep basin stills. The results show that the accumulated thermal energy in the still at sunset is the sole determinant of distillate output [2]. The performance of solar stills using photovoltaics, flat plate collectors, and hot air is investigated [3]. For enhancing pure water productivity, a desalination system using solar-heated membrane distillation is made up of membrane distillation and solar collectors. To address the inconsistency of solar energy from sunrise to sunset, this technically and economically feasible technology is designed to employ indirect solar heat to drive membrane distillation processes [4]. The heat integration scenario minimizes the total process's energy usage [5]. El-Agouz et al. [6] explained why the output of the modified stepped still is higher than that of the traditional still. According to recent research [7], solar stills with a linear parabolic trough collector can boost a desalination system's efficiency. A twin-glass evacuated tube collector and heat pipe are combined with a parabolic trough collector in this study. When aluminium conducting foils are employed in the area between the twin-glass evacuated tube collector and heat pipe, the rate of production and efficiency can reach 0.27 kg/(m^2 h) and 22.1 %, respectively. Efficiency of the solar collector has been calculated using steam generation in ETC (Evacuated Tube Collector). [8]. Many computational and experimental studies on various solar still configurations have been conducted in order to optimize the design by analysing the effect of environmental, operational, and design aspects on its performance. Selecting the proper cover tilt angle for different seasons and latitudes [9] is one of the most important parameters that has attracted a lot of attention. Wilson, a Swedish engineer, designed the first conventional solar still in 1872 to supply fresh water to a nitrate mining community in Northern Chel Aravind [10], and developed thermal models for all types of solar collector integrated active solar stills based on energy balance equations in terms of inner and outer glass temperature. The heat transfer caused by cooling water evaporation was explored by [11], and the still productivity was enhanced by injecting a portion of the cooling water into the basin as preheated makeup water. The performance of a conventional still with a uniform water flow above the glass cover was investigated, and it was found that by introducing a uniform water flow above the glass cover, the distillate output of the solar still was often doubled, and slightly reduced with increasing the flowing water above the glass cover due to a reduction in the temperature of the still's saline water [12]. An experiment on top cover cooling solar still productivity was conducted by [13]. The water inside the basin was heated in two ways: first, by solar energy absorbed in the basin, and second, by solar collector heating. The water in the basin heated up, causing evaporation. The vapour rose to the top of the glass cover and condensed to the bottom.

The condensation process was assisted by allowing cold water to pass between the two layers of the glass cover. The condensate trickled down the inner 19 glass surface, into a trough at the bottom of the glass cover, and out as fresh water. The production rate was associated with sun irradiance, ambient temperature, and cooling water flow rate, according to the findings. The effect of a v-corrugated absorber and PCM (Phase Change Material) on basin still productivity was investigated experimentally and discovered that the daily productivity of a v-corrugated absorber with PCM was 12 % higher than that of a v-corrugated absorber without PCM [14]. The impact of external and interior reflectors on the productivity of solar stills is investigated. External or internal reflectors were a good and inexpensive way to boost the solar irradiation directed to the basin liner or water as well as the still's distillate efficiency [15]. Anshika et al. [16] found that the overall efficiency of solar still increases by 9.86% when coupled with a flat plate collector, this report describes the experimental work carried out at (18^o 63' N, 73^o 84' E) to increase the performance of a stepped solar still with an ETC collector. The employment of a parabolic trough concentrator, heat sink, condenser, and sand on the performance of a solar still were investigated in [17], and saw that the efficiency was raised by 67%, 7.3%, and 6%, respectively. The results reveal that using PCM reduces freshwater productivity [18] during the day, with a considerable increase in the overall freshwater output of the still as the freshwater production is extended by 5 to 6 hrs after sunset. A conventional solar still with a single slope is coupled with a parabolic trough collector (PTC) and flat plate collector (FPC), and a thermal storage medium packaged glass ball layer (PLGB) was investigated experimentally [19], whereas the use of selective coating was studied to optimize various parameters affecting the performance of solar still [20]. The results show that the solar still with PTC-FPC-PLGB has more freshwater productivity when compared to typical solar still. According to a review of the literature and discussions with experts, the use of a parabolic concentrator with a V-groove to improve the performance of an evacuated tube collector has yet to be described. The performance of a solar still with a single slope with pockets inside the secondary basin for PCM and a parabolic concentrator to boost the solar still's performance has been investigated. Case 1: single slope solar still with constant flow rate, Case 2: a solar still with single slope with secondary stepped basin, Case 3: a solar still with single slope coupled with compound parabolic concentrator, and Case 4: a solar still with single slope with secondary stepped basin coupled with compound parabolic concentrator are the four cases studied and compared experimentally and it is found that the Case 4: A single slope solar still with a secondary stepped basin and a compound parabolic concentrator produces 1.72kg/m^2 with a system efficiency of 18.38%, while increasing the efficiency by 63.8 % over the reference case.

EXPERIMENTAL SETUP

Experimental Setup Design and Fabrication

The solar still setup is fabricated at Pune, India (32.7628° N, 96.8161° W) and made up of a single basin composed of 0.7 mm thick galvanised steel sheet having dimensions of 1.41 m x 0.70 m. Moreover, the secondary stepped basin made up of 0.7 mm thick galvanized steel sheet as shown in Figure 1. To increase the absorptivity, black paint is used on the wall of the solar still basin and secondary stepped basins. Cover glass is made up of toughened glass 4mm thickness. For the construction of the solar still, a gauge, 22 galvanized iron sheet is used. The basin is 1 m^2 in size, with a 2:1 aspect ratio (Figure 1). This is due to the fact that a 2:1 absorber aspect ratio allows for optimal solar energy collecting in the solar still as reported by El-Swify and Metias [21]. The solar still is surrounded by a 1-inch-thick glass wool insulation to reduce heat loss. Inside the basin, black paint is applied to properly utilize the sunlight through absorption in the absorber. A condensing cover, constructed of plain glass having a thickness of 5 mm and angled at 28°, is to be employed (approximately equal to the latitude location). To obtain significant amounts of incident sunlight during the day, the solar still must be aligned in the south direction.

As illustrated in Figure 2, an extra absorber in the form of a sliding tray (with comparable dimensions to the primary basin) is constructed. By adding 1 in. thick polystyrene sheets below the additional absorber, the height of the solar still chamber can be changed. This effectively changes the cavity dimensions of the basin while leaving the area of the absorber unchanged. Stepped Absorber Plate: A stepped absorber plate is a form of absorber plate that is attached to the top of a traditional basin (Figure 2). Following trays and inclined flat plate collectors make up the system. This provides an increased exposed area, increasing the rate of evaporation.

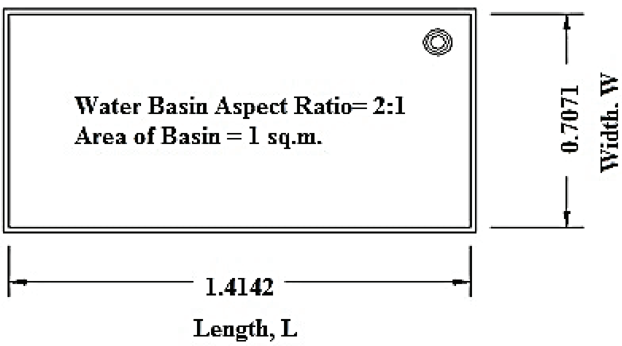

Figure 1. Basin area of solar still with aspect ratio 2:1.

Figure 2. Stepped absorber plate.

Properties of Tempered Cover Glass

Thickness: 5mm (Commercial solar water heater uses 4 mm optimum thickness for more efficiency). Length = 1385mm, Width = 680mm, 4-6th times more strength than normal glass of the same thickness.

Stand used for Mounting the Solar Still

Figures 3-4 show the stand for mounting the solar still.

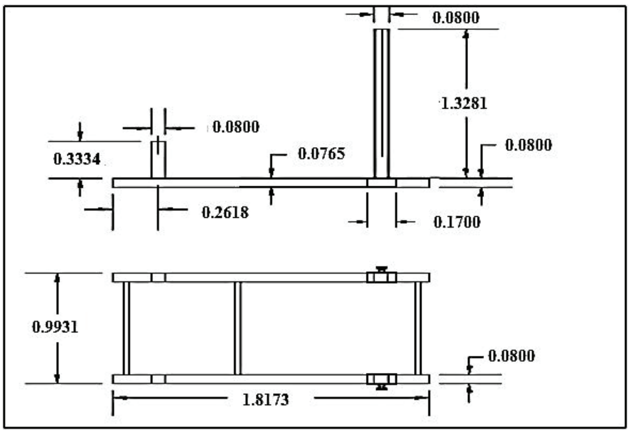

Figure 3. Stand used for mounting the solar still.

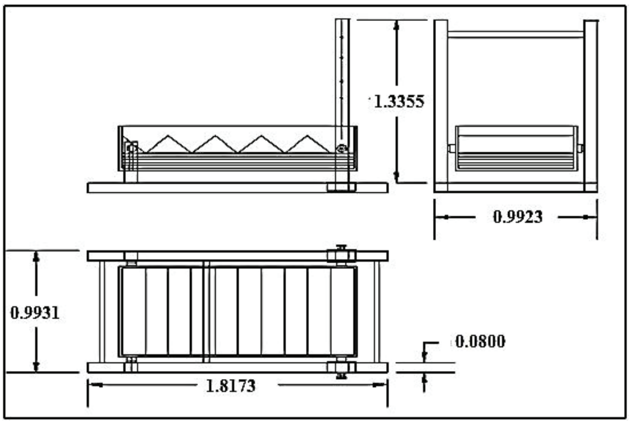

Figure 4. Solar still mounted on the stand.

Evacuated Tube Collectors (ETC)

When compared to flat plate solar collectors, ETC have greater efficiency. Only at noon are the sun rays perpendicular to the collector in flat plate collectors, therefore a portion of the sunlight impacting the collector's surface is always likely to be reflected. In an evacuated tube collector, however, the sun rays are perpendicular to the glass surface for the majority of the day due to its cylindrical shape. Due to the presence of vacuum in the tubes, the heat losses are considerably reduced.

Tubular Compound Parabolic Concentrator

There are three different parts in the setup, i.e., parabolic concentrator (Figure 5), evacuated tubes, and header.

Parabolic Concentrators

A novel idea proposed in this work is the CPC's (Compound Parabolic Concentrator) absorber being converted to an external heating device which supplies the preheated saline water to the single basin solar still through a natural thermo syphon. The advantage of a CPC is attaining higher temperature, which is utilized in this type of still for achieving higher rate of evaporation.

The compound parabolic concentrator with V-groove at the bottom of the evacuated tube transfers all sun rays to the lower side of the evacuated tubes, and hence increases the efficiency of evacuated tubes. The geometry of the "V" groove should match the following parameters to avoid gap losses.

$$\pi - 2\alpha \leq 2\varphi \leq 0.5\pi + \alpha$$
$$h \leq r tan^2\varphi + g(ctan^2\varphi - 1)/2$$

Where, $\varphi = Half\ angle\ of\ V$, *h= depth of V groove,*

The inner tube's lowest point in relation to the "V" groove's aperture, α is the angle produced by the line connecting A and the tube's center and the line AC. As the size of the EST and the width of the "V" groove (g = 0 for "V" groove), the depth (h) is a unique parameter to determine, so the depth of the groove is 12.29 mm ≤ h ≤ 14.52 mm for the evacuated tube of 47/58mm diameter.

Figure 5. Steel parabolic concentrator.

Figure 6. Borosilicate evacuated tube.

To study the performance of the evacuated tube solar collector. The parabolic reflectors with V-groove are placed below the evacuated tube to increase the performance of setup. Using reflectors, the output of a solar still can be improved up to 34%.

Evacuated Tubes

The evacuated tube has two concentric borosilicate glass tubes as shown in Figure 6. There is a vacuum present between these glass tubes. The outer tube has high transmissivity and minimal reflectivity. The inner tube has a layer of selective material and this selective material has high absorptance and low emittance properties. The table 1 shows the various properties of evacuated tubes while Figure 7 shows the cross section of borosilicate evacuated tubes.

Header

As shown in Figure 8, a header is designed and produced for the configuration. It has a square pipe that is 120 mm x 120 mm in size. This square pipe is equipped with eight

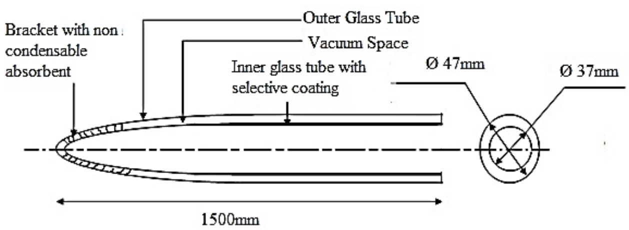

Figure 7. Cross section of borosilicate evacuated tubes.

Table 1. Properties of evacuated tubes

Parameter	Value
Number of evacuated tubes	8
Length	1500 mm
Diameter of Outer tube	47 mm
Diameter of Inner tube	37 mm
Weight	2.1 kg
Thickness of Glass	2.2 mm
Material of Glass	Borosilicate Glass 3.3
Absorptive coating	Graded CU/SS-ALN
Vacuum degree	$P<5\times10^{-3}$ Pa
Thermal expansion	3.3×10^{-6} /°C
Temperature-Insolation	>390°C
Absorptance	>93%
Emittance	<8%
Heat loss	$<0.8W/(m^{2}{}^{\circ}C)$
Maximum strength	0.8 Mpa
Resist cold	-35 °C
Resist hailstone	Ø 50 mm
Resist wind	50 m/s
Start-up temperature	<=25 °C

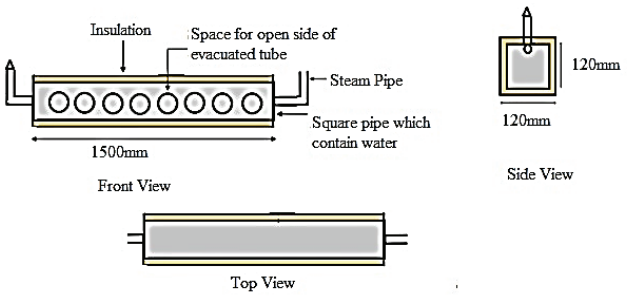

Figure 8. Cross Sections of Header.

holes. The open ends of the evacuated tubes are inserted into the holes, while the closed ends are held in place by a frame. Polystyrene insulation is placed over the square pipe. Insulation is 50mm thick. This insulation prevents heat loss from the header to the rest of the house.

Self-Cleaning Mechanism

The solar still's basin is kept clean by a self-cleaning mechanism, which prevents the accumulation of potentially harmful materials such as sodium and calcium residues. In water, sodium and calcium exist as positively charged ions. They are drawn on plates with negative electrodes (Basin). Sodium and calcium build up over time, rendering the electrode unusable and requiring the cell to be cleaned. The reverse polarity method is used by a self-cleaning system. Based on the impulses from the controller, the electrodes can be either positive or negative. The control device will adjust the polarity charge on a regular basis, preventing the accumulation of salt, calcium, and other minerals. As a result, you won't have to continuously remove and clean the basin to keep it in working order.

Instrumentation

1. Digital thermometer (with specifications as shown in Table 2)
   - Basin temperature (T_b)
   - Temperature of water (T_w)
   - Temperature of vapour (T_v)
   - Temperature of cover glass –inner (T_{gi})
   - Temperature of cover glass -outer (T_{go})
2. The distillate was measured using a measuring cylinder with a minimum count of 5ml.

Table 2. Instrumentation used in the experimental setup has the following technical specifications

Sr. no.	Instrument	Accuracy	Range	Error
1	Digital Thermometer	± 0.1°C	0-100°C	0.2%
2	Measuring Jar	± 5 ml	5-500ml	5%

Working Principle

Solar radiation falling on the surface of the tube is absorbed on the inner tube by the ETC collector, and the collected thermal energy is subsequently transmitted to the

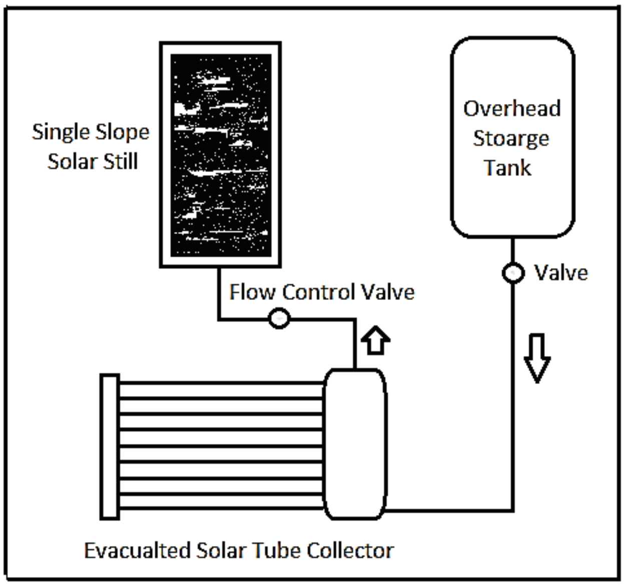

Figure 9. Schematic diagram of the solar still coupled with an evacuated tube solar collector.

Figure 10. Experimental setup.

working fluid travelling through the tubes. The temperature of the working fluid in the tube rises. To achieve the desired higher temperature, the outlet of the ETC is connected to the header. The solar still receives the hot water from the collector. After being exposed to the sun, the system begins to transfer heat. During the heating phase, convection of water molecules occurs, followed by evaporation and then condensation of the vapour to liquid water droplets on the glass surface. As a result of the sloped surface, these droplets drip down and accumulate in that channel. This is distilled potable water in its purest form. The solar still's condensing cover glass collects the condensed fresh water. The schematic diagram and actual experimental setup are as shown in Figure 9 and Figure 10, respectively.

RESULTS AND DISCUSSION

In this study, four cases are examined.

1. Solar still with a single slope and a constant flow rate
2. Solar still on a single slope with a secondary stepped basin
3. Solar still with a single slope and a compound parabolic concentrator
4. Solar still with secondary stepped basin and compound parabolic concentrator on a single slope. Various measurements are taken during the experimental process. The temperatures were recognized each one hour between 8:00 AM to 7:00 PM from 08/02/2019 to 13/02/2019, five temperatures were recorded. The relationship between ambient temperature with time for all experimental days is recorded and it is observed that the ambient temperature for all four days is nearly identical.

1. Temperature of basin material (T_b)
2. Water temperature inside the basin (T_w)
3. Vapour temperature between the condensing cover glass and the basin (T_v)
4. The temperature of the cover glass's inner side (T_{gi})
5. Temperature of the cover glass's exterior side (T_{go})

This research intends to maximize the productivity of desalinated water by strengthening the saline water evaporation process and improving the condensation process of evaporated fresh water. It is possible to improve the evaporation process.

Case 1: Single Slope Solar Still With Constant Flow Rate (Reference Case)

Temperatures at various locations such as the temperature of the basin, the temperature of the water inside the basin, the temperature of vapour between the condensing cover the basin, and the temperature of the outer and inner

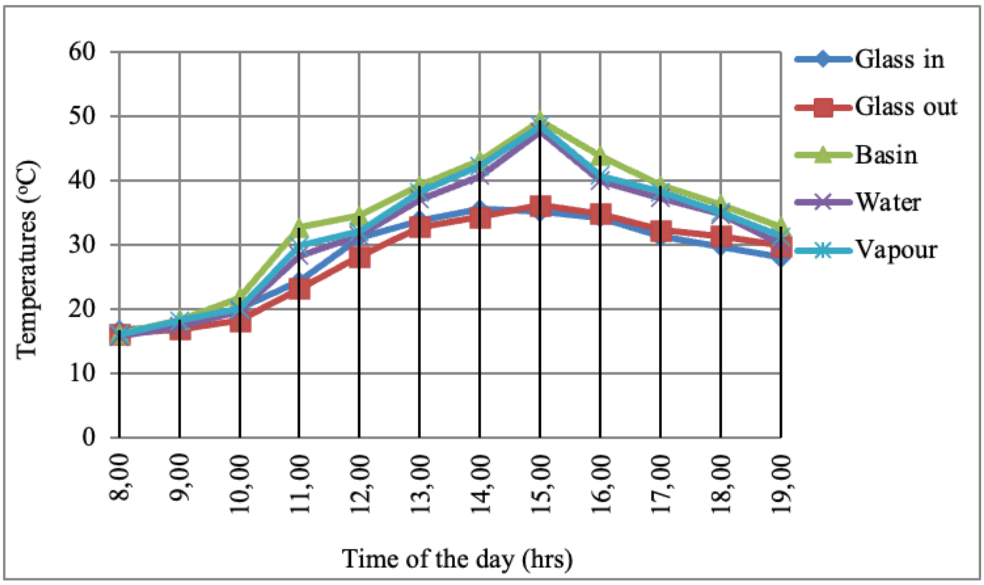

Figure 11. Relationship between solar still temperature with respect to time of the day.

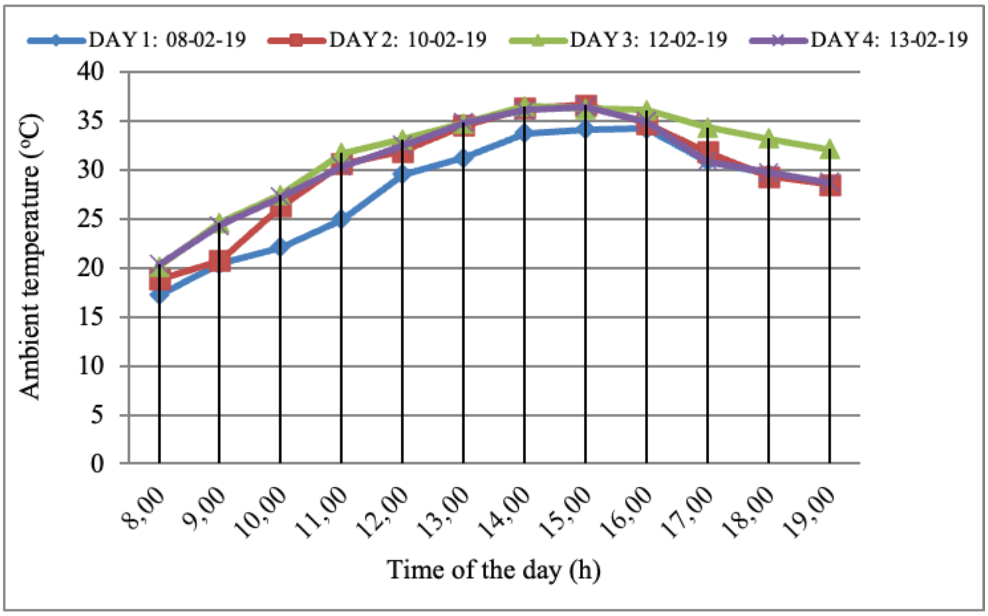

Figure 12. Relationship between ambient temperature with time on different days of experimentation.

surface of the glass were measured using digital thermometers. Figure 11 represents the temperature variation of several elements of a single slope solar still working at a constant flow rate with respect to the value of time of the day, with the maximum temperature obtained being around 50°C. The relationship between ambient temperature and time on different days of experimentation is depicted in Figure 12.

The temperature of the environment was also measured in relation to the time of day. Figure 13 represents the relationship between the hourly productivity of a still with a single slope working at a constant flow rate and time of day, with the maximum distillate output occurring about 3:00 PM. and being around 200 mL.

Case2: Solar Still with A Single Slope with A Secondary Stepped Basin

Inside the single slope, the solar still is a secondary stepped basin with pockets for PCM. The stepped basin allows for increased water evaporation space. Figure 14 represents the temperature change of various elements of a

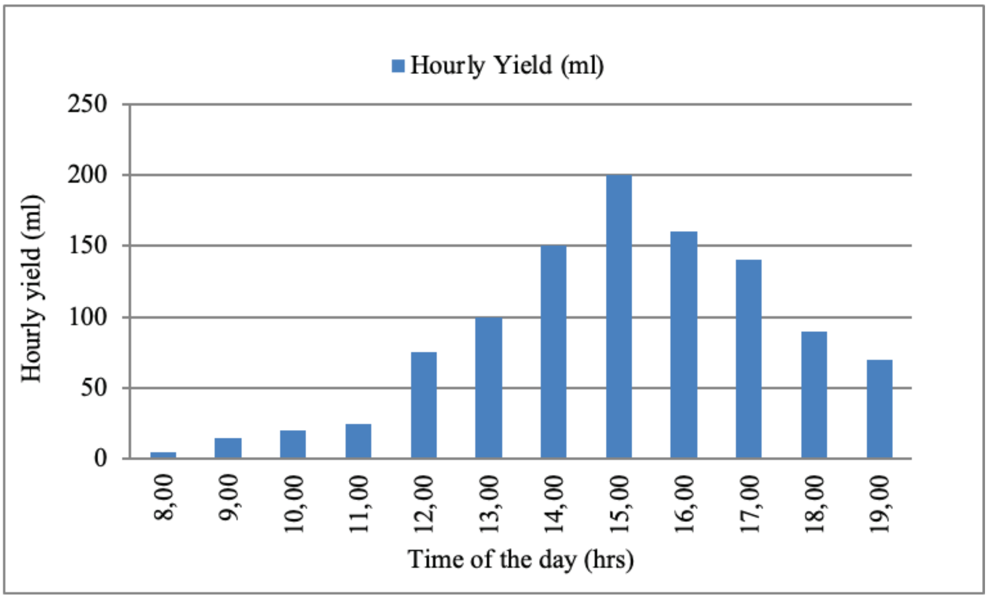

Figure 13. Relationship between hourly productivity with respect to time of the day.

single slope solar still operating at a constant flow rate and equipped with a secondary stepped basin with respect to the time of day, with the maximum temperature obtained as 62°C. Figure 15 depicts the link between the hourly productivity of a still with a single slope working at a constant flow rate and fitted with a secondary stepped basin and the time of day, with the greatest distillate output occurring about 3:00 PM. and being around 250 ml.

Case 3: Solar Still with A Single Slope and A Compound Parabolic Concentrator

Below the evacuated tubes, a complex parabolic concentrator with V-groove is placed. The performance of the evacuated tube can be the maximum contribution to the concentrator's reflection. Inside the stainless steel header, all evacuated tubes open. Figure 16 depicts the temperature change of several elements of a still with a single slope operating at a constant flow rate and connected to a compound parabolic concentrator with respect to the time of day, with the maximum temperature obtained as 62.5°C.

Figure 17 represents the relationship between the hourly productivity of a single slope solar still working at a constant flow rate and linked to a compound parabolic concentrator with reference to time of day. The greatest distillate yield is around 280ml around 3:00 PM.

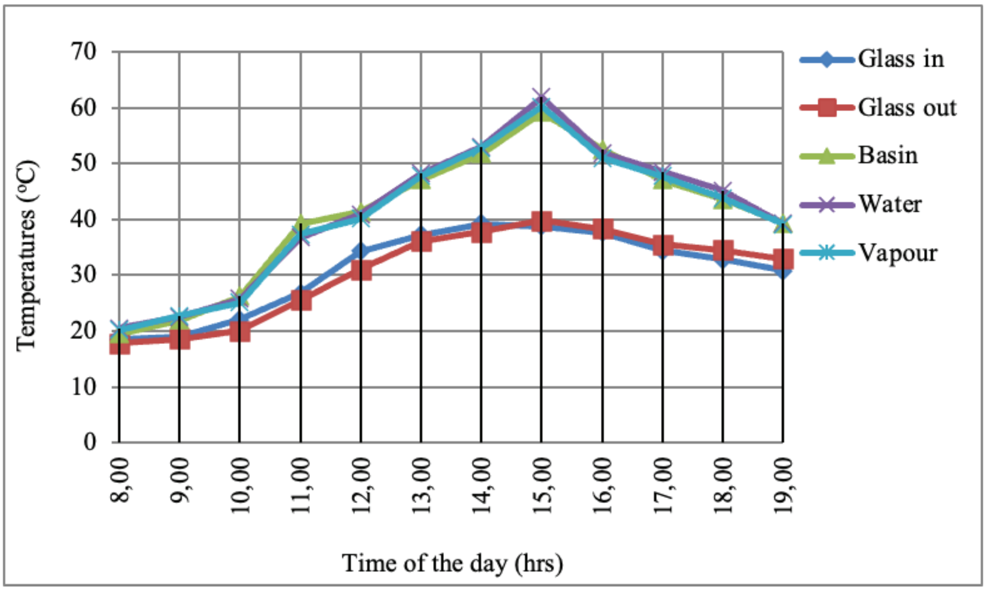

Figure 14. Relationship between solar still temperature with respect to time of the day.

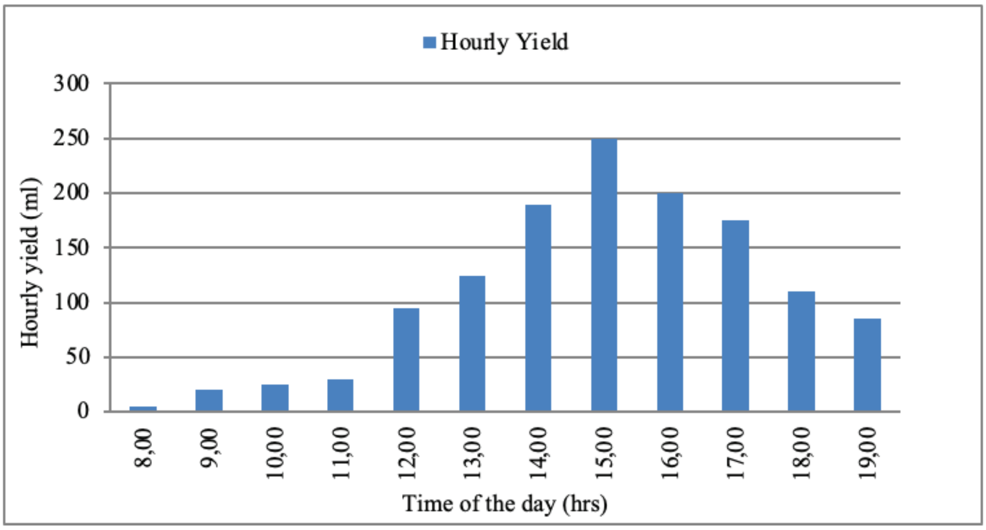

Figure 15. Relationship between hourly productivity with respect to time of the day.

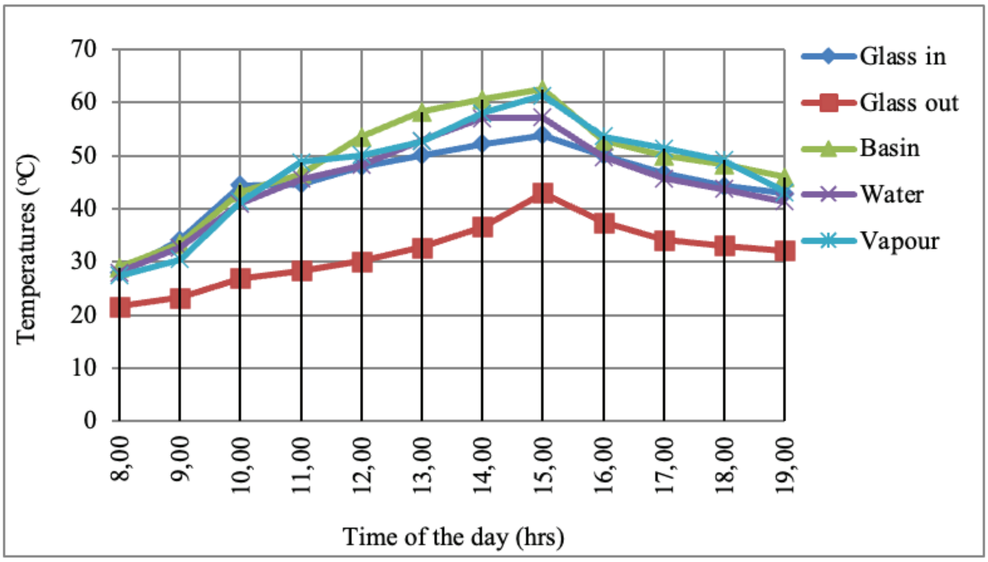

Figure 16. Relationship between solar still temperature time.

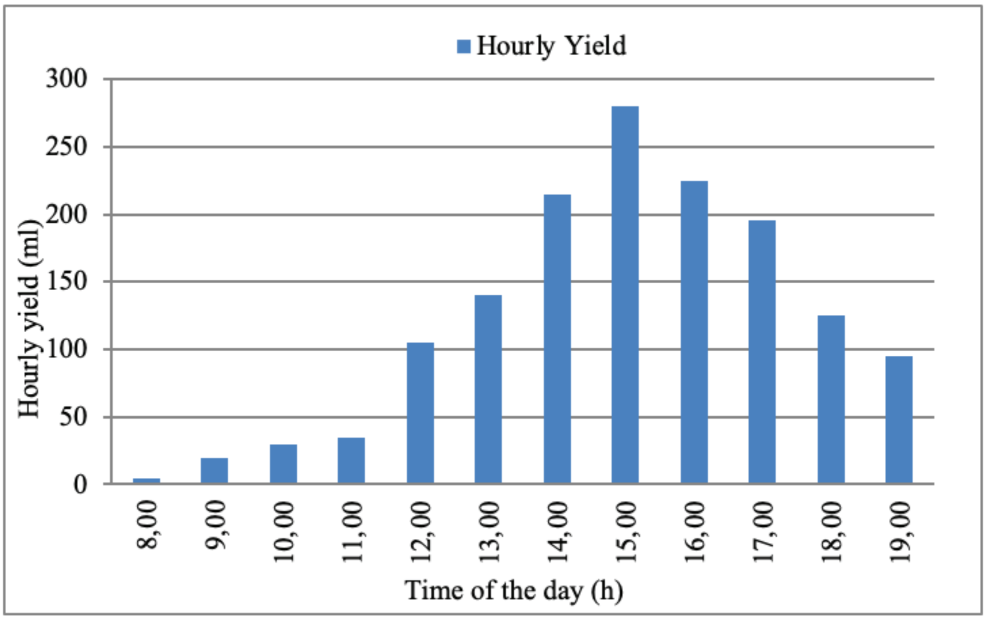

Figure 17. Relationship between hourly productivity with respect to time of the day.

Case 4: Solar Still with Secondary Stepped Basin and Compound Parabolic Concentrator

A solar still with a single slope and a secondary stepped basin, as well as CPC. Figure 18 shows the temperature change of various elements of a single slope solar still operating at a constant flow rate, fitted with a secondary stepped basin and coupled with a compound parabolic concentratorwith respect to the time of day, with the maximum temperature obtained as 70°C.

Figure 19 shows the relationship between hourly productivity and time of day for a single slope solar still operating at a constant flow rate, equipped with a secondary stepped basin and paired with a compound parabolic concentrator. The greatest distillate output is roughly 320ml around 3:00 PM. It is observed that the accumulated productivity of desalinated water is evaluated over time in various instances. The largest variance in productivity and efficiency is 1.72 kg/m^2 for solar stills with compound parabolic concentrators and stepped solar stills. Solar production is still 15 % when combined with a compound parabolic concentrator at 1.47 kg/m^2. Similarly, solar productivity declines by 12% with steps inside the basin, and

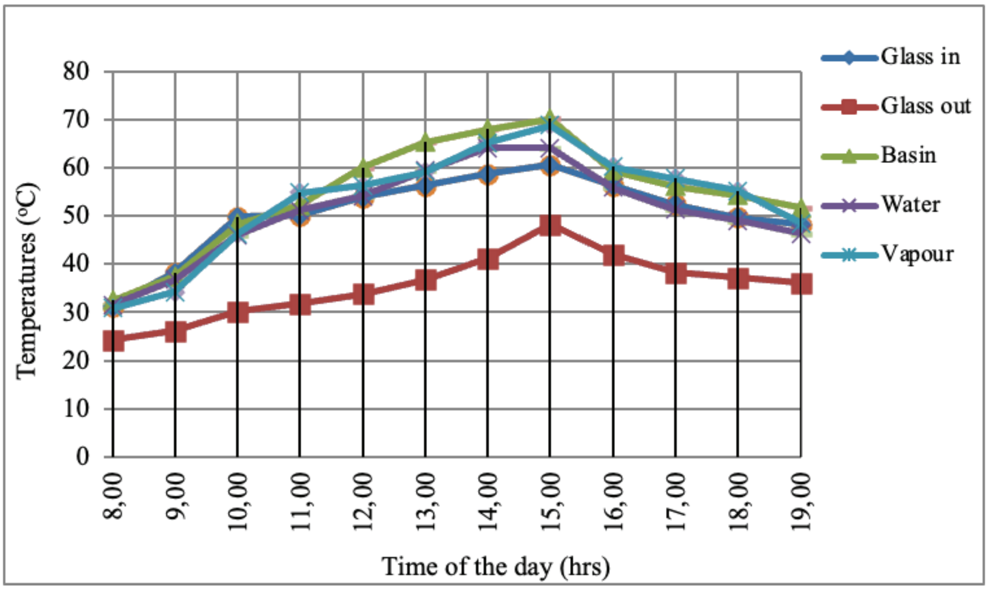

Figure 18. Relationship between solar still temperature with respect to time of the day.

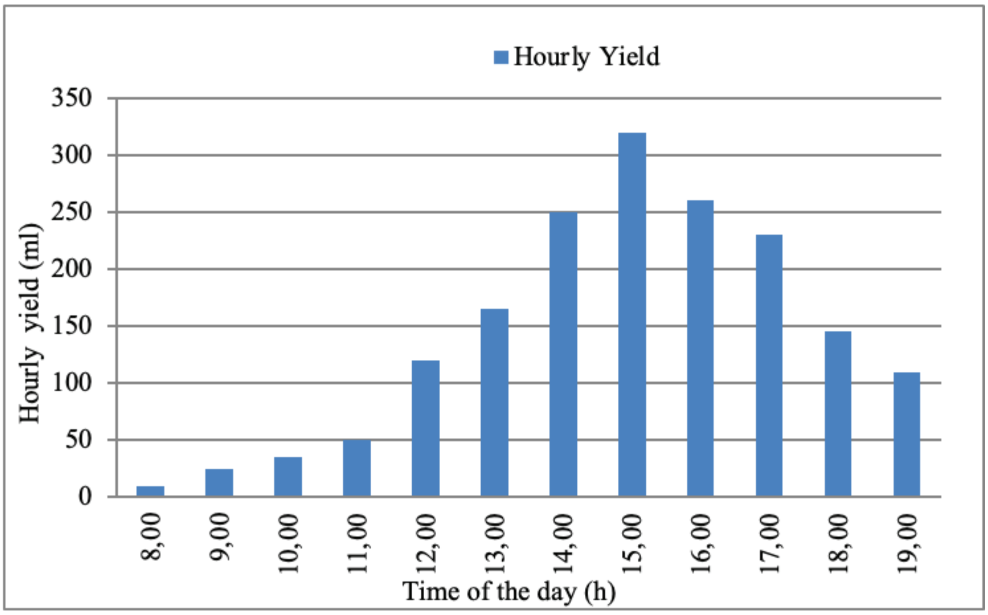

Figure 19. Relationship between hourly productivity with respect to time of the day.

it now stands at 1.32 kg/m^2. The productivity of a single basin solar system with no steps and a compound parabolic concentrator is still quite low, at 1.05 kg/m^2.

Table 3 shows the productivity and efficiency of solar stills which were determined using equations for various circumstances.

$$\text{Solar still efficiency}\,(\eta) = \frac{m\,x\,h_{fg}}{G\,x\,A}$$

where m is the total weight in kilograms of purified water collected during working hours. G is the overall radiation incident on the solar still in J/m^2 (assumed to be 20.58 MJ/m^2), h_{fg} is latent heat of evaporation in J/kg (assumed to be 2200 x 10^3 J/kg), A is the solar still projection area in m^2. Table 4 shows the comparison of productivity from the present work with the work performed by previous researchers.

Table 3. Daily solar still efficiency

Sr. no.	Case	Productivity (kg/m^2)	Efficiency (%)
1	Solar still with a single slope and a constant flow rate	1.05	11.22
2	Solar still with a single slope with a secondary stepped basin	1.32	14.00
3	Solar still with a single slope and a compound parabolic concentrator	1.47	15.7
4	Solar still with secondary stepped basin and compound parabolic concentrator on a single slope.	1.72	18.38

Table 4. Comparison of conventional solar stills with modified solar stills from previous researchers work

Sr. no.	Author	Work Done	Increase in Productivity in (%)
1.	Dawood M. et al.[22]	PCM with Evacuated tubes	34 %
2.	Dubey A. et al.[23]	Evacuated tubes	33.8%
3.	Mevada D. et al.[24]	Evacuated tubes with Condenser	73.45%
4.	Present Study	Evacuated tubes with Compound Parabolic Concentrator	63.8%

CONCLUSIONS

A basin solar still was built and tested. The research was conducted from morning 8:00 AM to 7:00 PM. The performance of a solar still is tested experimentally using a compound parabolic concentrator and a stepped basin. Case 1: A still with a single slope with constant flow rate has a productivity of 1.05kg/m^2 with efficiency of 11.22%, while Case 2: A still with a single slope with secondary stepped basin has a productivity of 1.32kg/m^2 and 14% efficiency of the system. Case 3: A still with a single slope with a compound parabolic concentrator produces 1.47kg/m^2 at 15.7% efficiency of the system. Case 4: A single slope solar still with a secondary stepped basin and a compound parabolic concentrator produces 1.72kg/m^2 with system efficiency of 18.38%. According to the data, using a compound parabolic concentrator with evacuated tubes and stepped basin, solar still delivers a maximum productivity of 1.72 kg/m^2 while increasing efficiency by 63.8% over the reference example.

NOMENCLATURE

φ	Half angle of V
h	Depth of V groove
r	Radius of tubular absorber
g	Displacement deviation of the receiver
c	Geometric concentration CPCs, dimensionless
η	Efficiency of solar still
m	Total weight of collected water
h_{fg}	Latent heat of evaporation in J/kg
G	Overall radiations J/m^2
A	Solar Still projection area in m^2

Subscripts

a	ambient
b	basin
gi	glass inner
go	glass outer
w	water
v	vapour

Abbreviations

ETC	Evacuated Tube Collector
PCM	Phase Change Material
CPC	Compound Parabolic Concentrator

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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