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ORIGINAL RESEARCH ARTICLE

Impact of jute covered hemispherical cups on the performance augmentation of a single slope solar still: An experimental investigation

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ABSTRACT

In this article, an experimental endeavour has been reported to enhance the performance of single slope solar still by placing jute-covered hemispherical plastic cups in the water. The logic behind the augmentation is that the jute causes capillary action, due to which a thin film of water forms on the surface of the jute. The plastic cups will act as heat insulation, which will try to block the heat from going to the basin water, hence resulting in heat localization and quick evaporation of thin water film. It has been observed that this adaptation has increased overall distillate output of the single slope solar still by 36.2%. The modified still performs best till 14:00 h due to high solar insolation. In the afternoon hours, the reduction of solar radiation adversely impacts its performance in comparison to the conventional single slope solar still. The overall cost of the distillate due to the augmentation of the jute-covered hemispherical plastic cups has been reduced by 24.34% in comparison to the conventional solar still.

Keywords: single slope solar still, solar distillation, heat localization, hemispherical cups, jute cloth, energy efficiency

1. Introduction

Scarcity of water is the most important concern for the whole world, especially for economically backward countries. The scarcity is not because of the lack of water resources (as Earth is surrounded by 3/4th of water) but due to the lack of fresh, drinkable water. Therefore, substantive efforts have been made by researchers to continuously search for ways to convert brackish water into potable water [1–3]. Their primary aim is to search for sustainable, eco-friendly, and economical ways to perform the task of water purification.

The Conventional Single Slope Solar Still (CSSSS) is one device that meets all the standards mentioned above [4,5]. CSSSS utilizes solar energy to evaporate water. The vapor then condenses, leaving impurities behind, to get potable water, providing a simple and efficient method for obtaining drinkable water in areas with scarce clean water sources [6,7]. However, the device suffers from low efficiency and large area requirement for substantive distillate production [8–11].

Many researchers are working on ways to improve the distillate production of CSSSS. Their findings have suggested that the efficiency and productivity of CSSSS are very strongly influenced by three primary factors: the temperature difference between water and glass, the evaporating surface area of water, and its characteristic dimension [12–14].

Jamil and Akhtar's research [15] explores how key dimensions affect the daily operations of a solar still. Afrand and Karimpour [16] have highlighted how climatic factors impact the distillate production in a solar still. Sodha et al. [17] examined the use of ground energy by integrating solar stills with the earth, while Dumka and Mishra analysed the exergy and energy in solar earth stills [18,19]. Tiwari and Mishra [20] suggested covering the area around the solar still with polyethylene to improve its efficiency. Hidouri et al. [21] creatively connected a solar still to an air compressor, which significantly increased distillate production, and they used Artificial Neural Network analysis to predict future performance. Zheng et al. [22], studied the significant seasonal and diurnal impacts of solar PV arrays on local microclimate and soil thermal regimes in the Gobi ecosystem. The mean annual net radiation and wind speed under PV arrays decreased by 92.68% and 50.53% respectively, while the air temperature increased by 0.87°C, emphasizing the need for sustainable management practices in the deployment of solar parks to mitigate their ecological effects. Elaziz et al. [23] improved solar still productivity by up to 91% using a rotating spherical ball, optimized feed water temperature, and machine learning models, achieving up to 6200 mL/m²/day and a thermal efficiency of 62%, surpassing conventional designs.

Rabhi et al. [24] studied the effect of adding fins to a solar still to boost performance, while Dumka et al. [25] added permanent ferrite ring magnets to solar stills to reduce water surface tension and act as sensible heat pockets. Kalidasa et al. reviewed various techniques to improve solar still performance [26], while Rashidi et al. [27] explored using rectangular porous media to enhance solar still productivity. Mishra and Tiwari [28] suggested incorporating metal chips and common coal into solar stills, while Deshmukh and Thombre [29] proposed using servo-therm medium oil as a thermal energy storage material. Dumka et al. [30] examined how different salt concentrations affect solar still performance, concluding that a 1% salt concentration produces the maximum distillate output. Danışmaz and Alhurmuzi [31] have reported a detailed review on the ways to extract the pure water from atmospheric air with the help of solar still. Alhurmuzi et al. [32] demonstrated that generating potable water from atmospheric air using silica gel and solar energy is effective, even in low-humidity regions like Kirkuk.

Kabeel et al. [33] studied a passive desalination system that incorporates paraffin wax and parabolic-shaped concentrators. Likewise, Arunkumar et al. [34] researched compound parabolic concentrators (CPC) stills that use carbon-impregnated foam and insulation with bubble-wrap, further extending their work to a computational fluid dynamics (CFD) model. Several researchers have used advanced CFD to model different types and solar stills so that the complex physics can be captured accurately [35–37]. The effectiveness of phasechanging materials (PCM) to absorb the latent heat is a proven fact, now a days PCM is used in several engineering devices [38]. Thus, the researchers have also used this energy storing capacity of PCM to enhance the performance of solar stills. In a study, Kabeel et al. [39] investigated using organic and inorganic PCM to boost solar still efficiency and examined the cost-effectiveness of integrating these PCMs into the distillation unit. In a recent study Dumka et al. [40] have reported the use of stearic acid, as a PCM, inside metallic tubes. They have reported an increase of 12.8% higher cumulative yield in comparison to conventional solar still.

Kabeel et al. [41] conducted an experimental study on solar stills, where they explored the use of sand and jute-knitted sandbags. In a separate investigation, Kumar et al. [42] looked into how honeycomb pads could increase the evaporation area through capillarity, aiming to boost the distillate output from the solar still. Moreover, Dumka et al. [43] described adding plexiglass and jute to solar stills to improve their performance, leveraging heat localization and the capillary action in jute. Sudalaimuthu et al. [44] demonstrated that, using Fe_2O_3-impregnated jute cloth in solar desalination systems increases absorber temperatures by up to 4.9°C and enhances energy efficiency, achieving a maximum of 48.02% at a 0.29 kg/min mass flow rate. This innovative approach improves overall productivity and efficiency, making solar desalination more viable for large-scale applications.

Several researchers have reported the use of wick to increase the surface area and heat concentration [45–51]. Apart from this the use of Plexiglas and jute cloth to increase the heat concentration and thin film evaporation have been reported by Dumka et al. [52].

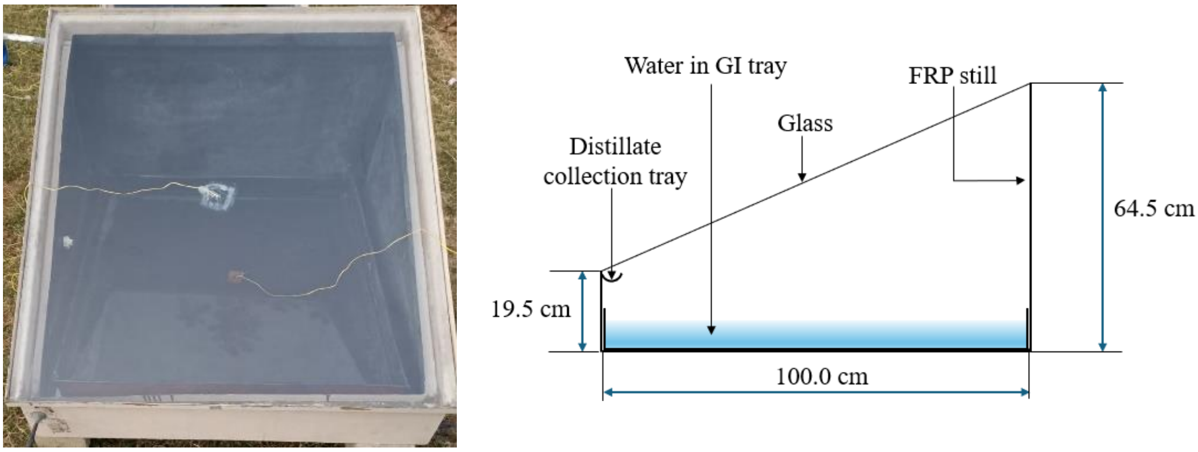
On similar grounds, Dumka et al. [53] have used plastic balls covered by jute to enhance surface evaporation and distillate yield. However, in that case, the curved surface is upward, which has led to more reflection and less absorption of solar insolation. The objective of this study is to reduce the reflection of balls by first cutting the balls into hemispherical cups and then covering them with jute cloth. The jute-enveloped hemispherical cups are placed in the basin water in such a way that the concave side faces upwards. This will not only reduce the reflection but will also increase heat concentration and thin film evaporation. Solar photovoltaics also considered as one of the most important options for increment in distillate output of solar still [64-65].

This study presents a considerable advancement in the field of solar stills by showing the effectiveness of integrating jute-covered hemispherical plastic cups (JCHPC) into the design of a single slope conventional solar still. The value of this research lies in its innovative approach to enhancing distillate output through capillary action and heat localization, resulting in a notable increase in overall distillate compared to conventional single slope solar stills. Additionally, the study provides a comprehensive analysis of results, showing that the modification in the solar still maintains higher temperatures and efficiency until peak radiation hours. Importantly, the research highlights a good amount of reduction in the cost of distillate output due to the augmentation, demonstrating both economic and operational benefits. Thus, the study contributes valuable insights into optimizing solar still design for improved performance and cost-efficiency. This work not only underscores the importance of heat localization and surface area in solar stills but also sets a model for future studies aiming to enhance solar distillation technologies.

2. Experimental Setup

Two 5 mm thick, Fibre-reinforced plastic (FRP) CSSSS were fabricated for the experimentation. The front (shorter) and back (longer) wall heights of the stills were 19.5 cm and 64.5 cm, respectively. From the inside, the solar stills are painted with matte-black paint to enhance the absorption of solar radiation. The stills were covered from the top with clear iron transparent glass with a thickness of 4 mm. Additionally; to hold the basin water, a black paint-coated Galvanized iron (GI) tray of 0.74 mm thickness was kept inside the still. Fig. 1(a) shows the photograph of CSSSS and its schematic diagram is shown in Fig. 1(b).

In one of the stills, which is called MSSSS (Modified Single Slope Solar Still), hollow, jute-covered hemispherical plastic cups (JCHPC) were placed in such a way that the concave part of the cups faces upwards. The photograph of one such JCHPC and the MSSSS are shown in Fig. 2(a) and 2(b), respectively.



(a) Photograph of CSSSS

(b) Schematic of CSSSS

Fig. 1: Photograph of CSSSS

(a) Photograph of JCHPC

(b) Photograph of MSSSS

Fig. 2: Hemispherical plastic cup and MSSSS

The jute used is of plain weave as it is one of the simplest and most common types of fabric weaves. The plain weave structure of jute fabric significantly enhances its capillary action capabilities. By creating numerous small and uniform capillaries, plain weave jute fabric effectively wicks water through adhesive and cohesive forces [54]. Thus, the use of JCHPC benefits the solar still in two ways. Firstly, it enhances the effective evaporative surface area through capillary action, resulting in a very thin water film on the jute surface. Secondly, the presence of jute resting on plastic facilitates heat localization. Consequently, faster evaporation occurs as solar radiation absorbed by the jute cannot transfer its energy to the water underneath the JCHPC, thus solely evaporating the thin water film over it. Each ball in the experimental setup measures 7.8 ± 0.1 cm in diameter, with a jute cloth thickness of 0.4 ± 0.1. These dimensions are selected to ensure sufficient capillary rise to keep the ball consistently soaked with water.

In May 2023, the experiments were performed at Mechanical Engineering department of JUET, Guna, India (24°26′07″N 77°09′39″E). The stills were supplied with 40 kg of water as a one-time feed, ensuring sufficient water in the basin even after wetting up the jute. Throughout the experimental endeavour, the measurements were recorded on an hourly basis. The distillate from the stills were collected and measured with the help of Borosil measuring flask. The solar insolation was measured with a solar power meter, TM-207. Temperature readings were captured using a k-type thermocouples. Temperature variables encompassed the temperatures of the condensing glass cover, water (of CSSSS and the top jute surface), and atmospheric temperature. The instantaneous (η_i) and overall efficiencies (η_o) of soar still are evaluated with the help of Eqn. 1 (a) and 1 (b) [2,55].

$$\eta_i = \frac{\dot{m}_{ew} L}{I(t)\, A_s} \tag{1 a}$$

$$\eta_o = \frac{\Sigma \dot{m}_{ew} L}{A_s \int I(t) dt} \tag{1 b}$$

where, L, $I(t)$, A_s, and $\dot{m}_{ew}$ are the latent heat of vaporization, solar radiation intensity, evaporation area, and instantaneous distillate output, respectively. The value of L is obtained with the help of expression given by Tsilingiris [56]: $(2503.943143 - 2.451556893 \times Tv) \times 10^3$. Where T_v is the mean of water (T_w) and inner condensing cover (T_{ci}) temperatures.

In addition to the aforementioned uses and benefits of the setup, there is a limitation: the accumulation of salt and other impurities on the jute over time necessitates regular cleaning (once every two weeks) to maintain the optimal performance of the MSSSS.

3. Uncertainty and Cost analysis

Uncertainty introduces doubt about the accuracy of a measurement and indicates its precision. If there's no accompanying statement about uncertainty, the result, seen as an estimate of the true value, is incomplete.

The standard uncertainty, u, for a measuring device with accuracy a and a uniform distribution of data is calculated as: $u = a/\sqrt{3}$. When uniform distribution is assumed, it is being stated that the error is equally likely to occur anywhere within a certain range. If the device has a defined accuracy, a, this indicates that the error can vary from $-a/2$ to $+a/2$. This formula calculates the standard deviation for a uniform distribution, reflecting the average level of uncertainty in the measurement based on the given accuracy. It gives an estimate of how much the measurements might deviate from the true value due to the device's precision limits [14,57–60]. Tab. 1 depicts the value of u for different instruments.

Tab. 1: The value of accuracy (a), measurement range, and standard uncertainty (u) for different instruments

	Thermocouple (°C)	**Solarimeter (W m^{-2})**	**Measuring cylinder (ml)**
a	± 0.1	± 10	± 1
Range	$-100 - 500$	$0 - 1999$	$0 - 250$
$\boldsymbol{u}$	0.06	5.77	0.6

When a measured quantity (y) relies on input parameters (x_i), the uncertainty linked with the measured quantity is established by employing Eqn. (2) [42]:

$$u(y) = \sqrt{\left(\frac{\partial y}{\partial x_1}\right)^2 \times u^2(x_1) + \left(\frac{\partial y}{\partial x_2}\right)^2 \times u^2(x_2) + \cdots} \tag{2}$$

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

$$u(\eta) = \sqrt{\left(\frac{L}{IA_s}\right)^2 \times u^2(\dot{m}_{ew}) + \left(\frac{1}{IA_s}\right)^2 \times u^2(I)} \tag{3}$$

It has been observed that the highest uncertainty associated with the thermal efficacy of the MSSSS is approximately 1.98%.

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 [2,61].

$$\mathrm{CRF} = \frac{\mathrm{i}(\mathrm{i}+1)^n}{(i+1)^n-1} \tag{4}$$

$$\mathrm{SFF} = \frac{\mathrm{i}}{(i+1)^n-1} \tag{5}$$

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 [62].

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

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

Following up, to compute the total annual cost Eqn. (8) is used [63].

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

The AMC (annual maintenance cost) is determined to be fifteen percent of FAC. Finally, the per liter cost of distillate is calculated as the ratio of the AC (annual cost) to the AY (annual yield) , as demonstrated in Eqn. (9) [53]:

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

Table 2 provides a detailed breakdown of the component costs for both the MSSSS and CSSSS, along with their respective salvage values. The analysis is based on a standard 15-year lifespan, which is typical for FRP solar stills. The total costs for MSSSS and CSSSS show a slight difference because the MSSSS includes JCHPC, resulting in a total cost of Rs. 6800 compared to Rs. 6600 for the CSSSS. All costs in the table are in Indian Rupees (Rs.).

Tab. 2: CSSSS and MSSSS salvage value and the installation cost of (in Rs.)

	CSSSS	**MSSSS**	**S**
FRP	6000	6000	600
Glass	500	500	-
Putty	100	100	-
Balls and Jute	-	200	-
Total Cost	6600	6800	

Tab. 3: Cost factors and CPL for stills

	CSSSS	**MSSSS**
CRF	0.147	0.147
SFF	0.027	0.027
FAC (Rs.)	970.2	999.6
ASV (Rs.)	16.2	16.2
AMC (Rs.)	145.53	149.94
AC (Rs.)	1099.53	1133.34
AY (L)	628.92	856.8
Total Cost (Rs./L)	**1.75**	**1.32**

Tab. 3 provides a detailed comparison between various factors and costs involved in computing CPL (cost per liter) for both the CSSSS and MSSSS.

4. Result and Discussion

Fig. 3 shows the variation of solar radiation intensity and ambient temperature (T_a) as a funciton of time. At the start of the experiment, the intensity of solar radiation recored was 500 W m^{-2} at an ambient temperature of 27.2°C. It increases at a steady pace and by 13:00 h attains a peak vlaue of 990 W m^{-2} at an ambient temperature of 39.1°C. Thereafter, it reduceces to zero value by 19:00 h. The average value of T_a recorded throughout the experiment was close to 32.15°C.

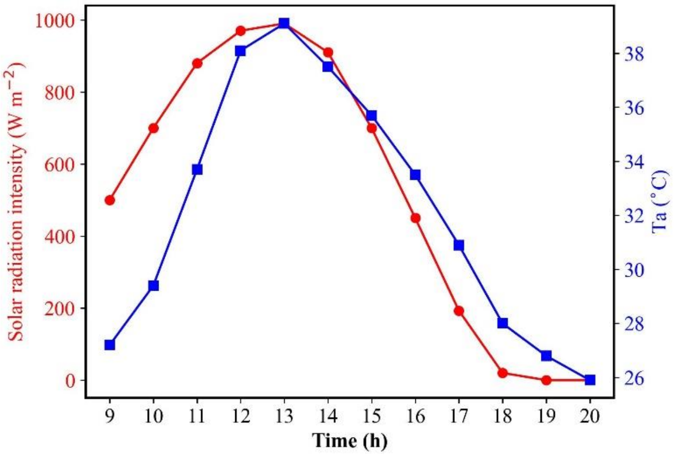


Fig. 3: Variation of Solar radiation intensity and ambient temperature

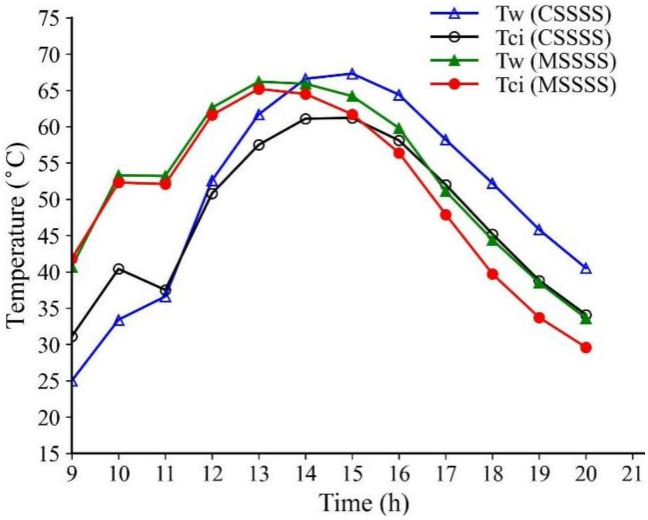


Fig. 4: Variation of water and inner glass temperatures in CSSSS and MSSSS

The variation of different temperatures with respect to the time is shown in **Fig. 4**. It is very much eminent from the plot that the temperature of water (T_w) on the surface of JCHPC is higher than that of water temperature in CSSSS until about 14:00 h after which the CSSSS takes it lead and maintains it until the end of the experiment. This is due to heat localization on the surface of JCHPC where the combination of jute and plastic is not allowing the heat to percolate it. Whereas in the CSSSS due to large heat capacity of water it is storing the thermal energy which it attains it peak at 14:00 h. Thereafter, as the thermal radiation falls, the T_w in MSSSS reduces. Whereas CSSSS utilizes its store energy to keep it temperature high for the remaining time. At 9:00 h, Tw in MSSSS is 62.8% higher, which reduces to 7.3% high at the peak radiation hour in comparison to CSSSS. Thereafter, CSSSS leads MSSSS by 1% at 14:00 h, and this difference increases to 20.5% by the end of experiment. The inner glass temperature (T_{ci}) in MSSSS leads that of CSSSS till 15:00, which is clear indication of high release of latent heat of condensation in MSSSS until this as compared to CSSSS. After this, CSSSS takes it lead and maintains it till the end of experiment.

The result of this high-water temperature in MSSSS is clearly seen in its distillate output as shown in **Fig. 5**. One can observe that till 15:00 h, the distillate obtained from MSSSS is higher than CSSSS. This is due to good capillary action in the jute cloth and high heat localization on its surface. Till this time, MSSSS gives a remarkable 86.1% higher distillate as compared to CSSSS. After 15:00 h, as the CSSSS has stored substantive amount of energy owing to its high heat capacity, it starts releasing and maintaining its water temperature high. Whereas in CSSSS, due to reduced solar radiations, the heat localization reduces, resulting in lower evaporation rate and ultimately a lower condensation rate. From 16:00 h until the end of experiment, CSSSS yielded 20.4% higher than MSSSS. Overall, MSSSS produced 36.2% higher distillate than CSSSS.

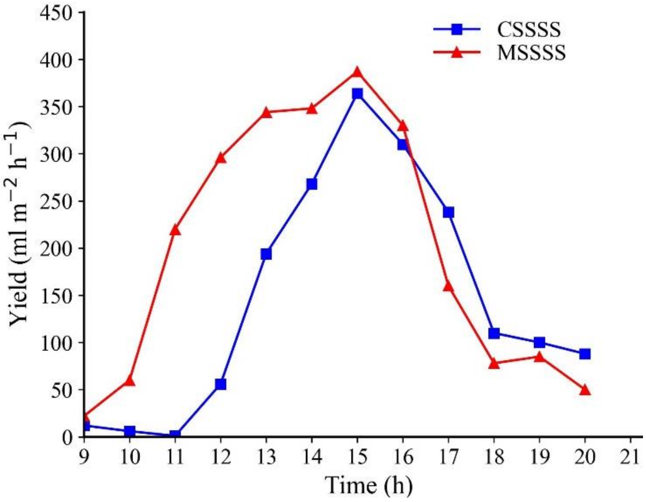


Fig. 5: Variation of distillate yield in CSSSS and MSSSS

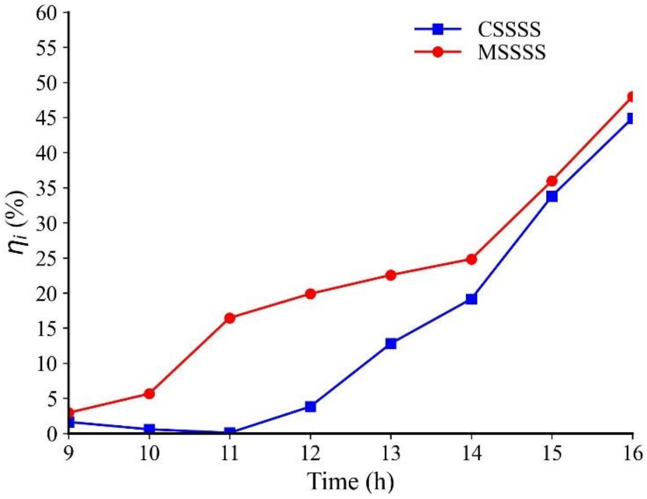


Fig. 6: Variation of instantaneous efficiency of CSSSS and MSSSS

This high distillate output from CSSSS can also be seen in the instantaneous efficiency plot, as shown in **Fig. 6.** The instantaneous efficiency of MSSSS is very higher than CSSSS until 15:00 h, after which this difference reduces due to the reduction in the solar radiation intensity on one hand and high heat capacity of water in CSSSS. The data till 16:00 h is shown in figure, as after this time, the solar radiations sharply reduces to zero, which may lead to wrong conclusion. Due to augmentation of JCHPC, the overall efficiency of MSSSS has increased by 31.7% compared to CSSSS.

The utilization of JCHPC in the MSSSS has led to a significant decrease of 24.34% in the cost of distillate output as compared to the CSSSS (Ref. Tab. 3). This implies that adopting the MSSSS might prove to be a feasible approach for enhancing both its distillate production and economic efficiency.

5. Conclusions

Based on the experimental study following conclusions can be drawn:

- Solar radiation intensity and ambient temperature varied throughout the experiment, peaking at 990 W m^{-2} and 39.1°C, respectively, at 13:00 h, with an average ambient temperature of approximately 32.15°C.
- Initially, the temperature of water on the JCHPC surface exceeded that of CSSSS until about 14:00 h, attributed to heat localization, but CSSSS later surpassed JCHPC in maintaining higher water temperatures.
- Distillate output from CSSSS was substantively lower than MSSSS until 15:00 h, due to effective capillary action and heat localization in MSSSS. The cumulative yield produced from MSSSS is 36.2% more than that of CSSSS.
- The overall instantaneous efficiency of MSSSS is observed to be 31.7% higher than that of CSSSS.
- The cost of distillate output from MSSSS has reduced by 24.34% as compared to CSSSS due the presence of JCHPC.

The study emphasizes the importance of heat localization and surface area in solar still design and optimization. Therefore, the daytime performance of CSSSS can be increased substantively by augmenting it with JCHPC in the peak radiation hours.

Conflict of interest

The authors declare that they have no conflict of interest.

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