A COMPARATIVE STUDY FOR ENHANCING SOLAR STILL PERFORMANCE AND EFFICIENCY THROUGH PCM-INTEGRATED FIN DESIGN

by

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This study introduces a novel solar still design that stores energy in a PCM with the use of fins. Three distinct types of stills were considered for this study of the fin and energy storage unit. Type I stills were conventional type, whereas Type II stills added round hollow fins above the basin liner. As with Type II, Type III used fins in addition a PCM-packed energy storage unit located below the basin liner. Over the basin liner, fins were added to the absorber to increase its surface area. Experiments were conducted using all three types, with the water level in the basin maintained at 3 cm throughout. It was calculated that conventional solar still may produce up to 3.25 L per m² per day. In contrast, Type II and Type III show increases in production of 17.54% and 48.61%, and 55.69%, respectively. In addition, modified solar still is proven to have a shorter pay-back period than conventional solar still.

Key words: *nocturnal productivity, exergy efficiency, thermal energy storage, solar still, PCM*

Introduction

Maintaining a healthy body requires drinking the necessary amount of water daily. The drinking water dilemma in emerging countries like India is mostly the result of rapid population growth and industrialization. Rapid depletion of freshwater resources like rivers, lakes, ponds, and underground-water belts occurred because of global warming and erratic climate change. These water sources are unusable because of the home and industrial garbage that is dumped into them. Therefore, it is important to find a more cost-effective and efficient method of purifying this brackish water for human consumption. It is possible to remove the salt and other impurities from brackish water and saltwater by a variety of processes, including membrane distillation, flash distillation, multi-effect distillation, capacitive deionization, reverse osmosis, vapor compression, ion exchange, and electrodialysis.

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Adding copper hollow fins and a PCM reservoir to a tubular solar still increased productivity by up to 90.1%, allowing for water production continue well after sundown [1]. The circular fins generated 1.4917 kg/m per day more distilled water than the square fins in an experimental comparison of hollow fin double slope solar stills [2]. Energy-efficient single slope solar still (SSSS) designs, such as circular hollow fins and sponge, have been shown to increase efficiency by as much as 79.98% [3]. When compared to conventional solar still (CSS), the economic viability and yield of SSSS that has been improved with a hollow finned absorber basin and PCM are far superior [4]. When compared to systems with a solid or hollow bottom-finned absorber basin, freshwater production by SSSS can be boosted by 41.67% and 20.81%, respectively [5]. Modified SSSS with block-shaped and slender fins, secondary condenser, and PCM chamber exhibits enhanced productivity during both day and night [6].

A pyramid solar still with hollow circular copper fins and a PCM can increase production by as much as 101.5% per day when compared to previous studies [7]. Using hollow cylindrical pin fins to boost PCM storage in a solar still increases overall freshwater yield by as much as 17% compared to conventional and 7% compared to PCM-based systems [8]. Basin-type solar stills benefit from active solar distillation, which doubles their daily distillate output compared to passive systems and shows promise for increased efficiency in colder regions [9]. Tilt angle optimization of solar still condenser surface significantly affects distilled water productivity, demonstrating up to twice the output of conventional designs in cold hilly conditions [10]. This innovative solar still design utilizes fins and PCM-based energy storage, which offers numerous advantages over more conventional methods [11].

A solar still constructed from a glass basin with hollow glass fins and energy-storing components demonstrates increases in heat transfer and total distillate yield of up to 3.61 kg per day [12]. The solar still model with the PCM composite under the basin liner outperforms the other two versions [13]. Study compares effects of water depth, single and double slopes, and charcoal energy storage on solar still performance, emphasizing potential for decentralized local water production using renewable energy [14]. Exploration of the shape, pressure, and volume changes that occur during the inflating and deflating of inflatable airbags used for underwater compressed air energy storage in maritime energy systems [15]. Desalination and regeneration of weak liquid desiccant are made possible by hybrid solar still utilizing waste granite thermal energy storage and forced convection, demonstrating the potential application oftechnology in liquid desiccant-based solar cooling systems [16].

The importance of forced condensation, thermal storage material, and forced evaporation on the performance of square pyramid solar still was investigated. The results indicate that forced evaporation coupled with thermal storage at a water depth of 30 mm may provide the optimum production, efficiency, and cost-effectiveness [17]. Enhances CSS performance by adding square pipes as fins and paraffin wax as energy storage media achieves significant efficiency improvements compared to conventional stills for various water depths [18].

Reviews parameters affecting pyramid solar still performance, including meteorological, design, and operating factors. Highlights improvements in productivity with PCM, v-corrugated absorber plates, reflectors, mirrors, and nanoparticles address low productivity in single-slope solar stills by adding thermal storage material [19]. Modi and Nagi [20] demonstrated higher yield and efficiency with thermal storage, particularly at a water depth of 30 mm. Demosthene project that aims to repurpose abandoned mines for thermal energy storage anddiscussed the site selection, thermomechanical and hydrothermal modelling, and the installation of an experimental underground thermal energy storage basin [21]. An investigation was conducted on pyramidal triangular solar stills have their energy storage media.

Construction of the basin involved the use of mild steel, quartz rock, and sieved red bricks. Fresh water flow can be increased by 30% using thermal energy storage within the basin [22]. Factors such as the thermocline's depth, the cumulative charge, and the half figure of merit uses sensor data and GraphPad Prism to analyze it, proving it can properly evaluate tank performance [23].

An experimental solar still was constructed from a flat plate collector, a parabolic trough collector, and a layer of packaged glass balls for thermal storage. The integration significantly enhances freshwater production rate and efficiency compared to CSS [24]. Different heat-absorbing materials like cotton cloths, jute, and rubber mats as bed materials for solar stills were compared and found that jute and rubber mats provide higher yield. The impact of insulation and incline on productivity are also analysed [25].

The necessity for waterfront improvement has not even been taken into account by the current works. This condition inspired the current study, which makes use of a finned latent heat energy storage device to boost solar still efficiency. While previous research shows that fins were used at both the PCM and basin watersides, this new work contradicts that finding. The volume of PCM lost to fins in the storage unit can be made up by the increased space provided by hollow fins above the basin liner. In addition, the round hollow fins used in the current work offer a novel approach to solar still energy storage.

The goal of this study is to determine the effect of fins on solar still performance by comparing the efficiencies of a CSS, a CSS with fins on the water side, a CSS with fins on the water side and a PCM unit without fins, and a CSS with fins on both the water and PCM sides. The context for this comparative analysis is.
- Total distillate output, evaluation of hourly productivity, and nocturnal productivity.
- Hourly evaluation and overall energy efficiency.
- Analysis of exergy efficiency based on the Second law.
- Cost benefit analysis for determining distillate prices and pay-back times.

Materials and methods

Overview of methodology

At first, a single slope CSS was built (without fins or PCM unit) and tested to see if the proposed design of circular hollow fins at the water and PCM sides would increase performance. To determine the ideal water depth for best productivity, the CSS was initially tested in a variety of water depths. Subsequently, more trials were conducted in the ideal water depth for the experiments. To facilitate further experimental trails and comparison analysis, the CSS was changed by incorporating circular hollow fins and a PCM unit, resulting in three modified solar stills (MSS).

The CSS having fins over baseliner (CSSF).

The CSSF coupled with PCM unit (CSSP).

The proposed design of circular hollow fins at the water and PCM sides was tested by first fabricating a single slope CSS (without fins and PCM unit) and running experiments. The CSS was first put through a series of tests at several water depths to determine the sweet spot for maximum productivity. After determining the optimal water depth, further experimental experiments were conducted. Three MSS were created by incorporating round hollow fins and a PCM unit into the CSS, allowing for additional experimental trails and comparative analysis.

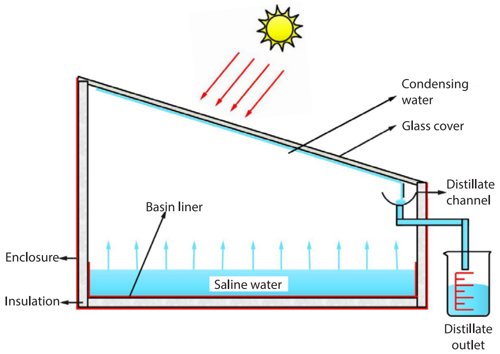

Figure 1. Schematic view of CSS

Experimental set-up

The four main parts of a condensate collection system are the basin, the glass cover, the insulation, and the condensate collecting channel, fig. 1. The base of basin and walls are insulated, and a slanted pane of glass covers the top. The Sun warms the salt water in the basin as it penetrates the transparent cover. This promotes evaporation, which leads to the formation of clouds above the salty sea. Vapor immediately condenses because its saturation temperature is lower than the inner surface temperature of the glass.

In this research, galvanised iron sheet of thickness 1.06 mm was used to create the CSS. To maximise absorption, matte black paint was used to the 0.5 m^2 surface area of the basin absorber. The glazing is made out of 4 mm thick tempered glass, which provides both robustness and transparency. Cuddalore, Tamilnadu, India was chosen as the testing site, and the face were slanted southward at an inclination of 12° . The heat loss in still was reduced in half by using 50 mm of thermocol to insulate the floor and walls. A chlorinated polyvinyl chloride pipe of length 1.1 m and diameter 0.0254 m was inserted inside the solar still at an inclination of 3° to collect the distillate output and convey it to the collecting jar.

The CSSF was achieved by integrating 32 mild steel (thermal conductivity 50 W/mK) circular hollow pipes as fins into CSS above the basin liner. Even though copper and aluminum are better options in terms of thermal conductivity. In order to keep the still's output from dropping due to the fins casting shadows over the basin's surface, their height was kept at 50 mm. Schematic view of the basin's round fins and arrangement details are presented in fig. 2.

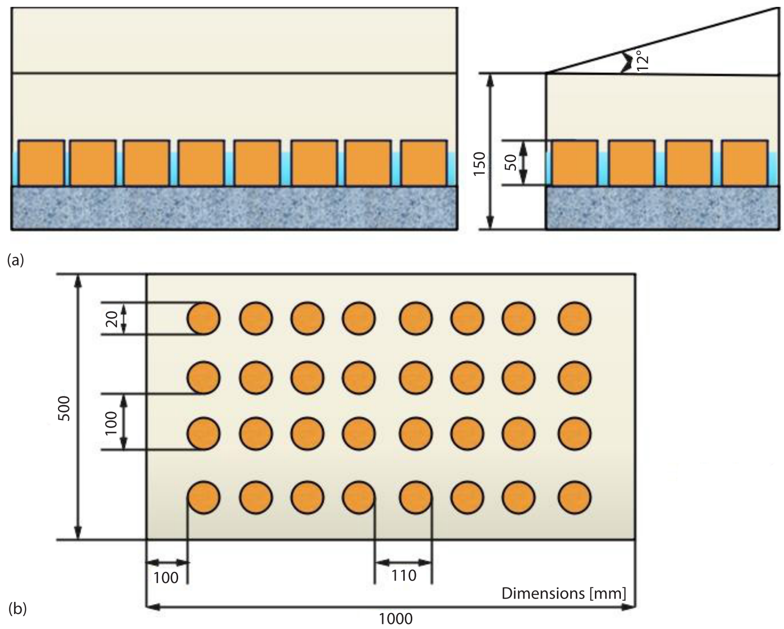

Figure 2. Fins on the basin liner; (a) photographic view and (b) arrangements of fins

An energy storage chamber was fastened below the basin liner to create a CSSP. Paraffin wax (6 kg) was used as a thermal storage medium that absorb the additional solar radiation collected during the day and release at night. Because of its low cost and wide availability, paraffin wax was used. In addition, a solar still can function at temperatures between 54 °C and 56 °C, which is where paraffin wax melts, fig. 3.

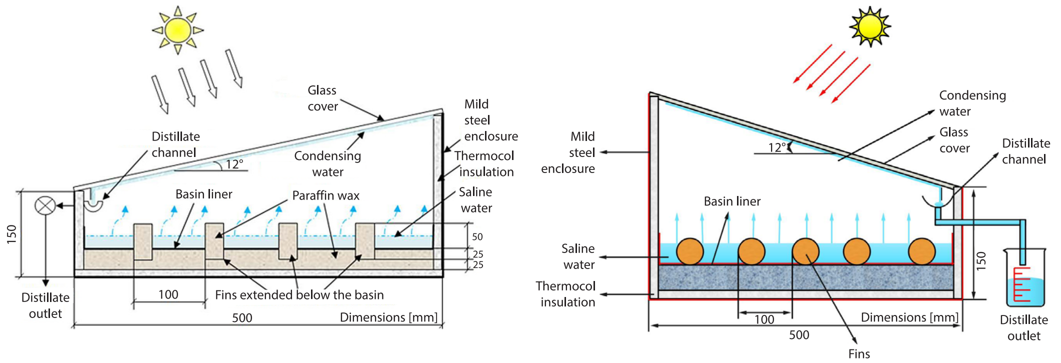

Figure 3. Schematic of the solar still with extended fins and energy storage

Experimental procedure

The experiment was conducted in Cuddalore, Tamilnadu, India (11.74°N, 79.77°E) over the winter on all the solar stills. The CSS was tested with 1 cm, 3 cm, and 5 cm of water in the basin to identify the ideal water depth for the CSSF and CSSP experiments. The ideal depth of water was used in subsequent tests:

– The temperatures of the basin water, the basin liner, the glass surfaces of the solar still chamber, the ambient air, and the energy storage material were all recorded using *K*-type thermocouples throughout each experiment.
– The temperature data from the numerous thermocouples were shown on a 12-point temperature indicator.

For this study, a solarimeter with a resolution of 1 W/m^2 and a dynamic range of 0-2500 W/m^2 was used to gauge the intensity of incident solar radiation. All thermocouples, the solarimeter, and the amount of distillate produced were measured and recorded every trial day from 9 a. m. to 9 p. m.

Experimental error analysis

In this endeavour, it is crucial to establish the extent to which various physical measurements of different metrics are inaccurate. Table 1 displays the accuracy, range, least value measured, and error percentage for each measuring device used in this study. The percentage errors of various measurement tools can be calculated using:

$$\text{Error} = \frac{\text{Accuracy of the instrument}}{\text{Minimum value of the output measured}} \times 100\% \tag{1}$$

Table 1. Range, accuracy, and % error of the measuring devices

S. number	Device	Range	Accuracy	Least value measured	Error [%]
1	Temperature indicator [°C]	0-280	+1	26	3.62
2	Thermocouple [°C]	0-120	±0.1	30	0.632%
3	Collecting jar [mL]	0-1000	–	120	11%
4	Solarimeter [Wm^{-2}]	0-2500 W	±1	32	3.4%

Efficiency of the solar still

Based on the measured variables of hourly productivity, m_w, and intensity of solar insolation received over the glazing, I_s, for the stated hour, the hourly energy efficiency of solar still was calculated:

$$\eta_i = \frac{m_w \times L_w}{A \times I_s} \tag{2}$$

where m_w [kgm^{-2}] is the hourly productivity, L_w [Jkg^{-1}] – the water's latent heat of vaporisation, expressed, A – [m^2] the basin absorber area of the still, and I_s [Wm^{-2}] – the solar intensity insolation received over the glazing.

The productivity per day can be calculated with the use of a comparable expression:

$$\eta_d = \frac{\sum m_w \times L_w}{A \times \sum I_s} \tag{3}$$

Results and discussion

Research shows that improving the passive solar still's efficiency by including fins and a series considerably increases its use. The purpose of this research was to determine how well PCM energy storage could improve the finned solar still's storage efficiency. Various configurations of solar stills, including those with circular hollow fins (CSSF), fins placed above the surface of the basin, and energy storage, were put to the test experimentally to observe which would be most effective.

Effect of water depth on productivity

The CSS was first tested in 1 cm, 3 cm, and 5 cm of water to determine the optimal depth for the remainder of the study. The differences in hourly output between solar stills operating at various water depths are compared in fig. 4. It has been noticed that shallower water depths have been more productive than deeper ones. The morning session of a solar still operated with 1 cm water depth can give a higher output than the afternoon session when the water level drops to 5 cm. In contrast, after noon, solar still with 3 cm water steadily degraded. Therefore, the optimal water depth for the SS with fins and energy storage was determined to be 3 cm of basin water depth.

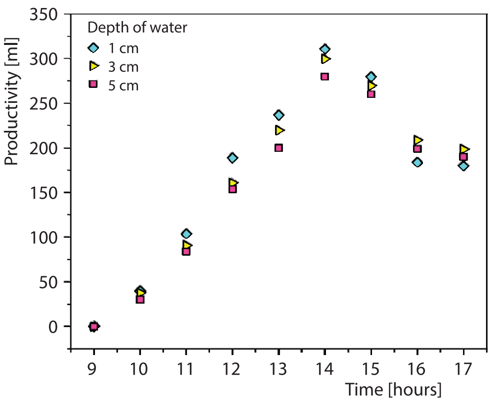

Figure 4. Comparison of hourly productivity of CSS various water depths

Hourly variation of water-glass temperature difference with respect to solar radiation

Evaporation from the brackish water in the basin occurs at a rate proportional to the temperature variance between the water and the inner surface of the glass cover. Figure 5 shows the fluctuating temperature gap between the glass cover and the water in the basin. Solar energy that would have been used to heat the basin water instead of stored in PCM. The CSS temperature rises sharply until 13.00 hours, when the intensity of incoming solar energy begins to diminish, and then falls dramatically. In addition, the PCM latent heat retrieval caused the enhanced solar stills to display more extreme temperature swings. When there is not enough sunlight, the latent heat from PCM keeps the water in the basin at a normal temperature. Until 17.00 hours, the temperature difference between CSSP and SSP is comparable, however after 17.00 hours, the SSP temperature difference is greater than the CSSP temperature difference. The presence of fins in the PCM unit was most noticeable at night.

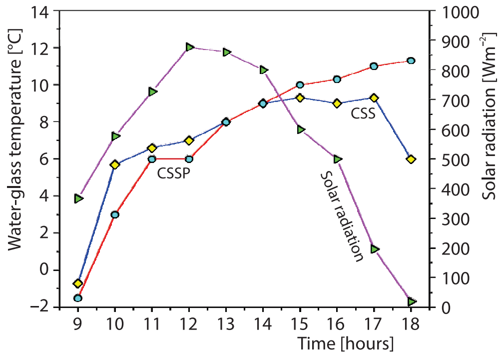

Figure 5. Comparison of temperature differences between glass inner surface and basin water of CSS, and CSSP

Hourly productivity and cumulative distillate output

Hourly productivity differences between CSS, CSSF, and CSSP were compared in fig. 6(a). Increased energy capture due to fins above the basin liner allows CSSF to achieve significantly higher productivity than CSS. When the sun goes downproductivity drops in both CSS and CSSF. While retrieving thermal energy from the energy storage material, stills with storage systems have demonstrated increased nighttime production. This is because PCM fins accelerate the melting and hardening processes of the materials. Therefore, the CSSP keeps the heat exchange rate between the basin water and PCM relatively constant throughout the day.

The cumulative benefit of using fins in both the baseliner and the storage unit was evident in the yield. Figure 6 shows the hourly variation in cumulative yield for all four scenarios. The cumulative yield of all modified cases has been higher than that of CSS throughout the day. After 18.00 phours, *i.e.*, once solar insolation has ceased, the production of CSS is effectively zero. As can be observed in tab. 2, the daily yield of changed stills is more than that of CSS. This suggests that CSS might not be as appealing without some sort of enhancing strategy.

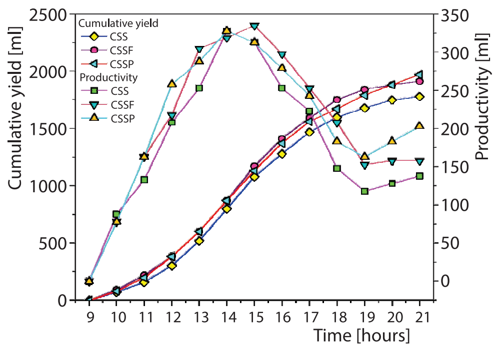

Figure 6. Comparision of cumulative output of CSS, CSSF, and CSSP and hourly productivity of CSS, CSSF, and CSSP

Table 2. Enhancement in daily yield due to the modifications made on CSS

S. number	Still type	Daily yield	Increase in daily output [%]		
1	CSS	1670 ml per day	–	–	–
2	CSSF	1990 ml per day	19.1	–	–
3	CSSP	2530 ml per day	51.4	27.1	–

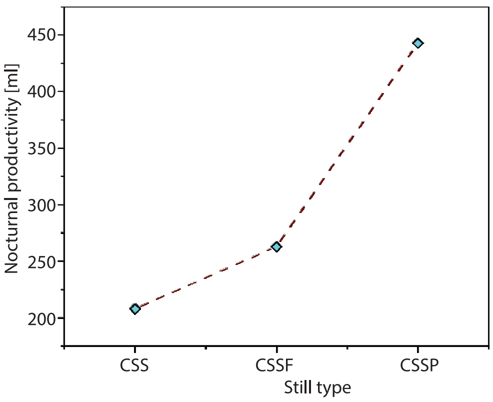

Figure 7. Comparison of nocturnal productivity of CSS with CSSF, and CSSP

When compared to CSS, CSSF appears to perform better, it exhibits the same nighttime behaviour as CSS and is unable to produce any yield at all. Stills equipped with storage unitsretrieve extra heat energy from the PCM and keep producing even when the sun is not shining. Figure 7 shows the nighttime output of all four instances. As can be seen, CSSF yields a marginal improvement in nighttime output over CSS. The CSSP produced about 2.5 times as productive at night as CSS. After sunset, PCM was the sole source of energy for distillate production. Due to their low thermal conductivity, PCM have a slow energy discharge rate. The quantity of distillate generated was directly related to the quantity of energy absorbed by the basin water.

Energy efficiency

Figure 8 compares the hourly energy efficiency of CSS and CSSP. The CSS has relatively high hourly efficiency during the morning session compared to other modified stills. All of the solar energy was not used to heat the basin water because PCM in stills with storage units absorbs a significant amount of the incident solar energy. Even in the afternoon, CSS is marginally more productive than other solar stills. Hourly efficiency of CSS begins to drop after 15.00 hours. When compared to other types of stills, CSS appears to be the best option. However, the overall efficiency results show the impact of the changes, fig. 9. Adding PCM below the finned basin liner boosts overall efficiency by 46%, while adding fins alone boosts efficiency by roughly 32%. The overall efficiency might be raised by 56% if fins were added to the PCM unit. In spite of a drop in efficiency during daylight hours, MSS units were more productive because of its increased output at night.

Behavior of phase change materials in energy storage unit

The importance of the energy storage unit in increasing both total distillate output and efficiency has been established in the preceding sections. However, as previously indicated, the energy storage unit helps to distillate production when the solar energy was not present. The phase change behaviour of PCM was studied by recording its temperature every hour during the experiment, and the findings are shown in fig. 10. As can be shown in fig. 10, whether the PCM storage unit has fins or not, the temperature of the PCM wasrising until 14.00 hours. This means the PCM keeps soaking up the solar rays till 14.00 hours. In contrast, the CSSP varies noticeably with the changing PCM temperatures throughout time. It has been noticed that the average PCM temperature in CSSP was lower than that in CSSF. The CSSP used a PCM to store sensible heat for nearly four hours, while fins only allow three hours of storage time. The

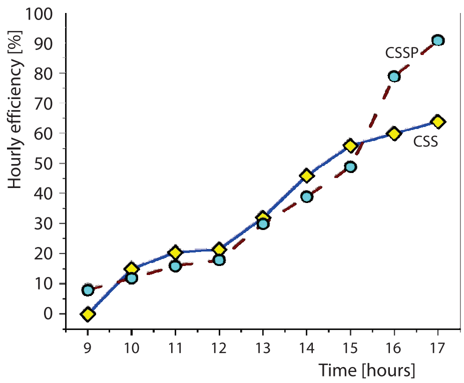

Figure 8. Comparison of hourly efficiency of CSS and CSSP

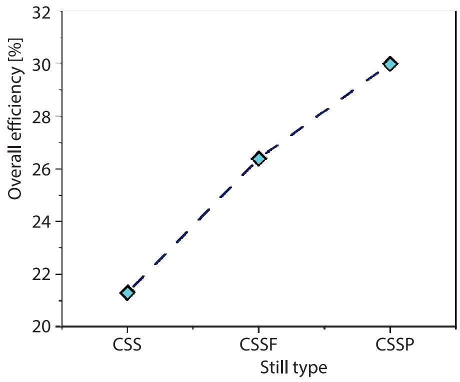

Figure 9. Comparison of the overall efficiency of CSS with CSSF, and CSSP

declining trend in PCM temperature after 14.00 hours demonstrates that the systems begin discharging energy to water. During the time spent recouping energy, the fins on both the PCM and water sides aid in the transmission of heat. The PCM temperature at 10.00 hours seemed to be adequate to discharge some energy, although the temperatures were not monitored after 10.00 hours. However, this could not have much of an effect on productivity in the long run.

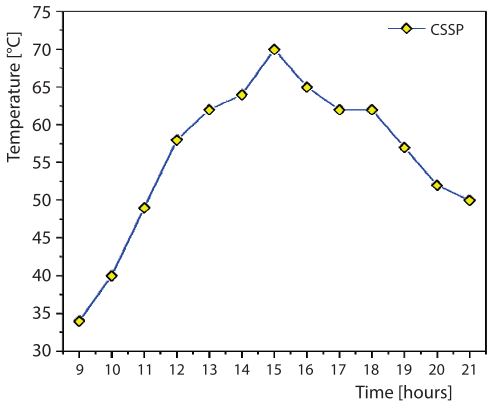

Figure 10. Evaluation of the temperature of CSSP

Conclusions

Solar still with fins and energy storage materials were the subject of research. Over the basin liner, circular hollow fins were placed to observe the changes. The following inferences were drawn from the experimental findings and analysis of performance.

- When compared to CSS, CSSF, and CSSP are both 17.54% and 55.69% more productive. Therefore, fins and an energy storage system considerably improve the solar still's thermal efficiency.
- In particular, the utilisation of fins and storage units may result in a 2.5-fold improvement in nocturnal productivity. Adding PCM into the morning hours reduces output. The PCM can be used at any time of day because it provides continuous efficiency even beyond 21.00 hours.
- Although CSS has a greater hourly energy efficiency than MSS, MSS has a higher total efficiency and is therefore, the preferred option.

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