Journal of Solar Energy Research (JSER)

Journal homepage: www.jser.ut.ac.ir

Conventional Solar Still Augmented with Saltwater Bottles: An Experimental Study

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ARTICLE INFO

Article Type:

Research Article

Received:18.03.2024
Accepted:03.06.2024

Keywords:
Solar Still
Cost analysis
Desalination
Saltwater bottles
Conventional solar still

ABSTRACT

This article presents advancements in the working of Single slope conventional solar still (CSS) through the integration of saltwater bottles. The saltwater contained within these bottles (totalling 40 in number) is dyed black to enhance its solar radiation absorption ability. Using their high heat capacity, these bottles efficiently store solar energy during peak radiation hours, subsequently releasing it during the evening or nocturnal periods. Results have demonstrated a consistent increase in the temperature of water within the Modified solar still (MSS) compared to its typical counterpart, notably observed after 14:00 h. Moreover, the cumulative yield obtained from the MSS surpasses that of the CSS variant by 25.4%. Augmentation with saltwater bottles has increased the efficiency of MSS by 25% as compared to the CSS. Furthermore, incorporation of saltwater bottles results in a notable reduction in the cost of distillate production, with a decline of 20%, as compared to the CSS. The study emphasises how using saltwater bottles as thermal energy storage reservoirs in solar distillation systems could have real-world applications. The results offer important information on enhancing the effectiveness and economic viability of water purification, especially in areas where there are issues with water scarcity.

1. Introduction

Water, which is the fundamental basis of human life, is a vital component whose shortage jeopardizes existence on the mother Earth. Regrettably, this indispensable asset is depleting swiftly, driven by the rise in global population and unregulated industrial growth. Alarming figures from the World Water Council suggest that by 2025, the supply of drinkable water can decrease from 6600 to 4800 cubic meters [1]. It's important to highlight that there exist numerous techniques for

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Cite this article: Dumka, P., Pandey, N., & Mishra, D. (2024). Conventional Solar Still Augmented with Saltwater Bottles: An Experimental Study. Journal of Solar Energy Research, 9(1), 1811-1821. doi: 10.22059/jser.2024.374131.1392

DOI: 10.22059/jser.2024.374131.1392

water purification, including reverse osmosis [2] and film distillation [3]. However, these approaches often face a dilemma as they require significant financial investment and substantial energy consumption.

Currently, the importance of an old yet effective water purification tool, called the solar distiller unit can be utilized. This economical device, fuelled by abundant solar power, was first created by Carlos Wilson in 1872 [4]. The system he innovated later came to be recognized as the Conventional Solar Still (CSS) [5,6]. Nevertheless, the CSS does possess certain inherent drawbacks, such as its significant spatial requirements and limited output capacity [7–9]. Therefore, the scientific community has shifted its focus towards enhancing the efficiency of the CSS, exploring a variety of materials and devices [10–14]. Numerous researchers have proposed various enhancements to improve solar still performance.

Tiwari and Tiwari [15] have investigated the impact of water depth on the performance of CSS. Similarly Taghvaei et al. [16] have also examined the influence of water depth on CSS. Dwivedi and Tiwari [17] have used different thermal models to understand heat transfer coefficients in the CSS. Rahmani et al. [18] have performed experiments on the CSS augmented with natural circulation loop. A detailed review on the methods to cool the inclined glass cover has been reported by Omara et al. [19]. Shafii et al. [20] have reported a novel method to get more distillate output from CSS by using methods to get more condensation on the side walls of CSS.

Jamil and Akhtar's [21] have reported the influence of characteristic dimension (height of condensing cover from the water surface at the center of still) on the productivity and efficiency of CSS. Furthermore, Afrand and Karimpour [22] clarified the significance of climatic parameters in determining the distillate results of a CSS. An in-depth review and relative evaluation of thermochemical water splitting cycles has been presented by Safari and Dincer [23].

Sodha et al. [24] delved into the integration of CSS with the earth to harness ground energy. Dumka and Mishra conducted a thorough exergy and energy analysis to understand the thermodynamic aspects of solar earth stills [25,26]. Tiwari and Mishra [27] introduced the use of polythene to cover the surrounding ground area of earth CSS to improve its efficiency. Hidouri et al. [28] innovatively combined CSS with an air compressor, resulting in a notable increase in distillate production, and utilized Artificial Neural Network analysis for future performance prediction. Rabhi et al. [29] assessed the incorporation of fins within the CSS to enhance its overall performance, while Dumka et al. [30] integrated permanent ferrite ring magnets with the CSS to mitigate water surface tension and serve as sensible heat pockets. Kalidasa et al. conducted an extensive review of techniques to enhance CSS performance [31], whereas Rashidi et al. [32] evaluated the potential of rectangular porous media to boost CSS productivity. Mishra and Tiwari [33] proposed the utilization of metal chips and common coal within a solar still, and Deshmukh and Thombre [34] suggested using servo-therm medium oil as a thermal energy storage material in CSS. Dumka et al. [35] inspected the effect of salt concentration on CSS execution, finding that a concentration of 1% yields the maximum distillate output. Farzi et al. [36] concluded that the sand-containing treatment with an average grain size of 2.8 mm had better productivity and thermal efficiency than other grain sizes, indicating that optimal grain size distribution significantly affects the performance of simple solar stills. Thermo-eco-environmental Analysis of a Solar/wind Driven Multi-Generation unit with Hydrogen and Ammonia Production has been reported by Hashemian and Noorpoor [37].

Kabeel et al. [38] investigated a passive desalination system that integrates paraffin wax and parabolic-shaped concentrators. Similarly, Arunkumar et al. [39] examined the implementation of compound parabolic concentrators (CPC) stills utilizing foam impregnated with carbon and insulation (bubble-wrap), expanding their research to include a model based on computational fluid dynamics (CFD). Additionally, Kabeel et al. [40] explored the utilization of organic and inorganic phase-changing materials (PCM) to improve CSS functionality, while also assessing the economic feasibility of integrating these PCMs with the distiller unit. Bhargva et al. [41] concluded that the daily productivity of the modified solar still improved by about 19% compared to the standard still when bamboo cotton wick was spread over the rectangular fins in the still basin. Subramanian et al. [42] demonstrated that solar desalination, enhanced with Nano-enhanced Phase Change Materials (NEPCM) and nano-enhanced absorption techniques, significantly improves efficiency. Incorporating CuO and AlN nanoparticles into paraffin wax and using nano-coated copper pipes resulted in a 55.8% and 49.5% increase in water production, respectively. Additionally, the use of nanoparticles reduced the melting temperature and improved the cost performance of the solar still.

Toosi et al. [43] found that the use of PCM, hybrid NPCM, and a magnetic field in a stepped solar still markedly increases distillate yield and efficiency, boosting the production rate by up to 98% and offering a cost-effective method for solar desalination. Goshayeshi et al. [44] showed that adding paraffin with 0.5 mass% graphene oxide to a semicircular absorber significantly improves daily freshwater output in solar stills, indicating a route to more efficient desalination systems. Toosi et al. [45] revealed that incorporating an external condenser and PCM chambers into a stepped solar still significantly boosts distillate productivity, with a 104% increase over the basic design, highlighting the effectiveness of these enhancements. Basiri et al. [46] examined the air-side thermal performance of rectangular plate heat sinks under combined convection, identifying optimal design parameters and developing empirical equations for calculating the average Nusselt number, thus providing valuable insights for enhancing cooling techniques in electronics and industrial applications.

An experimental study on CSS was presented by Kabeel et al. [47], where they have mentioned the incorporation of sand and jute-knitted sandbags. Kumar et al. [48] explored the utility of honeycomb pads to augment the evaporation area via capillarity, with the goal of enhancing distillate output from the solar still. Additionally, Dumka et al. [49] documented the incorporation of plexiglass and jute in the CSS to enhance its performance, using heat localization and capillary rise in jute.

This article investigates the influence of saltwater bottles on CSS performance. These bottles will function as energy storage reservoirs within CSS by absorbing thermal energy during daylight and releasing it throughout the evening and night. This process helps sustain higher water temperatures during low or no radiation periods, leading to increased distillate yield and enhanced efficiency. The article discusses and reports several notable findings observed during the experiments.

The integration of saltwater bottles within the conventional solar still (CSS) was chosen due to its ability to significantly enhance solar energy absorption and retention. Saltwater has a high heat capacity, allowing it to store substantial thermal energy during peak sunlight hours. Dyeing the saltwater black further maximizes energy absorption. This method is cost-effective, easy to implement, and environmentally sustainable, making it an ideal solution for increasing the efficiency and practicality of solar stills.

There are numerous noteworthy advantages to incorporating saltwater bottles into a standard solar still (CSS). First off, it raises the distillate yield by by preserving higher water temperatures at night and in the evening. This improves thermal efficiency. Second, this technique makes distillate production less expensive, increasing its economic feasibility. Additionally, the alteration is easy to apply and cost-effective due to the utilisation of easily accessible and affordable materials like plastic bottles and saltwater. Lastly, this eco-friendly strategy makes better use of solar energy, supporting long-term water filtration solutions.

The novelty of this study lies in the innovative integration of saltwater bottles dyed black within a conventional solar still (CSS) to enhance its efficiency and performance. Unlike previous approaches that have focused on various materials and configurations, this research uniquely utilizes saltwater bottles as thermal energy storage reservoirs. Even in times when there is little to no sun radiation, these bottles retain higher water temperatures and increase distillate yield by absorbing solar energy during the day and releasing it at night.

Gaps in the Literature:

- Limited Use of Thermal Energy Storage: While many materials and improvements have been studied in the past, little is known about the application of thermal energy storage techniques, which can greatly increase the operational efficiency of solar stills during the hours when the sun isn't shining.
- Cost-Effective Solutions: A lot of the improvements that have been suggested in the literature call for sophisticated and costly setups or materials, which might not be able to be widely implemented in environments with limited resources.
- Comprehensive Performance Analysis: Extensive experimental research are required that not only boost yield but also thoroughly assess cost-effectiveness and overall efficiency gains.

Main Differences from Previous Work:

- Integration of Saltwater Bottles: This study presents saltwater bottles as an easy-to-use, affordable way to store and release thermal energy, improving performance during off-peak hours, in contrast to studies that concentrate on passive or mechanical improvements (such fins, magnets, or PCM).

- Enhanced Thermal Absorption and Retention: The bottles absorb solar light more effectively by colouring the saltwater black, an effect that hasn't been thoroughly studied in previous studies.
- Economic Feasibility: In addition to increasing distillate yield, this study shows a notable reduction in distillate production costs when compared to CSS, addressing the financial limitations that are frequently connected to solar still improvements.

2. Experimental setup

Two CSS, each with vertical wall lengths of 19.5 cm and 64.5 cm, were constructed using fiber-reinforced plastic (FRP) material, which is known for its lightweight and excellent thermal resistance properties. The interiors of the stills were brushed black to enhance solar radiation absorption. A Galvanized Iron (GI) tray, 0.74 mm thick, was utilized for the basin-water, having an area of 1 m^2 and a side wall height of 15 cm. This tray was also glazed black to improve solar radiation absorption. The lid is a 4 mm thick, clear transparent glass was placed on top, and side sealing was accomplished using putty. Fig. 1 depicts the schematic representation of the CSS.

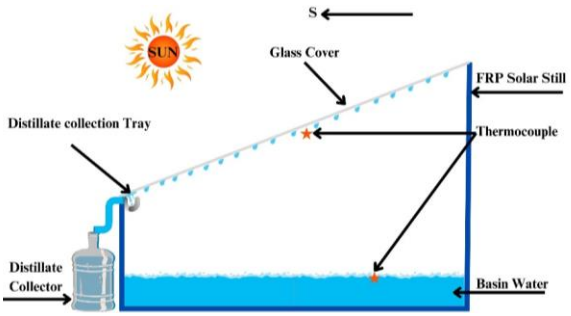
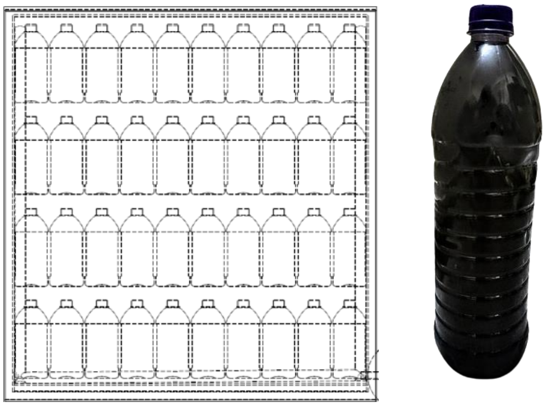


Figure 1. Graphic representation of CSS

In one of the CSS, forty LLDPE bottles filled with black dye salt water (30g of salt for every 100 g of water) were uniformly placed, as shown in Fig. 2(a). The photograph of one such bottle is shown in Fig. 2(b). The base diameter of each bottle is 10 cm and its height is 23 cm. This still in the article is called MSS (Modified solar still).



(a) Schematic of SWBs in MSS

(b) Photograph of SWB

Figure 2. Schematic arrangement of SWB in the still and the actual photo of SWB

The purpose of using saltwater in the bottles is to make thermal energy storage pockets in the still, as the thermal energy holding capacity of water increases as a result of the salt addition. Moreover, a small quantity of dye is also added to these bottles so that the colour of the saltwater becomes black, which will result in more absorption of solar radiation. In the daytime, these bottles will serve as sensible energy storage compartments that will hold the energy, and in the evening and late-night hours will release this stored energy. This will keep the temperature of the basin water higher even in the nocturnal hours. Fig. 3 shows the schematic arrangement of MSS.

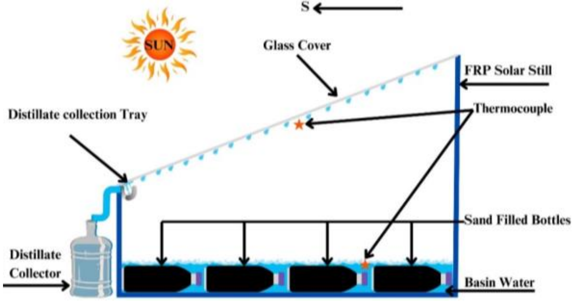


Figure 3. Schematic of MSS

Hourly measurements of the distillate were taken using a graduated cylinder, while solar radiation intensity was gauged using a solar-powered meter (TM-207). Temperature readings were obtained using K-type thermocouples. The experiments were performed in the April month of 2023 at JUET, Guna, India (24°26′07″N 77°09′39″E). In all experiments, the basin water remained at a constant weight of 40 kg. This choice was based on the previous trial experiments, which revealed that the

SWB are completely dipped in the water. Throughout this investigative research, a multitude of crucial measurements were conducted on an hourly basis, as detailed below:

- Temperature of basin water (in CSS), inner condensing cover (both CSS and MSS), SWB (in MSS), and surrounding atmosphere.
- Intensity of solar radiation.
- Distillate output

In the experimentation, several assumptions are made to simplify the analysis and ensure that the results are consistent and interpretable. Here are some common assumptions:

- It is assumed that the system has reached a steady state.
- The solar radiation is assumed to be uniform across the surface of the solar still.
- Heat losses due to conduction, convection, and radiation through the sides and bottom of the still are assumed to be negligible.
- The transparent cover of the solar still is assumed to have no absorption or reflection losses, meaning all incident solar radiation passes through it.
- The temperature of the water and the inner surfaces of the still is assumed to be uniform.
- The vapor produced is assumed to be pure water vapor, with no contaminants or other substances evaporating.
- All vapor that rises condenses on the cover and is collected as distilled water, with no losses.
- The water in the basin is assumed to remain in a single-phase liquid state, without any significant boiling.
- It is assumed that there are no chemical reactions occurring within the water or between the water and the materials of the still.

The first law efficiency for a solar still is specified as the extent of energy taken up by the vapours compared to the total energy received for the task of evaporation, mathematically it is represented as Eqn. 1.

$$\eta=\Sigma(m_{ew} \times L)/\Sigma(A_s \times I \times 3600) \qquad (1)$$

where, L is estimated on the basis of the Tsilingiris relation [50], which is evaluated at mean vapour temperature ($T_v = (T_w+T_{ci})/2$), m_{ew} is the hourly distillate in kg/h, I is the solar flux in W/m^2, and A_s is basin water area in m^2.

3. Uncertainty and Cost analysis

Uncertainty leads to the acknowledgment of a suspect concerning the result of a quantification, serving as an indicator of its precision. In the absence of an accompanying declaration of uncertainty, the outcome, viewed as a calculation of the true value, lacks fullness.

Table 1 provides comprehensive information on the operating ranges, accuracies, and standard uncertainties associated with the instruments used in the measurements. The standard uncertainty (u) of an instrument with an accuracy of 'a' is determined as: $u=a/\sqrt{3}$ [51,52].

Table 1. *a*, range, and *u* of the measuring devices

Instrument	Accuracy	Range	Standard Uncertainty
Graduated Cylinder (mL)	± 1	0–250	0.6
Thermocouple (°C)	± 0.1	-100–500	0.06
Solarimeter (W m^{-2})	± 10	0–1999	5.77

When a measured quantity (y) relies on input parameters (x_i), the uncertainty linked with the measured quantity is established by employing Eqn. (2) [48]:

$$u(y)=((\delta y/ \delta x_1)^2\times u^2(x_1)+ (\delta y/ \delta x_2)^2\times u^2(x_2)+\ldots)^{1/2} \qquad (2)$$

The uncertainties associated with the thermal efficacy of the solar distiller is computed utilizing Eqn. (3).

$$u(\eta)=((L/(IA_s))^2\times u^2(m_{ew})+ (1/(IA_s))^2\times u^2(I))^{1/2} \qquad (3)$$

It has been observed that the highest uncertainty associated with the thermal efficacy of the MSS is approximately 1.97%.

In the cost analysis, the first step is to evaluate the Capital Recovery and Sinking Fund Factors (*CRF* & *SFF*). These factors are calculated for a life expectancy (n) of the still set at 15 years and an interest rate (i) of 12%, using Eqn. (4) and Eqn. (5) shown below.

$$CRF = i(i+1)^n/((i+1)^n-1) \qquad (4)$$

$$SFF = i/((i+1)^n-1) \qquad (5)$$

By incorporating the values of *CRF* and *SFF* with the initial financing and recover value, one can determine *FAC* (First Annual Cost) and *ASV* (Annual Salvage Value) respectively. This process is achieved through Eqn. (6) and Eqn. (7), respectively [53].

$$FAC=CRF\times P \tag{6}$$

$$ASV=SFF\times S \tag{7}$$

Following up, to compute the total annual cost Eqn. (8) is used [54].

$$AC=FAC+AMC-ASV \tag{8}$$

The *AMC* (annual maintenance cost) is determined to be fifteen percent of *FAC*. Finally, the per litre cost of distillate is calculated as the ratio of the *AC* (annual cost) to the *AY* (annual yield) , as demonstrated in Eqn. (9) [55]:

$$CPL=AC/AY \tag{9}$$

Table 2 delineates the cost breakdown of components for both MSS and CSS, along with their respective salvage values. The evaluation is conducted based on the standard 15-year lifespan, which corresponds to the typical longevity of FRP solar stills. It's worth noting a slight disparity in the total costs between MSS and CSS due to the inclusion of SWB in MSS. The total cost of CSS sums up to Rs. 6600, while MSS is slightly more expensive, totalling Rs. 6640. All monetary values presented in the table are expressed in Indian Rupees (Rs.).

Table 2. CSS and MSS salvage value and the installation cost of (in Rs.)

	CSS	MSS	S
FRP	6000	6000	600
Glass	500	500	-
Putty	100	100	-
Bottles	-	40	-
Total Cost	6600	6640	

Table 3. Cost factors and CPL for stills

	CSS	MSS
CRF	0.147	0.147
SFF	0.027	0.027
FAC (Rs.)	970.2	676.08
ASV (Rs.)	16.2	16.2
AMC (Rs.)	145.53	146.412
AC (Rs.)	1099.53	1106.29
AY (L)	401.76	503.64
Total Cost (Rs./L)	**2.74**	**2.19**

Table 3 provides a detailed comparison between various factors and costs involved in computing CPL (cost per litre) for both the CSS and MSS.

4. Results and Discussion

Fig. 4 illustrates the change of *I* and ambient temperature (T_a) with time. At 8:00 h, the value of *I* was 166 W/m^2 which progressed to the highest magnitude of 990 W/m^2 by 13:00 h. At the peak radiation hour, the surrounding temperature was 39.5°C. Thereafter, the radiation gradually decreases, and by 18:00 h, their intensity diminishes to 30 W/m^2 with a surrounding temperature of 30°C.

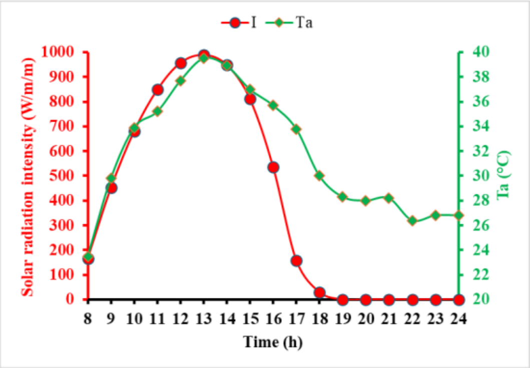


Figure 4. Change of solar *I* and T_a

The change of basin water temperature (T_w) in CSS and MSS along with the temperature of saltwater in the bottles (T_{swb})are presented in Fig. 5. From 9:00 to 12:00 h, T_w in CSS is a little higher than MSS. This is since the SWB in MSS must be absorbing sensible energy during this time. And by 12:00 h, their charging might have been on the verge of completion. Thereafter, MSS takes the lead and throughout the experiment T_w in MSS stays elevated than CSS, due to the gradual release of stored energy by SWB. The maximum deviation between T_w for MSS and CSS is of 13% which is attained at 19:00 h. This high value of T_w after 14:00 h in MSS can also be understood with the help of T_{swb} curve. T_{swb} is always higher than T_w in MSS until 24:00 h (midnight), this difference is causing a continuous transfer of the thermal energy from the bottles to the water in MSS.

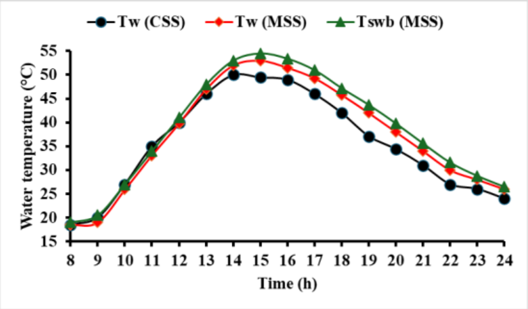


Figure 5. Change of water temperatures in MSS and CSS

Fig. 6 shows the change in inner glass temperature (T_{ci})for the stills as a function of time. Till 12 :00 h, T_{ci} for CSS is higher than MSS. This is due to the charging of bottles in MSS, which has resulted in lower T_w in MSS and lower evaporation rate. This low evaporation rate will result in low condensation rate of vapours on the glass, hence a low rate of latent heat release which leads to low value of T_{ci} in MSS. After 14:00 h, as T_{ci} in MSS increases the T_{ci} also increases and this is maintained till the conclusion of the experiment. This high value of T_{ci} in MSS after 14:00 h is representative of the high condensation rate on it. At 19:00 h, the difference of T_{ci} in MSS and CSS is maximum viz. MSS leads CSS by 11% at this time.

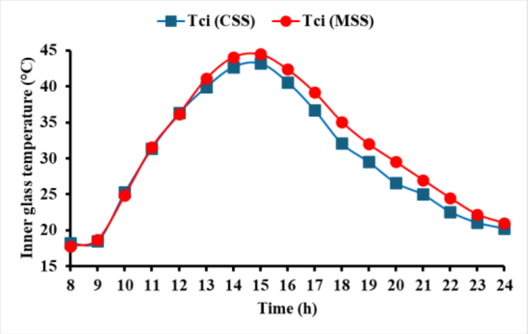


Figure 6. Change of T_{ci} in MSS and CSS

Fig. 7 shows the change in distillate output from CSS and MSS with time. As the T_w in CSS is more than CSS till 14:00 h, the yield from CSS is also high because till this time the SWB's are absorbing energy, resulting in smaller T_w in MSS compared to CSS. At the commencement of the experiment, MSS lags the CSS by 50%. The reduced yield from MSS persists until 13:00, during which MSS trails behind CSS by 3.3%. After 13:00 h, the yield from MSS is greater than from CSS until the completion of the experiment, owing to the release of sensible energy from SWB. The highest percentage rise in the yield from MSS is noted at 21:00 h, where MSS leads CSS by 100%. During the charging time of SWB's, CSS leads MSS by only 27%, whereas from 14:00 h until the completion of the experiment MSS leads CSS by 33%. Overall, the cumulative yield from MSS and CSS is 1399 ml and 1116 ml, respectively, indicating that MSS leads CSS by 25.4%.

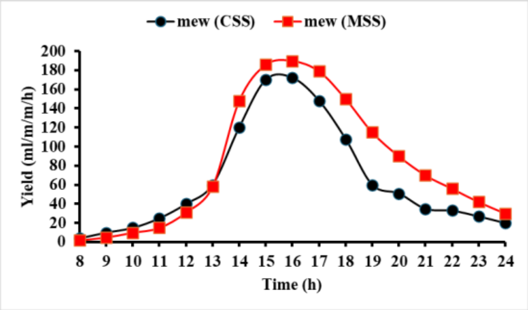


Figure 7. Hourly yield from CSS and MSS

The overall efficiency of MSS as obtained using Eqn. (1) is 25% higher than CSS (Ref. Fig. 8).

Fig. 8: Overall efficiency of CSS and MSS

The utilization of SWB in the MSS has led to a significant decrease of 20% in the cost of distillate output as compared to the CSS (Ref. Table 3). This implies that adopting the MSS might prove to be a feasible approach for enhancing both its distillate production and economic efficiency.

5. Conclusions

Based on the experimental work done in this article, the following inferences can be drawn:

- Most of the time during the experiment, the MSS consistently outperformed the CSS in terms of T_w and T_{ci}.
- CSS briefly surpassed MSS in T_{ci} due to lower evaporation rates caused by the charging of SWB in MSS until 12:00 h. MSS maintained higher T_{ci} values after 14:00 h, indicating sustained high condensation rates and enhanced performance.

- Distillate output analysis revealed MSS consistently yielding more distillate than CSS after 13:00 h, with the highest percentage lead observed at 21:00 h.
- Cumulatively, MSS produced 25.4% more distillate than CSS, highlighting its superior efficiency. The incorporation of SWB has increased the thermal efficiency of solar still by 25%.
- The use of SWB in MSS resulted in a notable 20% decrease in the cost of distillate output compared to CSS, demonstrating MSS's economic viability.

Therefore, adopting MSS offers a promising solution for improving distillate production and economic efficiency in solar distillation systems, particularly in regions facing water scarcity challenges.

While this study has provided valuable insights into the effectiveness of integrating saltwater bottles in conventional solar stills, several avenues for future research merit exploration. Firstly, further optimization of the saltwater bottle configuration, such as varying the number of bottles or their positioning within the solar still, could enhance overall system performance. Additionally, investigating the long-term durability and maintenance requirements of the modified solar still system would provide valuable information for practical implementation. Furthermore, conducting comparative studies with other solar distillation enhancements and exploring hybrid systems combining multiple technologies could offer new insights into improving water purification efficiency.

Lastly, extending this research to field trials in real-world conditions and assessing the socio-economic impacts of deploying modified solar still systems in water-scarce regions would be crucial for evaluating their practical feasibility and scalability.

Acknowledgments

Funding: The present work has received no funds in any manner from any organization.

Conflicts of interest: The authors declare that they are not involved in any organization or entity with any financial interest.

Nomenclature

CSS	Conventional solar still
MSS	Modified solar still
CPC	Compound parabolic concentrators
CFD	Computational fluid dynamics
PCM	Phase-changing materials
FRP	Fiber-reinforced plastic
GI	Galvanized iron
CRF	Capital recovery factors
SFF	Sinking fund factors
FAC	First annual cost
ASV	Annual salvage value
AMC	Annual maintenance cost
AC	Annual cost
AY	Annual yield
T_a	Ambient temperature
T_w	Change of basin water temperature
T_{swb}	Temperature of saltwater in the bottles
T_{ci}	Change of inner glass temperature
m_{ew}	Distillate output

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