CHARGING-DISCHARGING CHARACTERISTICS OF MACRO ENCAPSULATED PHASE CHANGE MATERIALS IN AN ACTIVE THERMAL ENERGY STORAGE SYSTEM FOR A SOLAR DRYING KILN

by

Shailendra KUMAR** and V. S. Kishan KUMAR

Forest Products Division, Forest Research Institute, Dehradun, India

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The present study explores suitability of two phase change materials (PCM) for development of an active thermal storage system for a solar drying kiln by studying their melting and solidification behaviors. A double glass glazing prototype solar kiln was used in the study. The storage system consisted of a water storage tank with PCM placed inside the water in high density polyethylene containers. The water in the tank was heated with help of solar energy using an evacuated tube collector array. The melting and solidification temperature curves of PCM were obtained by charging and discharging the water tank. The study illustrated the utility of the PCM in using the stored thermal energy during their discharge to enhance the temperature inside the kiln. The rate of temperature reduction was found to be higher for paraffin wax as compared to a fatty acid based PCM. The water temperature during the discharge of the PCM showed dependence on the discharge characteristics of each PCM suggesting their suitability in designing active thermal storage systems.

Key words: *solar drying kiln, thermal storage, PCM, paraffin, charge and discharge*

Introduction

Due to intermittent nature of solar energy availability, need of solar thermal energy storage has been felt in many aspects of industrial processes. Wood drying is an important operation in wood processing. Drying of wood is very energy intensive and time taking process [1, 2]. Many designs of solar kilns for wood drying have already been developed across the globe. However, solar kilns have some usual limitations also as solar radiation is not available after Sun set. For commercial wood processing, the ability of the drier to process continuously throughout the day and night is very important in order to decrease the total production time. Thus, due to intermittent nature of solar energy, necessity of the heat storage system was felt for solar kilns which led to development of many designs of solar timber kilns capable of storing heat in the day time and utilizing it in night time, thus enhancing the dryer operability and utility [3-5]. However, most of the works related to solar wood drying kilns are based on sensible heat storage. Zhang *et al.* [6] has discussed application prospect and the importance of the latent heat storage technology in wood drying. Latent heat based thermal storage has been used in many applications from solar water heating [7] to space-craft thermal systems [8].

* Corresponding author, e-mail: kumarsro@icfre.org

Most of the thermal storage systems include sensible heat storage and latent heat storage [9]. The latent heat storage has advantages over sensible heat storage due to high storage density and isothermal nature of storage. Common sensible heat storage materials are water, gravel bed, sand, concrete, *etc.* [10]. Paraffin and fatty acids are important classes of organic PCM. A fatty acid is a carboxylic acid with a long side chain of HC and follows the general molecular formula of $CH_3(CH_2)_xCOOH$ where x is the number of carbon atoms in the HC chain. The PCM like paraffin are popular among the researchers as thermal storage material. Paraffins are alkanes with general formula C_nH_{2n+2}. Paraffin consists of a mixture of mostly straight chain n-alkanes CH_3–(CH_2)–CH_3. The crystallization of the (CH_3) – chain releases a large amount of latent heat [11]. The melting point and heat of fusion increase with increase in molecular weight [12].

Organic PCM is easily and cheaply available but is known to show undesirably lower thermal conductivity. For suitability of PCM for development of PCM based thermal storage system the major areas of importance are: determination of thermophysical properties, container system and encapsulation, thermal stability, heat transfer enhancement, *etc*. Melting and freezing characteristics of PCM are very important aspects in selection of PCM for particular applications. A significant piece of information can be extracted from simple freezing curves of PCM [13]. For designing a thermal storage system, the actual phase transition temperature range should be known [12].

The objective of the present work was to study the charge and discharge characteristics of two PCM in an active thermal storage system in a solar kiln.

Materials and methods

Figure 1 represents the schematic diagram of the experimental set-up used in this study which comprises of a prototype solar kiln, an evacuated tube collector (ETC) array and a water tank for thermal storage.

Solar kiln

A double glass glazing, south facing double inclined roof solar timber dryer of 1 m^3 wood capacity was used in the study. The outer dimension of the kiln were 3.8 meters long in south-north direction, 2.3 meters wide in east west direction, and 2 meters height of north most wall with tapers in two inclination angles southwards. The collector system was made of matte black painted galvanized iron (GI) sheet which run parallel to glass glazing not only to south facing roofs but also to east and west walls. Additional aluminum finning at the inner side of the roof collectors was provided for efficient heat removal. The floor of the kiln was insulated with help of 12 mm thick plywood and 75 mm glass-wool. The north wall of the kiln is insulated with 6 mm thick plywood and 100 mm thick glass-wool layer. The details of this kiln's design are described elsewhere [14].

Thermal collection and storage system

This consisted of an ETC array to heat water using available solar energy, a water tank to store this hot water and a heat exchanger (HE) system to transmit the heat from the hot water into the kiln. These arrangements are described:

– *The ETC array to heat water*

The ETC array consisted of 100 ETC tubes which were connected in parallel as shown in fig. 1. The outer diameter and length of each tube are 2 cm and 145 cm, respectively. The water in this array gets heated up during day time due to solar radiations. This hot water is

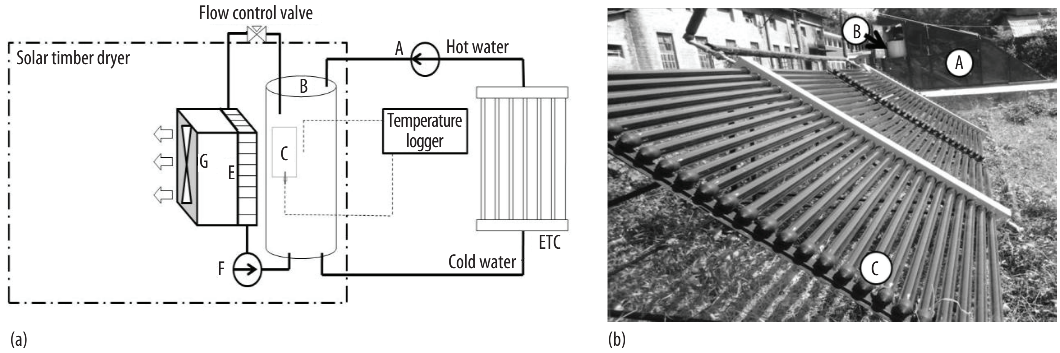

Figure 1. (a) Diagrammatic representation of the thermal storage system;
A – pump for circulating water between ETC array and storage tank, B – thermal storage tank, C – HDPE panels containing PCM, E – heat exchange system, F – pump for circulating water between storage tank and HE, G – air circulating fan to circulate heated air from HE
(b) Image of the solar dryer with thermal energy storage system;
A – semi-green house type solar kiln, B – thermal storage system, C – ETC array

pumped into the water storage tank placed inside the kiln using a 0.373 kW pump, fig. 1(a). This pump was able to maintain an average flow rate of 9.2 liters per minute.

– *The hot water storage tank*

As previously described the hot water from ETC was pumped into a 200 liters capacity tank placed inside the solar kiln. A level of 180 kg of water was maintained in this tank during the experiment.

The tank was insulated with 50 mm thick glass wool layer.

The tank was provided with a pair of inlets and outlets at both the top and bottom sides. The inlet at the top allowed flowing hot water from ETC into the tank. The pump mentioned earlier was used to regulate this process. The outlet of the top of the tank was used to supply the hot water to the HE system. The tank was positioned above the level of ETC array so that water in the tank will automatically flow into the tubes of ETC to get heated by solar energy. A temperature probe was inserted into the tank from the top to record water temperatures.

– *The HE system*

In order to make a HE, an iron box of dimensions 62 cm × 62 cm × 62 cm was made. Four sides of the box were covered with GI sheets to make it air tight. The other two sides of the box were left open. In one open end of the HE box, an aluminum radiator was fixed. The radiator had two rows of fins, having core size of 53 cm × 53 cm × 6.5 cm and overall size of 58 cm × 70 cm × 6.5 cm. This system was placed inside the kiln in such a way that the hot water from the tank will always be siphoned into it through its inlet at the top side. The second and opposite opening of HE box was fitted with a four blade ventilation fan which could flow the hot air with average velocity of 8.3 m/s through an opening of 20 cm diameter. The outlet at the lower side of the HE was connected to the inlet at the lower side of the storage tank with a 0.373 kW pump. This helped in circulating water from HE to the storage tank with an average flow rate of 25 liters per minute. Thus, the water level in the storage tank was maintained at a constant level throughout the experiments.

The outlet at the bottom of the storage tank was used to recycle the cold water to the ETC array during day time to heat up again.

The PCM and its macro encapsulation

The water is used as heat transfer as well as heat storage media as previously described. In addition, two organic PCM contained in high density polyethylene (HDPE) were placed in the hot water storage tank. The first PCM was a commercial one named OM 55™ (OM), which is a mixture of fatty acids. This PCM is commercially produced by M/S Pluss Polymers Pvt Ltd, Gurgaon, India [15]. The second PCM used is paraffin wax (PW), Type-II [16].

The thermophysical properties of the PCM are given in tab. 1.

Table 1. Thermophysical properties of PCM used in the study

Property	Unit	OM, Anon. [15]	Paraffin wax (Type-II), Reddigari *et al.* [17]
Melting temperature	°C	55	61
Latent heat	$kJkg^{-1}$	210	213
Solid density	kgm^{-3}	840	861
Specific heat (liquid)	$kJkg^{-1}K^{-1}$	0.73	2.38
Specific heat (solid)	$kJkg^{-1}K^{-1}$	2.3	1.8
Thermal conductivity (solid)	$Wm^{-1}K^{-1}$	0.135	0.4

Blow molded HDPE panels named Thermotab™ (produced and supplied by M/s Pluss Polymers Pvt Ltd., Gurgaon, India) were used for macro encapsulation of the PCM. The panels have been designed in such a way that circular grooves and ridges on the side walls increase the surface area. Two HDPE containers, fig. 1(a) (C) each having 3 kg OM and PW were placed in the hot water storage tank vertically. Each container had one temperature sensor inserted and sealed from bottom side as melting takes place from top to bottom points in axial direction [18]. The sensor tip was approximately 2.5 cm above the bottom of the container. Thus, it is assumed that if the temperature of PCM at bottom of the container goes above melting point, all the PCM in the container has molten.

The experiment

All the doors and vents of the kiln were kept open throughout the charging and discharging experiment in order to ensure that the kiln had no role in charge and discharge of PCM. The ETC pump was switched on at approximately 10:20 a. m. The charging cycle was started by circulating hot water from ETC array to storage tank. The outlet at the bottom of the storage tank allowed circulation of water between the tank and the ETC array so that the water in the tank was always hot. This hot water was used to charge the two PCMs placed inside the tank. The water in the storage tank reached its maximum temperature (72 °C) by 4:00 p. m.

After the two PCM were fully charged, the hot water in the tank was allowed to pass through the HE system. Simultaneously the fan of the HE system was switched on so that the heat from the hot water flowing through the HE system is exchanged to the surroundings inside the kiln. In this process the water temperature starts falling down simultaneously the PCM start discharging stored heat. The water circulation between the storage tank and the HE system was maintained using the pump, fig. 1(a) (F). During this phase of the experiment, water circulation between the storage tank and the ETC array was stopped.

Temperature measurements recorded

Various temperature measurements taken during the experiment are:
– the temperature of water in the storage tank, and
– the temperatures of the two PCM.

These temperatures were recorded using probes and the readings were stored in a data logger at regular intervals of less than two minutes.

The experiment was repeated on four days in during Jan-Feb, 2015 and it was found that the temperature responses were very similar depending only on the sunshine quality of a particular day. Hence, the charging and discharging pattern are being discussed with the help of temperature curves of a single day.

Results and discussion

Figure 2 gives the temperatures of water in the storage tank and the two PCM during the charging and discharging process at different times after the start of the experiment.

Charging and discharging rates of the PCM

Figure 2 shows that temperatures of the PCM rise gradually with water temperature till melting temperatures of the PCM are reached. This occurs around 300 minutes and 320 minutes, respectively, for OM and PW since the start of the experiment. During this phase, the transfer of heat in PCM is purely by conduction and results in sensible heating. It is seen from fig. 2 that as soon as water temperature reaches above melting points of the PCM (OM, 155 minute and PW 200 minute), temperature curves show reduction in slopes from points A and E. Thereafter, the increase in temperature of PCM is at slower rate up to B and F, fig. 2. This lower increase in temperature indicates that melting is occurring near container walls. Melting is dominated by convection and since, thermal conductivities of the PCM are low, tab. 1, very little heat is expected to be available at the points where temperature sensors have been placed inside the PCM. From B to C and F to G, relatively constant temperatures are observed for PW and OM respectively. It indicates that melting front has reached near temperature sensors. From points C and G onwards, there is a steep rise in temperature showing complete melting of PCM in containers. The fact that the average heat transfer increases sharply due to strong natural convection with increasing molten layer thickness has been reported using $Na_2SO_4 \cdot 10\ H_2O$ as a PCM by Sharma and Chen [19].

Since, the temperature probes were placed in the bottom of HDPE containers, fig. 2 shows that by 320 minute, all the PCM was molten in containers. Although, the time for completion of melting is dependent upon temperature of heat transfer fluid, it can be concluded that in practical solar water heating conditions, when sky is clear, OM may be molten in approximately 5 hours and PW in 5.33 hours in months of Jan-Feb as shown in fig. 2. Since the present set of experiments were performed in winter season (Jan-Feb), the rate of temperature rise in heat transfer fluid (water) is expected to be high in summer season leading to decrease in total melting time.

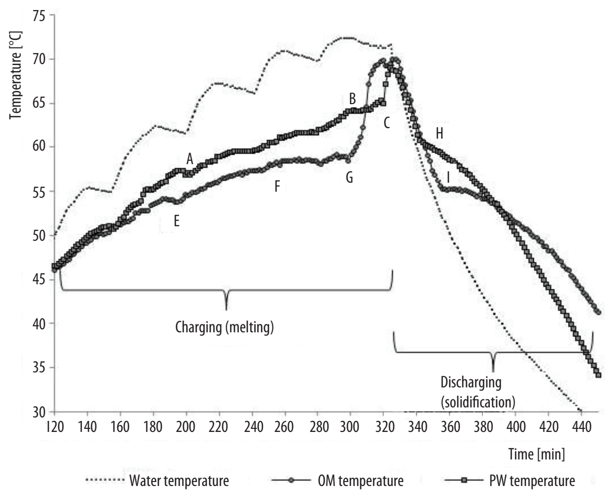

Figure 2. Charging curves of two PCM under hot water circulation

The water storage tank contains two types of thermal storage media *i. e.* water and PCM. Water stores heat in form of specific heat, while heat is stored in PCM in form of latent heat of phase change *i. e.* solid to liquid, which has higher storage density. In the winter season, the low intensity solar heat may not result into higher increase in temperature of water, whereas, PCM may store heat at lower temperatures *i. e.* melting points. Thus, use of PCM as thermal storage media has many advantages over water.

The rate at which thermal energy can be taken from PCM storage is limited by rate of freezing/solidification. The rate of solidification is the function of transport of mass and heat [12]. The temperatures of the molten PCM start dropping at a fast rates (almost similar to that of the water in the tank) until they reach their respective melting points (points H and I in fig. 2). After this point, each of the PCM loses its temperature at much slower rates compared to water in storage tanks. Of the two PCM OM looks to lose its thermal energy slower compared to PW. For example the temperature of PW and OM after 450 minute are 35 and 42 °C, respectively. These correspond to temperature reduction rates of approximately 0.25 °C per minute and 0.14 °C per minutes, respectively, for PW and OM after they had started discharging from corresponding melting points.

For comparison purpose the rates of temperature reductions were calculated from the points when both the PCM attained similar temperatures during the discharge phase. This occurred at around 52.6 °C and at 391.5 minutes. After one hour (*i. e.* at 451.5 minutes) the temperatures were 40.7 and 33.6 °C for OM and PW, respectively. This corresponds to 11.9 °C per hour reduction for OM and a very large 19 °C per hour reduction for PW. This can be attributed to the higher thermal conductivity of PW (0.4 W/mK) compared to that of OM (0.135 W/mK), tab. 1. The mass transport does not occur in solidification (unlike melting which is dominated by convection) and the transport of heat during this phase is dominated by conduction. Both of the PCM show sharper freezing temperature intervals. The PCM having large freezing temperature interval are less suitable for thermal energy storage [20].

One has to keep in mind that the higher temperatures retained by the PCM compared to that of water in storage tank are in spite of the fact that heat from the freezing PCM is taken up by the water during this phase. In other words, the drop in water temperatures would have been much steeper in the absence of PCM.

Charging of the PCM by the hot water

Having looked at the charge and discharge pattern with respect to the time used up for the heating up of water by the ETC, it would now be interesting to understand how the hot water in the storage tank helps in charging the two PCM. Figure 2 gives the charging pattern of the two PCM against the rise in temperature of water in the storage tank which was being heated up by solar energy using the ETC array.

Figure 3 is indicative of the fact that both the PCM take up heat in almost similar patterns from the water which itself is being heated up by solar energy. The individual characteristics of the two PCM are also illustrated in the figure in that after OM has reached its melting point (55 °C), the rise in temperature looks to be faster for PW which is yet to arrive at its melting point. For example when the water temperature has reached 72.3 °C, the OM temperature is at 60.1 °C. At this time the PW temperature is at 64.1 °C. The OM reached its melting point when the water temperature was around 65.4 °C. Whereas at this instant, the PW has reached a temperature of 57.8 °C which is about 3° below its

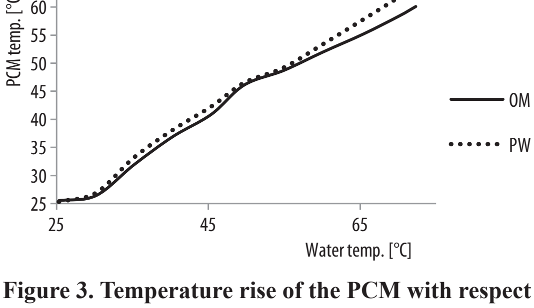

Figure 3. Temperature rise of the PCM with respect to the temperature of hot water charging them

melting point. On an average, the PW is able to maintain a higher temperature than OM during the charging phase owing to its higher thermal conductivity. The PW seems to be reaching its melting point when the water temperature was around 70 °C. This illustrates the difference in the charging patterns of the two PCM when being allowed to be charged in the same surroundings.

Heating of the water by the discharging PCM

As the two PCM have been completely melt and the water temperature reached its maximum value of around 72 °C, the hot water supply to the storage tank was stopped. From this time onwards both the water and the PCM will start losing heat thereby showing a reduction in the temperatures. In this process, the PCM will go into their solid phases in due course. The idea of the experiment was to utilize this discharging heat to keep the water in the tank warm which can be circulated through the HE system which in turn can provide heat energy to the kiln. Figure 4 gives the temperature of the water in the storage tanks plotted against the temperatures of the two PCM during their discharging phases.

The discharge graph has started from around approximately 70 °C for the PCM and water. The water temperature seems to drop almost linearly until a particular point in each case. Figure 4 shows that these points are approximately the melting points of the two PCM. Thus, the change in temperature reduction pattern of water bears a relationship with the discharging PCM. This fact was not so clear in fig. 2 where the water temperature was dropping smoothly with time. Thus, we can say that the temperature of water (which actually is the heat provider to the kiln in the night time) has significant dependence on the PCM used to store heat during the day time. The graph indicates that after freezing of PCM has started, the behavior of water temperature gets affected.

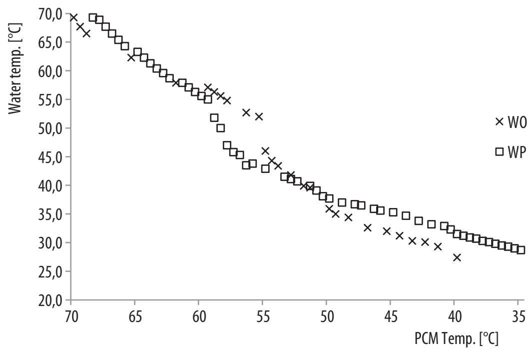

Figure 4. Water temperatures plotted against the temperatures of the PCM during their discharging phase
WO represents water temperature plotted against OM temperature and WP represents water temperature plotted against PW temperature

However, it is seen that after freezing has started, the temperature of OM has gone down only to 40 °C with which water temperature is maintained at 27 °C. In the case of PW, the same water temperature is maintained when the PW temperature has dropped down to 32 °C. The slower fall of temperature in OM than PW indicate its comparatively lower thermal diffusivity in liquid *i. e.* core portion is still in liquid phase while freezing is taking place near container surface. The question of which of these PCM would be better to maintain higher temperature of water for longer durations can be addressed by conducting these experiments by using more PCM separately. However, the fact that use of these two PCM in designing a thermal storage system using water as the heat transfer fluid is illustrated in the study.

Conclusions

The obtained results indicate that for low temperature operations like solar kiln wood drying, the PCM under investigation are suitable for development of thermal storage system in combination with heated water. The day time solar energy can be utilized to heat the stored water which can charge the PCM. In the nights, the stored heat of the PCM can be successfully utilized to keep the atmosphere inside the kiln warmer using the discharged thermal energy of the PCM. The solidification curves of the PCM suggest that both the PCM are promising materials to make thermal storage system for a solar kiln.

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