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EXPERIMENTAL ANALYSIS OF THE PERFORMANCE OF SINGLE SLOPE SOLAR STILL INCORPORATED WITH LATENT HEAT STORAGE SYSTEM

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Abstract*- This work aims to explore the efficiency of the single-slope solar still with a latent heat storage device combined with phase change equipment and its impact on freshwater productivity. Four different cases are considered for comparative analysis, and name of the cases are: conventional solar still, PCM based solar still, solar still coupled with hollow cylindrical fins inlaid in PCM, solar still using both PCM and steel wool fibers on the basin. The experiments are performed under the same climate condition (Longitude: 91^{0}58'15.7" N; Latitude: 22^{0}27'36.2") on the same day. The result revealed that solar stills based on PCM have a negative effect on daytime productivity and positive effect on overnight productivity. While putting steel wool fibers on the basin of PCM based solar still increases daytime productivity, it has an adverse impact on nighttime productivity. However, the highest thermal efficiency (29.46 %) is achieved on hollow cylindrical fins inlaid in phase-change material among all solar still experiments.*

Keywords: Solar still, PCM, Steel wool fiber, Temperature analysis, Productivity analysis.

1. INTRODUCTION

Potable water is considered safe to drink or to use for preparing foods. The quantity of water needed for drinking varies. It relies on physical activity, age, health problems, and environment [1]. One might assume that water shortages should not be of great concern to humans when considering how much water there is in the ocean, particularly when 70% of the earth's surface is covered in it [2]. Only 3 percent of the waters that occupy 70 percent of the surface of the earth are regarded freshwater. Besides, about 2.6% of this freshwater is not available to humans. They are either locked in polar ice caps and glaciers, stored in the air or in the land, highly polluted or taken too far below the earth's surface [3].

Solar still is a device that is used for desalination technology. Using the heat of sun energies in saline water to evaporate and then cool and retrieve freshwater. On the internal part of the glass, the purified water vapor passes through the reduced part of the still and is then gathered in a locked container that is used as drinking water [4]. Solar still is primarily two kinds namely, active solar still and passive solar. In general, passive solar still only utilizes solar radiation to evaporate water for distillate production. On the other hand, in the form of solar collectors, active solar still requires the addition of certain mechanical sources [5]. Sensitive and latent energy storage products are used in the solar still to collect energy during sunshine hours and release it in the evening hours to boost night production [6].

2. METHODOLOGY

2.1 Design and Construction

There are four different cases to experiment with.

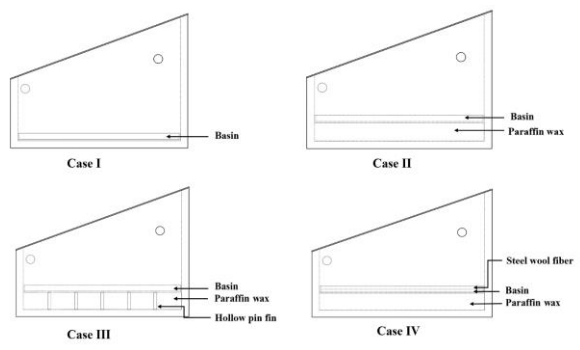
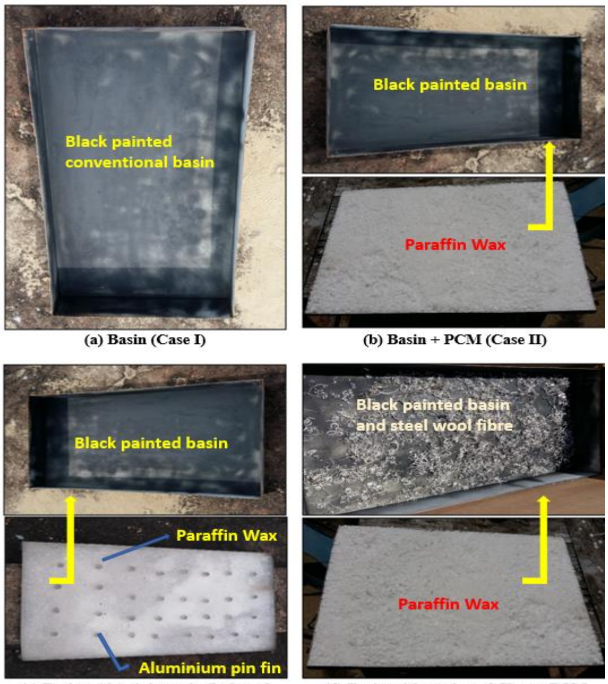


Fig.1: Schematic diagram of four case studies

Four similar proportions of single slope solar stills are implemented at the same place on the east-west axis so that those can receive the same amount of solar radiation for performance analysis and comparison. The absorber basin and PCM container have the same effective area of (0.75m x 0.45m) = 0.3375 m^2. Both are fabricated from mild steel with a thickness of 3mm. The thickness of the glass cover is 3mm. The basin plate is painted black for capturing the maximum solar intensity.



(a) Basin (Case I) (b) Basin + PCM (Case II)

(c) Basin+ Aluminium pin fin based PCM (Case III) (d) Basin with steel wool fiber + PCM (Case IV)

Fig.2: Solar still basin and PCM container for four different cases

There are three PCM containers and each container is fully packed with 4 kg of paraffin wax. The photographic view of paraffin wax is shown in Fig.2 (b). In case 3, aluminium pin fins embedded in PCM and a total 32 (4 x 8) hollow cylindrical pin fins (20 mm outside diameter, 1mm thickness and 15 mm long) are used which is shown in Fig.2(c). In case 4, 500g steel wool fibers are used on the still basin which is shown in Fig.2 (d).

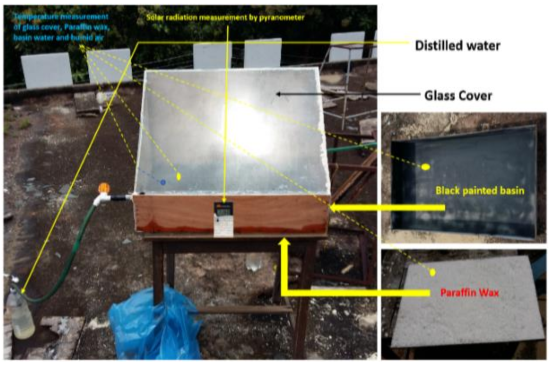


Fig.3: Detailed isometric view of PCM based single slope solar still

There is a detailed isometric representation of PCM based single slope solar still is shown in Fig.3. For conventional solar still, there is only a black painted basin inside the solar still frame. A channel is placed at the backside of the wooden frame to provide saline water in the basin. PCM container is placed beneath the still basin and is sealed with sealant glue to ensure that there is no leakage between the PCM container and the still basin. A channel for receiving water through the slope of the glass is placed just end of the glass slope and it is connected with a container that collects freshwater. In case 3 where aluminium pin fins are embedded in the PCM reservoir and there are steel wool fibers on the basin in case 4. Other components are the same as Fig.3. The measurement process described in Fig.3 is the same for all cases. All the solar still frames have a slant angle with 38^0.

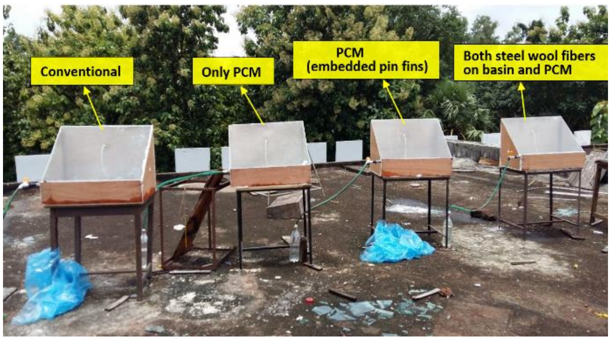


Fig.4: The experimental setup

2.2 Experimental Procedure and Measurement

In this study, four different cases of experiments are conducted on the same day with the same solar radiation at different times. PCM has the ability to absorb latent heat and to release that heat after sunlight is dimmed. So, the comparison is taken at daytime and also at overnight whole 24 hours from 4th August 2019 8 am to 5th August 2019 at 8 am. The daytime productivity value is taken from 9 am to 5 pm and overnight productivity value is taken on the next day at 8 am.

For experimental purposes, paraffin wax is thoroughly chosen as PCM. The paraffin wax's melting point is 56 ^{0}C. The average paraffin wax melting time is greater than the duration of solidification. The paraffin wax shifts its stage when the temperature reaches 56 ^{0}C from solid to liquid and when the sunlight is dimmed, it is used to release heat.

The feed water is given in the still basin from the inlet water tube. Solar energy is entered into the glass and is vaporized the water upward to the glass surface and that vapor is condensed to the glass surface. The condensed water has a run down to the tiny inclined triangle channel to collect in the container due to the gravity and tilting of the glass cover. The output freshwater is the productivity of solar still.

There are different measurements have taken for solar still thermal analysis, productivity and efficiency. Absorber basin plate temperature (T_p), PCM container temperature (T_{pcm}), humid air temperature (T_{ha}), water temperature (T_w) and ambient temperature (T_{amb}) are measured with the thermometer. Glass surface temperature (T_g) is measured with the thermocouple. A pyranometer is used to measure solar radiation (G). The productivity of water is measured by a weight machine. Several graphs are plotted for temperature evolution and productivity of solar stills for each case for 48 hours.

A flow diagram of the whole procedure of this experiment is established in Fig.5.

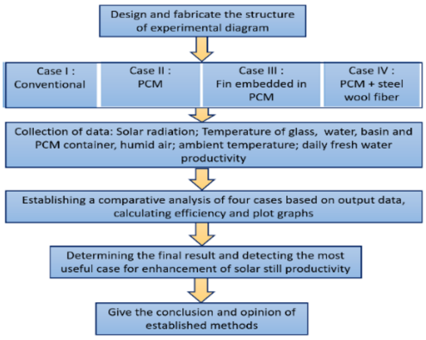


Fig.5: Flow diagram of the experimental procedure

3. RESULT AND DISCUSSION

All experimental works were performed from 8 a.m. of August 4, 2019, to 8 a.m. of August 6, 2019, for the duration of 48 hours which is calculated for 24 hours of each day.

3.1 Temperature Analysis of Solar Still

Studying the temperature assessment of each portion of the solar still in time provides a decent idea of how the solar still works and performs and aids to understand the outcomes of solar still productivity.

3.1.1 Effect of Conventional Solar Still

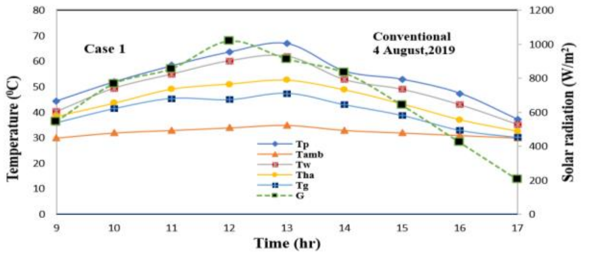


Fig.6: Temperature evolution of conventional solar still (August 4, 2019)

On 4th August 2019 temperature analysis of conventional solar still is shown in Fig.6 with a graph that is plotted from the data obtained from the experiment. Here the maximum value of solar radiation was 1018 W/m^2 at 12 pm and the higher absorber plate temperature was 67 ^{0}C. All the temperatures are gradually increased with the increment of solar radiation then decrease gradually as solar radiation is decreased.

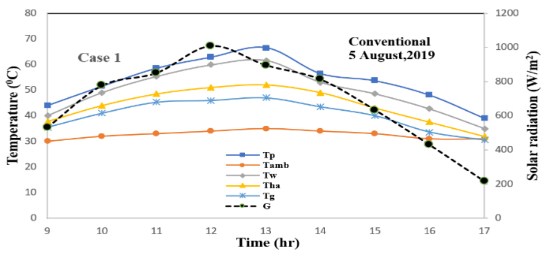


Fig.7: Temperature evolution of conventional solar still (August 5, 2019)

On 5th August 2019 temperature analysis of conventional solar still is shown in Fig.7. Here the gradual temperature change was just the same as the previous day. But the highest solar radiation was 1008 W/m^2.

3.1.2 Effect of Phase Change Material

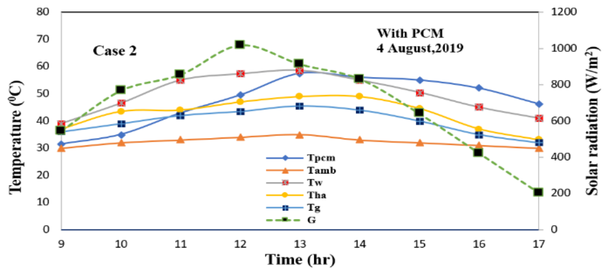


Fig.8: Temperature evolution of solar still with PCM (August 4, 2019)

On 4th August 2019 temperature analysis of solar still with PCM is shown in Fig.8. Here, compare to a conventional solar still, the temperature increase was slower. But when solar radiation was decreasing it had better temperature than the conventional because of the latent heat capacity of paraffin wax. It was melted at 56^{0}C but when solar radiation and ambient temperature was started decreasing, paraffin wax had released its heat to the basin. So that water, humid air and glass temperature was higher than conventional after 2 pm.

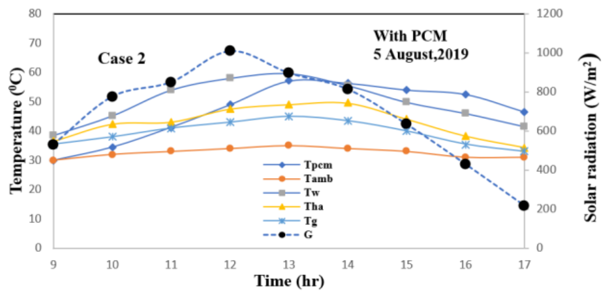


Fig.9: Temperature evolution of solar still with PCM (August 5, 2019)

Similar temperature analysis on 5th August 2019 of conventional solar still is shown in Fig.9.

3.1.3 Effect of the Embedded Pin Fins in PCM

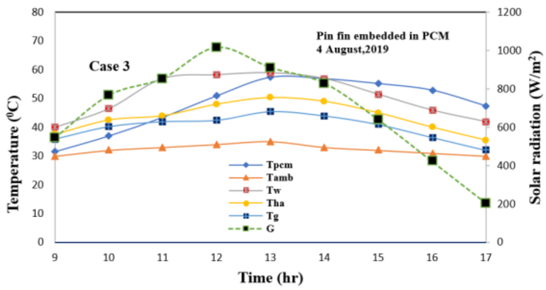


Fig.10: Temperature evolution of solar still with pin-fin embedded in PCM (August 4, 2019)

On 4th August 2019 temperature analysis of solar still with pin-fin embedded in PCM is shown in Fig.10. Aluminium pin fins implanted in PCM have resulted increasing heat transfer through phase change material. Although the gradual temperature increase is lower than conventional solar still till 1 pm, it has a greater temperature gradient after 1 pm than both conventional and only PCM based solar still.

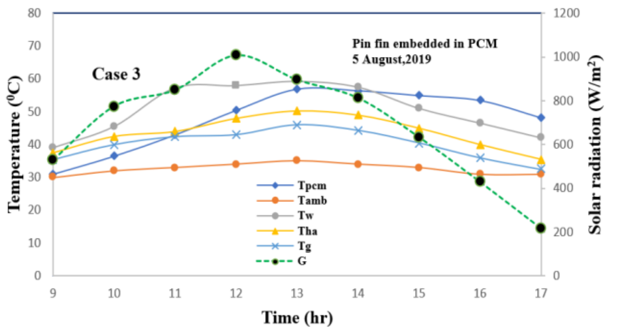


Fig.11: Temperature evolution of solar still with pin-fin embedded in PCM (August 5, 2019)

On 5th August 2019 temperature analysis of conventional solar still is shown in Fig.11 where the temperature gradient is the same.

3.1.4 Effect of Steel Wool Fiber with PCM

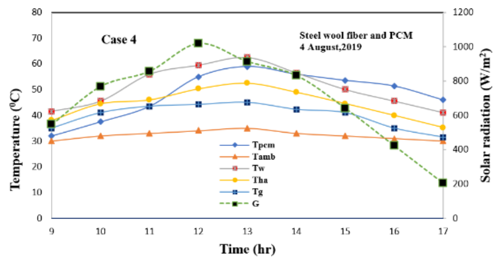


Fig.12: Temperature evolution of solar still with steel wool fiber and PCM (August 4, 2019)

On 5th August 2019 temperature analysis of solar still with steel wool fiber and PCM is shown in figure 12 where we can see the temperature gradient, in this case, is highest on the comparison of other PCM based solar still and better temperature gradient than conventional solar still after 1 pm.

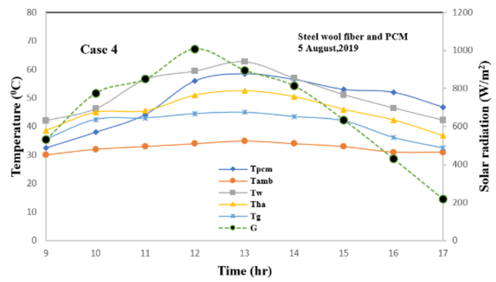


Fig.13: Temperature evolution of solar still with steel wool fiber and PCM (August 5, 2019)

On 5th August 2019 temperature analysis of solar still with steel wool fiber and PCM is shown in Fig.13.

3.2 Productivity Analysis of Solar Still

The productivity of distilled water is obtained by the quantity of pure water per unit area of the absorber plate. The productivity of freshwater was different in four different cases. Hourly productivity in respect of time is plotted for four cases on a graph is shown in Fig.14. The productivity of water (Kg/m^2 hr) was highest on August 4, 2019 at 1 pm and that was 0.55, 0.48, 0.51 and 0.56 respectively for the case I, case II, case III and case IV. At overnight it was highest at case 3 and that was 0.97 Kg/m^2 hr.

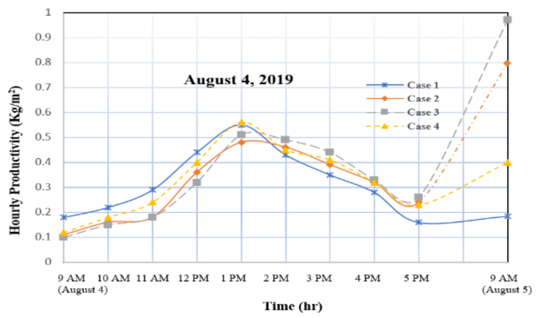


Fig.14: Hourly freshwater productivity along the day and night for case 1, 2, 3 and 4 (August 4, 2019)

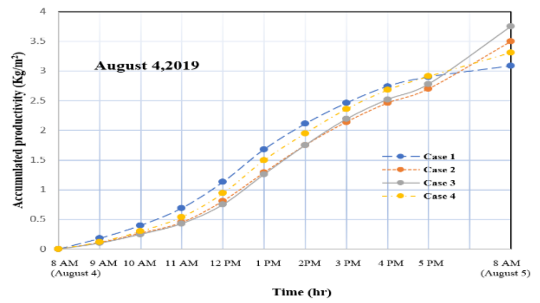


Fig.15: Accumulated freshwater productivity along the day and night for case 1, 2, 3 and 4 (August 4, 2019)

The accumulated productivity of water (Kg/m^2) is the gradient of water productivity with respect to time is shown in Fig.15.

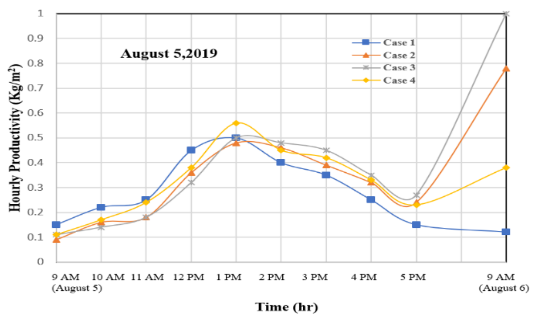


Fig.16: Hourly freshwater productivity along the day and night for case 1, 2, 3 and 4 (August 5, 2019)

The hourly freshwater productivity for four cases is shown in Fig.15.

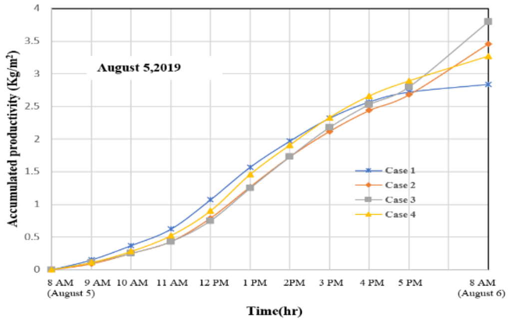


Fig.17: Accumulated freshwater productivity along the day and night for case 1, 2, 3 and 4 (August 5, 2019)

Overnight productivity is highest for case 3 (embedded pin fin). On August 4 overnight productivity of case 1,2,3,4 were 0.185, 0.8, 0.97, 0.4 Kg/m^2 respectively. On August 5 overnight productivity of case 1,2,3,4 were 0.12, 0.78, 1, 0.38 Kg/m^2 respectively.

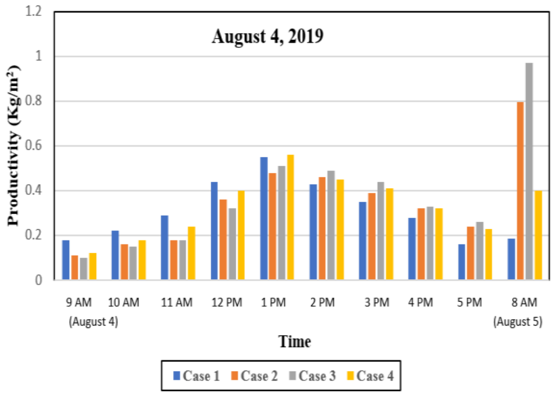


Fig.18: Daytime and nighttime productivity for 24 hours (August 4, 2019)

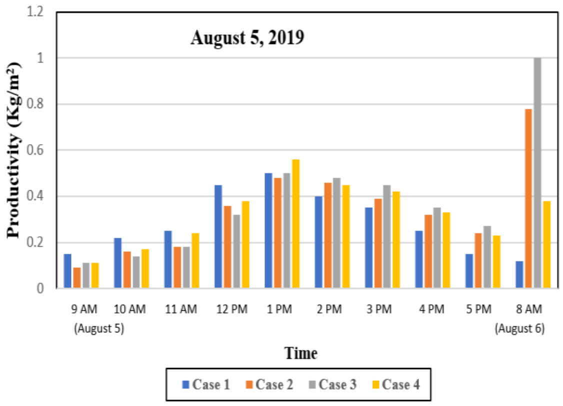


Fig.19: Daytime and nighttime productivity for 24 hours (August 5, 2019)

In Fig.18 and Fig.19 the daytime and nighttime productivity of freshwater for August 4 and August 5 respectively are shown with the different bar charts. There are four different colors for four cases indicating the productivity variations for each hour. The experiment of 24 hours productivity started from 8 am and ended the next morning at 8 am.

3.3 Efficiency Analysis of Solar Still

For all considered instances, solar still thermal efficiency is calculated to analyze the outcome. Use the following formula to calculate the thermal efficiency of solar still. [7].

$$\eta_{th} = \frac{(P_d \times L_{av})}{(A_p \times I_d \times \Delta t)}$$

where P_d is total distilled water productivity in m^3, L_{av} is concealed heat of evaporation of water in J/Kg, A_p is the anticipated area of solar still in m^2, I_d is the entire daily solar intensity in W/m^2, Δt is the time in sec.

L_{av} = 2260 kJ/Kg.

After calculating the following result of solar still efficiency is obtained.

Table 1: Solar still productivity and thermal efficiency (August 4, 2019)

Study cases	Case 1	Case 2	Case 2	Case 4
Total daily radiation (W/m^2 day)	6202	6202	6202	6202
Total daily productivity (Kg/m^2)	2.9	2.7	2.78	2.91
Thermal Efficiency	29.33%	27.3%	28.2%	29.46%

Table 2: Solar still productivity and thermal efficiency (August 5, 2019)

Study cases	Case 1	Case 2	Case 2	Case 4
Total daily radiation (W/m^2 day)	6157	6157	6157	6157
Total daily productivity (Kg/m^2)	2.72	2.68	2.8	2.89
Thermal Efficiency	27.73%	27.34%	28.46%	29.46%

Table 1 and Table 2 contain the Total daily radiation, total daily productivity and thermal efficiency of solar still on August 4 and 5, 2019 respectively. The highest thermal efficiency of the solar still which is 29.46% for case 4 (steel wool fiber) on both August 4 and August 5 and lowest thermal efficiency is 27.3% and 27.34% for case 2 on August 4 and August 5 respectively.

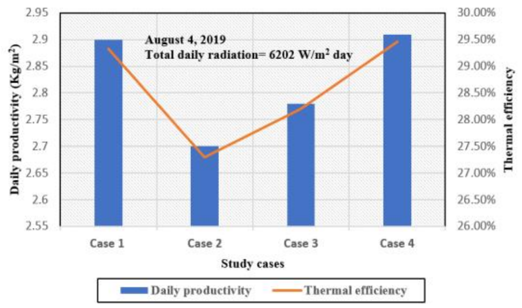


Fig.20: Graphical interpretation of daily productivity and thermal efficiency of four cases (August 4, 2019)

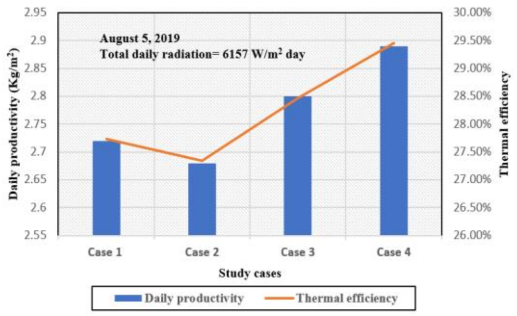


Fig.21: Graphical interpretation of daily productivity and thermal efficiency of four cases (August 5, 2019)

In Fig.20 and Fig.21, the graphical representation of daily productivity and thermal efficiency of four cases is established for better understanding the variation of productivity throughout the experiment.

4. CONCLUSIONS

This study has investigated the improvement of the daytime yield of freshwater from PCM based solar still, hollow pin fin embedded in solar still and steel wool fibers with PCM. The main conclusions of this experiment are:

- PCM reduces daytime productivity than conventional still but increases nighttime productivity at a higher rate.
- The total accumulated freshwater productivity is higher at PCM (embedded hollow pin fins) based solar still.
- For PCM based solar still with steel wool fibers on basin enhances daytime productivity but decreases overnight productivity.
- Among all tested cases PCM based solar still with steel wool fibers has achieved the highest thermal efficiency.
- This experimental study is done on a full sunny day with a duration of 48 hours and similar results are found in two separate successive days.

However, by studying more detailed about the specified fin materials and fibers, more enhancement of distilled water productivity could be acquired. Moreover, in this study, these results are obtained not for a specified geographical area but there are a lot of technical methods used.

5. ACKNOWLEDGMENT

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7. NOMENCLATURE

Symbol	Meaning	Unit
PCM	Phase Change Material	[-]
T_p	Absorber Plate Temperature	(° C)
T_{pcm}	Temperature of PCM	(° C)
T_{amb}	Ambient Temperature	(° C)
T_w	Temperature of Water	(° C)
T_g	Temperature of Glass	(° C)
T_{ha}	Humid Air Temperature	(° C)
G	Solar Radiation	(W/m^2)
η_{th}	Thermal Efficiency	[-]
P_d	Total Daily Productivity	(Kg/m^2)
L_{av}	Evaporation of Water	(J/Kg)
A_p	Anticipated area of solar still	(m^2)