

A Study on the Thermal Performance of a Shallow Solar Pond Integrated with Paraffin as PCM for in situ Solar Thermal Storage Water Heating Facility

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Abstract— Growing energy needs and increasing environmental concern necessitates the use of renewables and to explore the alternative energy sources for the polluting fossil fuels. One such alternative is solar energy produced by the sun and is being collected and stored in different thermal storage medium. In this paper, the thermal performance of a Shallow Solar Pond (SSP) for its thermal storage capability with and without PCM has been investigated experimentally. The experiment has been performed during the months of February and March of 2015 under the climatic conditions of Gandhigram [Latitude 10.26°N, Longitude 77.93°E]. The SSP was fabricated in the laboratory and its performance was tested for six different water loads from 25 to 50 liters in steps of increase of 5 liters per day. The observations were made for the six successive sunny days. The commercially available paraffin wax encapsulated with the iron pipes of length 0.6m and diameter of 0.022m was used as phase change material.

In this work an attempt has been made to investigate the thermal performance of the SSP independently in providing hot water during sunshine and non sunshine hours with and without the incorporation of phase change material (PCM). From the experimental results, it has been obtained that the best performance for the shallow solar pond has been achieved when the SSP was integrated with PCM assembly. The increase of volume of water load resulted with a steady decrease of the T_{max} when loaded with water alone. The T_{max} observed for SSP with PCM loading, the decrease of T_{max} was found to be very slow and it was found to have value centrally around the temperature of 70°C. When comparing the resulting storage water temperature T_{max} at the early morning prior to the sunrise of the next day, for the two modes [with and without PCM] it was found to be higher when the SSP was loaded with the PCM material along with the loaded water volume. It is concluded that the shallow solar pond with PCM may be used as a hot water source for domestic applications by collecting and storing solar energy at the same point.

Keywords— Shallow Solar Pond, Phase Change Material, in situ thermal Storage, PCM encapsulated Iron Pipe assembly.

I. INTRODUCTION

A Shallow Solar Pond (SSP) refer to stagnant large body of water with black bottom and capable of collecting and storing solar energy. The name shallow itself implies the depth of the pond which is relatively small and ranges from 3 to 15 cm depth. The SSP has a capability for heating a large volume of water to an appreciable high temperature. It is also one of the cheapest methods for harnessing the solar energy. In the shallow solar pond, the black LDPE liner laid over the bottom surface of the pond absorbs the solar radiation. As a result the stored water gets heated. M.S.Sodha, et al., [1], have reported a simplified analytical model to predict the performance of a Shallow Solar Pond water heater which combines both collection and storage in a single unit. Essentially the water heater consists of a metallic (G.I.) tray, inner and bottom surfaces are painted black and were covered with a transparent sheet at the top. The side of and bottom surfaces of the assembly are well insulated. The unit had stored substantial amount of heat for next day morning use. When the top cover was properly insulated during the night time. Ramadan et al. [2] have investigated the thermal performance of a shallow solar pond (SSP) under the batch and open cycle modes of heat extraction. On the basis of the experimental results, it has been concluded that the best performance of the pond was achieved when the pond was used with double glass covers and an outer mirror with tilt angle adjusted at every half an hour. The year round performance of the SSP has indicated that the designed SSP could be used as heat source for most domestic

applications during most days of the year. El-Sebaai.A.A [3] has investigated shallow solar pond integrated with a baffle plate was theoretically and experimentally tested with prevailing weather condition of that location. On the basis of the obtained results, the following conclusions had been drawn, that the performance of pond with the baffle plate was better than that of the pond without the plate. The proposed model has been used for the investigation of the performance of the SSP's with baffle plates with very good accuracy. Aboul-Enein et al. [4] have investigated the thermal performance of a shallow solar pond under the batch mode of heat extraction. It has been concluded that the best performance of the pond was achieved and from the experimental results the pond could able to provide 88 liters of hot water with the maximum temperature of 60°C at the sunset hours. The same amount water obtained at 47°C in the morning of the next day and which has been used for most domestic application. Zhongliang-Liu et al., [5] have investigated the thermal storage system, a heat pipe, heat exchanger with latent heat storage arrangement. The system was operated in three basic different operation modes for charging, discharging and simultaneous charging/discharging modes of operation. The experimental results have shown that the heat exchanger performed the designed functions very well and was found to store and release the thermal energy efficiently. H.P.Garg et, al, [6] have discussed that paraffin was qualified for its heat of fusion for thermal storage applications. Due to their availability in a large temperature range and with the desired thermo physical. The thermo physical properties of the paraffin wax are tabulated below.

Table 1: Thermo-Physical Properties of paraffin wax as PCM.

Properties	Paraffin Wax(PCM)
Latent heat of Fusion	209KJ/Kg
Specific heat capacity	2.85KJ/Kg ⁰ C
Melting temperature	56-60 ⁰ C

In this study, an attempt has been made to enhance the thermal storage capacity of the fabricated shallow solar pond (SSP) by using PCM encapsulated iron pipes for in situ solar thermal collection and storage. The performance of SSP has been investigated experimentally under the climatic conditions prevailed during the month of Feb-March 2015. The thermal performance of the SSP with the incorporation of PCM capsule and without PCM capsule was compared and the measured temperature was used to calculate its instantaneous collection efficiency. The thermal performance, with and without PCM storage effect have been tested during successive sunny days and the results have been reported here.

II. MATERIALS AND METHODS



Fig1. Pictorial view of the Shallow Solar Pond

A pictorial diagram of the constructed shallow solar pond is shown in Fig1. The SSP was fabricated by a metal rectangular tray made of GI sheet of thickness 0.002m of dimensions 1.18m x 0.68m x 0.10m with an aperture area of 0.802m². The black polyurethane foam (PUF) of thickness 0.012m was used for insulation on all sides and bottom of the metal tray to be used as SSP to reduce the heat loss. In order to capture the better solar energy a Low Density Polyethylene (LDPE) black sheet liner of 200 micrometer thickness was laid all along the bed side and inner peripheral sides of the shallow solar pond and was laid leak proof to hold the water after loading the SSP with known volume of fresh water. A clear transparent polyvinyl chloride (PVC) plastic sheet of 150 micrometer thickness was laid over the water surface as a evaporation suppressing membrane. A transparent glass cover of thickness 0.005m and dimension 1.25m x 0.75m was used to cover the pond.

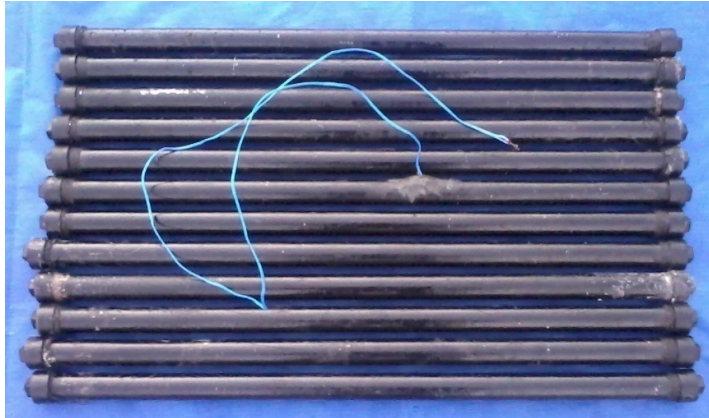


Fig2. Pictorial view of the PCM encapsulated iron pipes.

A hollow iron pipe of thickness 0.015m for a length of 0.60m and diameter of 0.022m with both sides closed with the end cap was used to hold the PCM inside the pipe and the pipes are painted black to absorb the solar radiation. The pipes were filled with the commercially available paraffin wax. For this study 12 numbers of pipes were taken and each pipe was filled with 0.250kg of paraffin wax, totally 3kg of paraffin wax was used. Shallow Solar Pond was investigated by increasing the storage volumes from 25 liters to 50 liters in steps of 5 liters a day. The pond was operated under batch mode. The SSP was operated in two modes, one was with PCM encapsulated iron pipes and another was without PCM encapsulated iron pipes. The SSP was filled with tap water at 7.00am and the experiments were conducted until 7.00am of the next day to study the storage capability of the SSP. During the night hours the pond was covered with PU foam of thickness 0.012m to reduce the night time heat loss. Calibrated copper constantan thermocouples were used to measure the temperature at different location of the pond as well as water. The ambient temperature was taken by using thermometer with an accuracy of 0.1⁰ C. The global solar radiation incident on the pond cover was measured using a pyranometer. The measured values of different temperature are used for calculating the instantaneous heat collection efficiency and heat loss coefficient.

The Hottel – Whiller – Bliss (HWB) equation for the instantaneous rate of heat collected per unit area of the shallow solar pond [7] is given as,

$$Q = (\alpha\tau)I - U_L(T_f - T_i) \tag{1}$$

The instantaneous collection efficiency (η_i) of the SSP is defined as

$$\eta_i = Q/I = (\alpha\tau) - U_L(T_f - T_i)/I \tag{2}$$

It is also useful to define the daily collection efficiency η_d as

$$\eta_d = mC_p\Delta T/AIT \tag{3}$$

III. RESULTS AND DISCUSSION

The experiments have been performed to investigate the pond performance and thermal storage capability, when it was filled with water and kept without PCM iron pipes condition. The SSP was operated from 7am to 7am of the next day, the maximum temperature of pond water was found to be lag about 1-4 hours behind the maximum ambient temperature and solar radiation respectively. After sunshine hours the pond was covered with PU foam to reduce the night time heat loss. During the

morning period from 7am until noon most of the heat is utilized for heating the pond water and absorber sheet. However, during the afternoon period the temperature of the pond water increases. From fig.3 shows that the hourly variation of pond water temperature, solar insolation and ambient temperature with respect to time for 25 liters of SSP with and without PCM iron pipes.

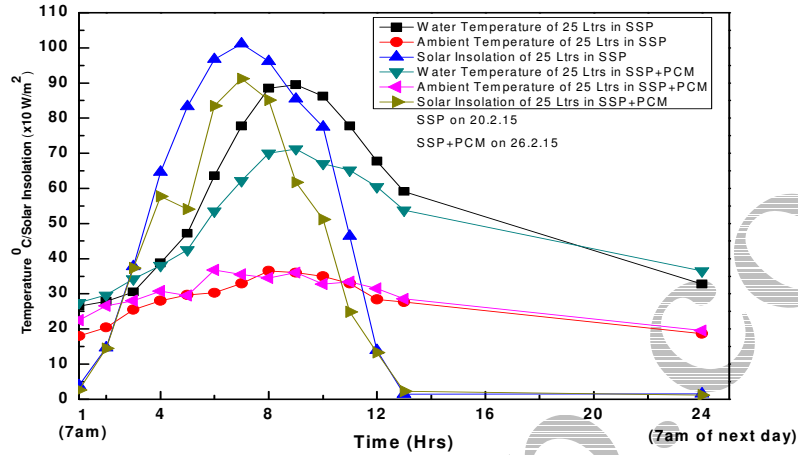


Fig.3 shows that the hourly variation of pond water temperature, solar insolation and ambient temperature with respect to time for 25 liters of SSP and SSP+PCM.

The SSP with 25 liters storage volume of water obtained the maximum temperature of 89⁰C and 71⁰C with the ambient temperature of 36.5⁰C and 36⁰C for the typical sunny days of 20 Feb 2105 and 26.Feb.15 for SSP and SSP+PCM respectively. It is seen that the maximum value of solar insolation has maximum of 1011 W/m² and 912 W/m² at noon. The total solar radiation incident on the SSP and SSP+PCM was 7245 W/m² and 5804 W/m² respectively. From fig.3 shows that there was a gradual increase and decrease in water temperature when pond was operated with PCM and rapid increase and decrease in water temperature when pond was operated without PCM. When the pond water temperature was tested on the 7am of the next day the water temperature was 32.8⁰C, 36.5⁰C with the ambient temperature of 18.5⁰C and 19.7⁰C for the SSP and SSP+PCM respectively.

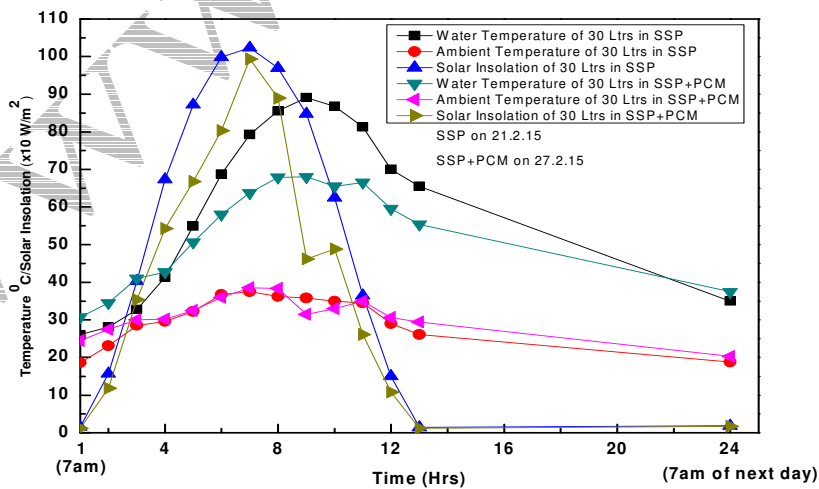


Fig.4 shows that the hourly variation of pond water temperature, solar insolation and ambient temperature with respect to time for 30 liters of SSP and SSP+PCM.

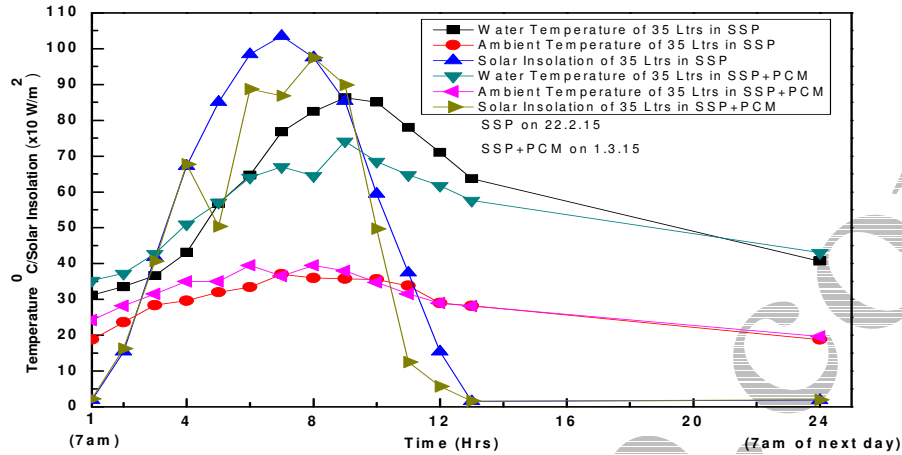


Fig.5 shows that the hourly variation of pond water temperature, solar insolation and ambient temperature with respect to time for 35 liters of SSP and SSP+PCM.

Hourly variation of water temperature, solar insolation and ambient temperature are shown in fig.4, 5 for the 30 and 35 liters of storage volume of pond water. From the fig 4, the maximum temperature for 30 liters of storage volume was 89°C and 68°C with the ambient temperature of 35°C and 31.5°C for the typical sunny days of 21 Feb 2105 and 27.Feb.15 for SSP and SSP+PCM respectively. It is seen that the maximum value of solar insolation of 1023 W/m² and 993 W/m² at 1pm, the total solar radiation on that typical days are 7131 W/m² and 5830 W/m² for SSP and SSP+PCM. The water temperature on the next day was 35°C, 37.5°C with the surrounding ambient temperature of 19°C and 20.5°C. fig.5 shows that the 35 liters of storage volume of water has the maximum temperature of 86°C, 74°C with the ambient temperature of 35°C, 37°C and the highest solar insolation of 1035 W/m² and 974 W/m² at 2pm, the total solar radiation was 7116 W/m² and 6114 W/m² for SSP and SSP+PCM on 22 Feb 2105 and 1.Mar.15 respectively. On 7am of the next day the pond water temperature was 40°C, 43°C with the outside ambient temperature of 18.5°C, 20°C for SSP and SSP+PCM.

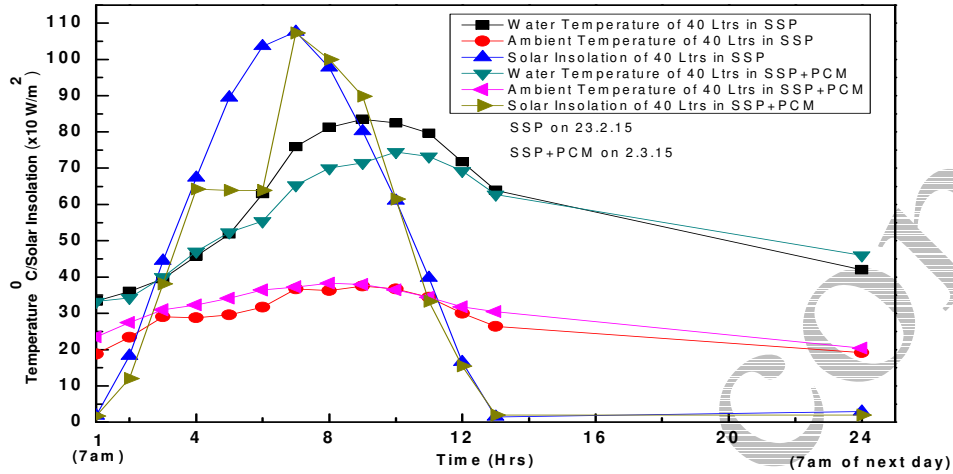


Fig.6 shows that the hourly variation of pond water temperature, solar insolation and ambient temperature with respect to time for 40 liters of SSP and SSP+PCM.

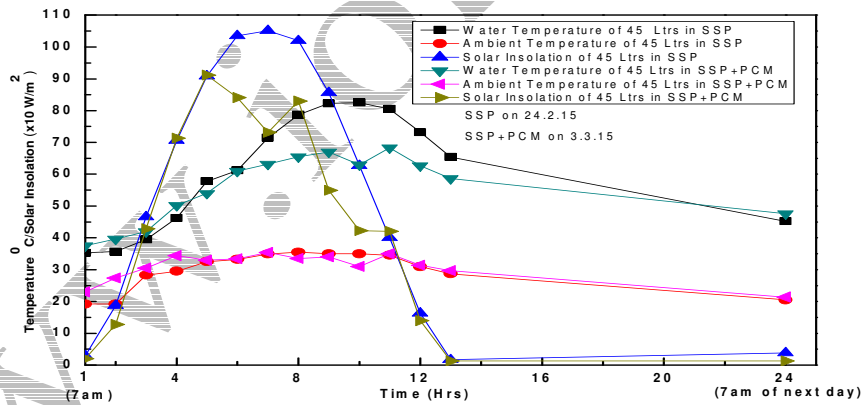


Fig.7 shows that the hourly variation of pond water temperature, solar insolation and ambient temperature with respect to time for 45 liters of SSP and SSP+PCM.

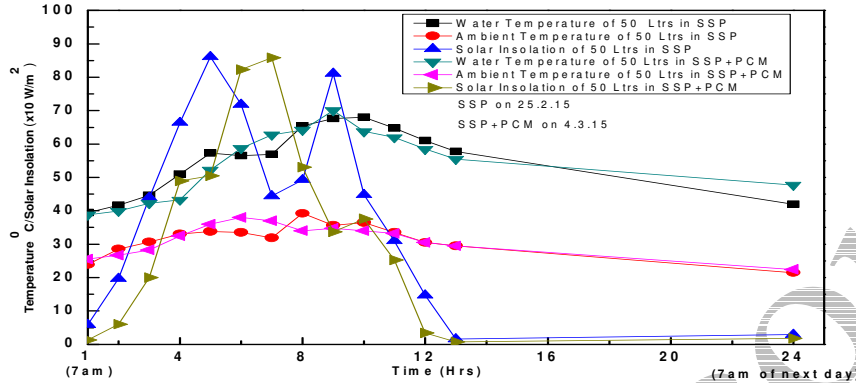


Fig.8 shows that the hourly variation of pond water temperature, solar insolation and ambient temperature with respect to time for 50 liters of SSP and SSP+PCM.

It is seen from the results of fig.6 the maximum values of the pond water temperature was found to be 83°C, 75°C for the ambient temperature values of 37°C, 36°C and the maximum values of solar insolation 1076W/m², 1072W/m² at 1pm on the days of 23.2.15 and 2.3.15 for SSP and SSP+PCM respectively. The total solar radiation incidents on these days are 7325 W/m² and 6552 W/m². The water temperature on the next day for the SSP and SSP+PCM was 42°C, 46°C with the ambient temperature of 19°C and 20°C respectively. Fig 7. Shows that SSP with 45 liters storage volume of water obtained the maximum temperature of 82°C and 67°C with the ambient temperature of 35°C and 35°C for the typical sunny days of 24 Feb 2105 and 3.Mar.15 for SSP and SSP+PCM respectively. It is seen that the maximum value of solar insolation has maximum of 1050 W/m² and 840 W/m² at noon. The total solar radiation incident on the SSP and SSP+PCM was 7503 W/m² and 6160 W/m² respectively. The pond water temperature at 7am of the next day was 45°C, 48.5°C with ambient temperature of 20.5°C and 21.5°C respectively. The results obtained from the fig.8 that the 50 liters of storage volume of water has the maximum temperature of 68°C, 70°C with the ambient temperature of 36°C, 35°C and the maximum solar insolation of 811 W/m² and 858 W/m² at 1pm, the total solar radiation was 5636 W/m² and 4502 W/m² for SSP and SSP+PCM on 25 Feb 2105 and 4.Mar.15 respectively. On 7am of the next day the pond water temperature was 42°C, 47°C with the ambient temperature of 21°C, 22°C for SSP and SSP+PCM.

A. Efficiency of the Shallow Solar Pond

The efficiency of the SSP is calculated using Hottel-Whillier-Bliss model and the thermal performance Curve was drawn for the variations of the efficiency versus the reduced parameter $\Delta T/I$. Least square fit has been used to determine the SSP characteristic parameters. For the SSP

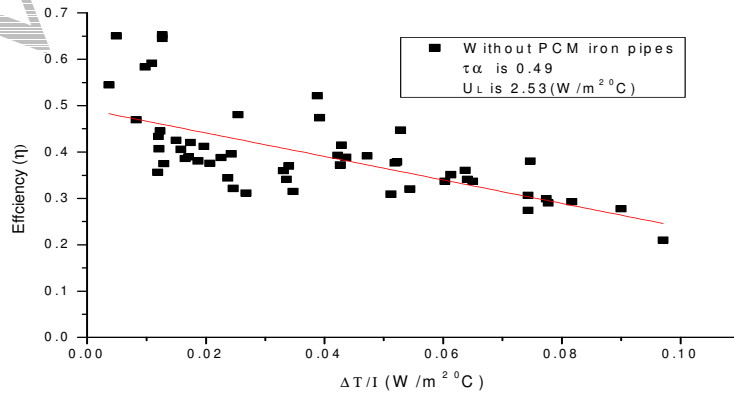


Fig.9 overall thermal performance curve for the range of 25 to 50 liters of water loaded in the SSP without PCM assembly.

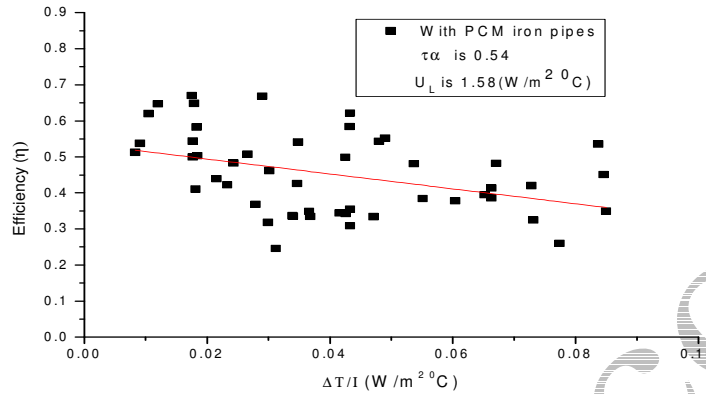


Fig.10 overall thermal performance curve for the range of 25 to 50 liters of water loaded in the SSP with PCM assembly.

and SSP+PCM types a straight line with negative slope has been obtained. The intercepts of the obtained lines yield the factor of transmittance-absorptance product ($\tau\alpha$) as 0.54 and 0.49 for with and without PCM iron pipes respectively. The slopes of the efficiency lines are proportional to the overall heat loss coefficient (U_L) as 1.58 and 2.53 ($W/m^2 \text{ } ^\circ C$) for SSP and for SSP+PCM respectively. From the obtained results the efficiency of the SSP with PCM was found to be higher than that of SSP without PCM.

IV. DISCUSSION

The Shallow Solar Pond with and without PCM was experimentally studied for its efficiency, hot water temperature at the next day and overall heat loss. When the SSP is operated without PCM, the maximum water temperature of $89^\circ C$ for 25 and 30 liters of loaded volume and the maximum temperature of water obtained on the next day at 7AM is $45^\circ C$ for the loaded volume of 45 liters. When the SSP is operated with PCM, the maximum water temperature of $75^\circ C$ and the water temperature obtained on the next day at 7AM is $47.5^\circ C$ for the loaded volume of 40 liters. The efficiency of the SSP with and without PCM is 0.54 and 0.49 respectively. The highest temperature of the SSP without PCM was $89^\circ C$ and the highest ambient temperature was $34^\circ C$. So that ΔT with the SSP is high naturally lead to lot of heat loss. When discuss about the solar insolation it is higher for the SSP operated without PCM. The SSP operated with PCM the highest temperature centered around $70^\circ C$. The SSP with PCM has got additional heat absorptance due to the black paint coated on the iron pipes. The high intensity of solar radiation starts to melt the paraffin wax from the morning hours until noon, subsequently it gets decreased in temperature and becomes solid state again by releasing sensible heat into water, during the low solar radiation time and even after sunshine hours. It is inferred that the SSP operated with PCM was having a solar collection efficiency as $\tau\alpha$ product 12.5% better than that of the SSP without PCM.

V. CONCLUSION

On the basis of the obtained experimental results, the SSP operated in batch mode condition with and without PCM. The storage volume of 30 liters of the SSP without PCM attained a temperature $89^\circ C$ and the SSP with PCM has attained the maximum temperature of $75^\circ C$ for the maximum storage volume of 40 liters of water. The water temperatures on the next day of the SSP with PCM are much higher than those of SSP without PCM, which ranges from $36^\circ C$ to $47.5^\circ C$ respectively. The efficiency of the SSP with and without PCM is 54% and 49% which is 12.5% higher than SSP without PCM. From the performance analysis it is observed that the Shallow Solar Pond operated with PCM iron pipes are more efficient as a source of hot water required at off sunshine hours and the next day use for domestic and low temperature industrial applications.

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