



Experimental Investigations on Thermal Storage in a Solar Dryer

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Abstract – Thermal energy storage for solar dryer has recently attracted increasing interest as the availability of solar energy is intermittent. The effectiveness of thermal energy storage using Phase Change Material (PCM) in solar dryer application was investigated in this work. A solar cabinet dryer having 3 evenly spaced trays that provide maximum heat flow with drying area of 0.5 m² (each) that caters to a family was constructed and its performance evaluated. The experiments were done on the dryer with and without thermal storage for 3 days each during the month of April when the sunshine remains considerable in Annamalai Nagar located at 11.39° N Latitude and 79.69° E Longitude. The temperature at different vital locations was recorded from 10 a.m. onwards until the cabinet temperature fell to that of the atmosphere. The mass flow rate of air during experimentation varied between 0.001-0.003 kg/s. A paraffin (n-docosane)-kerosene composite of 12.5 kg and 2:1 mass ratio was used for thermal storage in the dryer. The PCM was filled in 20 numbers of 20 mm diameter aluminum tubes having 500 mm length and 100 aluminum cans of 150 ml capacity (excluding space for phase change). The results were analysed for the variation of thermal absorption and storage based on air velocity, temperature gradient, and solar intensity. The cabinet temperature remained 25-30°C higher than that of atmosphere during mid-day. The peak heat gain fell by 18% on the days of experimentation with thermal storage due to the heat conducted by PCM pipes. On an average, the thermal efficiency of the system with thermal storage improves by 50 % of its efficiency without thermal storage unit. It was found that the dryer with thermal storage can sustain the required temperature for 3 hours after sunshine hours and then it falls gradually.

Keywords – n-docosane, paraffin, phase change material, solar cabinet dryer, thermal energy storage.

1. INTRODUCTION

In a tropical country like India, the main source of economy and livelihood is agriculture. Even though farmers are trying to increase the crop productivity, it is very difficult to preserve them due to lack of cheaper and effective technology. Thermal energy storage has been an active area of research at present. Efficient alternative energy utilization must involve energy storage to cater to the fluctuations in demand and to obtain a higher performance. Energy storage system assumes greater significance in situations dealing with intermittent supplies of input energy. The selection of thermal storage system for an application depends on factors such as storage duration, economics, temperature supply and utilization requirements, storage capacity, heat losses and space availability. Thus this experimental work has the objectives of finding the supply temperature and thermal storage duration in accordance with the dryer requirements and PCM storage space availability.

2. PHASE CHANGE MATERIAL (PCM)

A good thermal energy storage medium must remain stable with high heat capacity. The technology of solar thermal storage using sensible heating of a media called

as first generation storage systems has developed well and so being utilized commonly. The technology of latent heat based solar thermal storage has good applicability and is being developed by considerable research right now. Latent heat storage systems using phase change materials have high thermal storage capacity when compared with that of sensible heat storage materials. The PCM behavior depends on the environmental conditions of the solar system which involves thermal cycling utilizing the latent heat. Thus one of the best approaches has been to use phase change materials (PCM) for the thermal storage. Thermal energy storage system can accumulate energy as sensible heat or as the heat of fusion or a combination of both. Latent heat storage is better than sensible heat storage as it has high storage density and lesser temperature swings. PCMs can store 2-3 times more heat or cold per volume or per mass, as can be stored as sensible heat in water in a temperature interval of 20°C [21]. Thermo-chemical systems are based on breaking and reforming molecular bonds in a reversible chemical reaction. The stored heat depends on the quantity of storage material, the endothermic reaction, and the extent of conversion [15].

To diversify PCMs, several composites that can undergo phase change cycle have been developed with slight modifications of their original properties [26], [34]. Depending on the applications, first, the PCMs should be selected based on their melting temperature. Materials that melt below 15°C are used for storing coolness in air conditioning applications, while materials that melt above 90°C are used for absorption refrigeration. All other materials that melt between these

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two temperatures can be applied in solar heating and for heat load leveling applications. These materials represent the class of materials that has been studied most [32].

3. PARAFFIN WAX

Paraffin is one of the most preferred thermal storage materials. Paraffin can absorb large amounts of heat during charging without increasing temperature significantly. When the ambient temperature drops below the phase change temperature, it solidifies, releasing stored heat.

Based on an extensive study by Lane *et al.* [2] there are about 20,000 substances with the melting point in the range 10-90°C. The majority of them was abandoned for application due to the improper melting point, melting with decomposition or lack of essential reference data [12]. Among these PCMs, paraffin has shown outstanding performance for application in low-temperature thermal energy storage systems for solar heating and cooling [9], [10]

Several researchers have investigated on thermal storage using paraffin. Zalba *et al.* [4] have discussed various experimental techniques used to determine the behavior of storage materials in melting and solidification, which includes thermo physical properties such as melting point, heat fusion, thermal conductivity and density. Rathod and Banerjee [31] studied the thermal behavior of a paraffin and found that inlet temperature had a higher effect on the heat fraction during the PCM melting than the mass flow rate. Miro *et al.* [35] proposed a methodology to select a suitable PCM for a thermal storage application. The selection of a PCM must be based on the phase change thermal range, enthalpy, specific heat, and thermal cycling stability. Klux *et al* [18] studied the feasibility of storing solar energy using phase change materials in small cylinders. They found that the PCM containers are well suited for thermal storage applications. Researchers developed several composite materials to improve the thermal conductivity of paraffin based phase change materials [24], [25]. Recently, several works [7], [11], [13] have been carried out to study the thermal characteristics of paraffin. Those studies have found paraffin as a good storage material.

Paraffin have been predominantly used as PCM because of the following reasons: easy availability, large latent heat per unit volume, low melting temperature, low vapor pressure and small volume changes on phase transformation [19]. Paraffin has stable properties as it does not show any change in thermal properties even after 1000s of thermal cycles [6]. Paraffin wax is safe, non-reactive and compatible with all metal containers [1], [3], [7]. PCM melts and solidifies congruently, and the melting front moves from the top to the bottom of the PCM container whereas the solidification front moves from bottom to the top along the axial distances in the PCM container [22]. Two geometries commonly employed as PCM containers are the rectangular and cylindrical containers [16]. In particular, cylindrical containers accounts for more than 70% in all the used

low-temperature thermal energy storage systems [17]. Encapsulation is one of the methods to improve the thermal performance of the PCM by minimizing the radial distance between the thermal conductivity enhancement material (container material) and the paraffin. Thus the paraffin wax becomes a core enveloped within a solid shell structure [14], [28], [29]. The shell of capsules protects the core material from interacting with the heat transfer fluid whereby it enhances the stability of the PCMs, while potentially improving the heat transfer efficiency because of the large surface-to-volume ratio [28]. This substantially enhances the heat transfer performance up to 37% as compared to pure paraffin wax during constant heat flux tests [29].

Advantages of using paraffin are high heat storage capacity, low storage temperature, isothermal operation and lesser storage space [6,8]. The results from previous works [8, 13] indicate that paraffin based PCMs can be adjusted to have a melting point within the range suitable for applications related to drying of fruits and vegetables.

Docosane is a saturated aliphatic hydrocarbon which is not affected by aqueous solutions of acids, alkalis, most oxidizing agents, and most reducing agents. It has the chemical formula $C_{22}H_{46}$ ($CH_3(CH_2)_{20}CH_3$). This belongs to the group of compounds that are characterized by straight or branched carbon chains with the generic formula $C_{(n)}H_{(2n+2)}$, which means that the compound contains only single bonds between the carbon atoms and contain the maximum possible number of hydrogen atoms per carbon atom. Its physical form varies with molecular weight. The solid form of this saturated hydrocarbon known as alkane or paraffin is waxy and soft. Since the present work is aimed at the development of paraffin based thermal storage unit for a solar cabinet dryer, it is focused on the determination of the extended time of drying due to thermal storage after peak sunshine hours. This research work falls in an area of international interest as it deals with energy conservation and efficient use of solar energy.

4. EXPERIMENTAL SET UP OF THE SOLAR DRYER WITH PCM AS HEAT STORAGE

The objective of a solar cabinet dryer is to supply the product with more heat than that of ambient air by increasing the vapor pressure of moisture held in the crop and decreasing the relative humidity of the air thus increasing its moisture carrying capacity and ensuring low equilibrium moisture content. Drying rate depends on the temperature and relative humidity of the surrounding air and the properties of the material to be dried. Some of the crops commonly grown in developing countries are better suited for solar drying as case hardening and other damages are less at low temperatures.

Solar dryers are much suitable for tropical countries as the available solar energy is sufficient to serve the heat requirements. Natural-convection dryers don't require mechanical or electrical power, simple in

construction, easy to maintain and inexpensive. Mold formations are lesser in solar drying process [14].

The use of PCM as an energy storage medium is now a worldwide considered option with a number of advantages. The combination of solar energy and the use of PCMs in any thermal energy system may result on alleviating the problem of pollution due to the reduced use of fossil fuel based energy sources. Also, the energy demand can be managed by storing when it is available and using it later [19]. Thermal storage depends on the capillary forces and surface tension forces that act on the PCM during the incorporation [33].

Solar dryer used in this experiment was of cabinet type having 3 trays with drying area of 0.5 m² (each). The trays were evenly spaced to allow maximum heat flow. The experimental setup consists of a solar dryer which can be coupled to a solar collector which acts as an auxiliary heat recovery unit. Both the components have PCM based thermal storage compartments at their base through which the incoming air enters below their absorber plates. The whole structure is insulated to minimize heat loss.

The PCM mixture of paraffin to kerosene having mix ratio of 2:1 was used so as to maintain the melting point in the desired range. The composite PCM has been found as fit for solar thermal storage in the cabinet dryer due to its form-stable property, usability, suitable

thermal conductivity, good melting temperature and satisfying latent heat storage capacity. Two types of the container were used to hold the PCM which was 20 numbers of 20 mm diameter aluminum tubes with 500 mm length and 100 aluminum cans of 50mm diameter and 120 mm length each having 150 ml capacity (excluding space for phase change). The total quantity of PCM used was 12.5 kg.

Paraffin based PCMs have low thermal conductivity and leakage of liquid complications [23], [30]. Hence the cans and tubes were partially filled (cans with 10 kg of PCM and tubes with 2.5 kg of PCM - 65% by volume) with PCM to allow enough space for phase change thus avoiding leakage. The leakage of molten composite PCM depends on solid-liquid phase change and movement of the interface due to capillary and surface tension forces. The type and quantity of PCM were arrived based on the temperature requirements to suit the storage space availability.

The PCM tubes were placed directly under the aluminum sheet which acted as the main solar energy absorber while the PCM cans were placed on the floor of the solar collector as shown in Figures 1 and 2. During the test, the PCM containers were placed or removed (as required) to suit the experiments with and without thermal storage. The quantity of PCM remained the same.

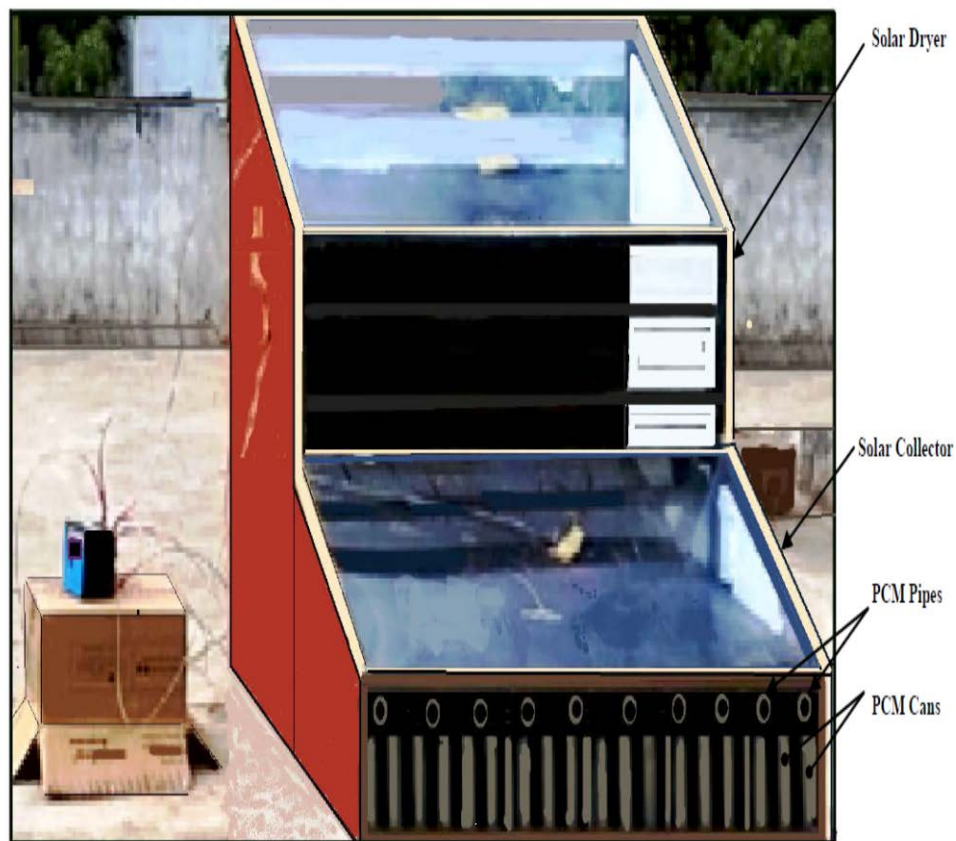


Fig.1. Dryer with thermal storage.

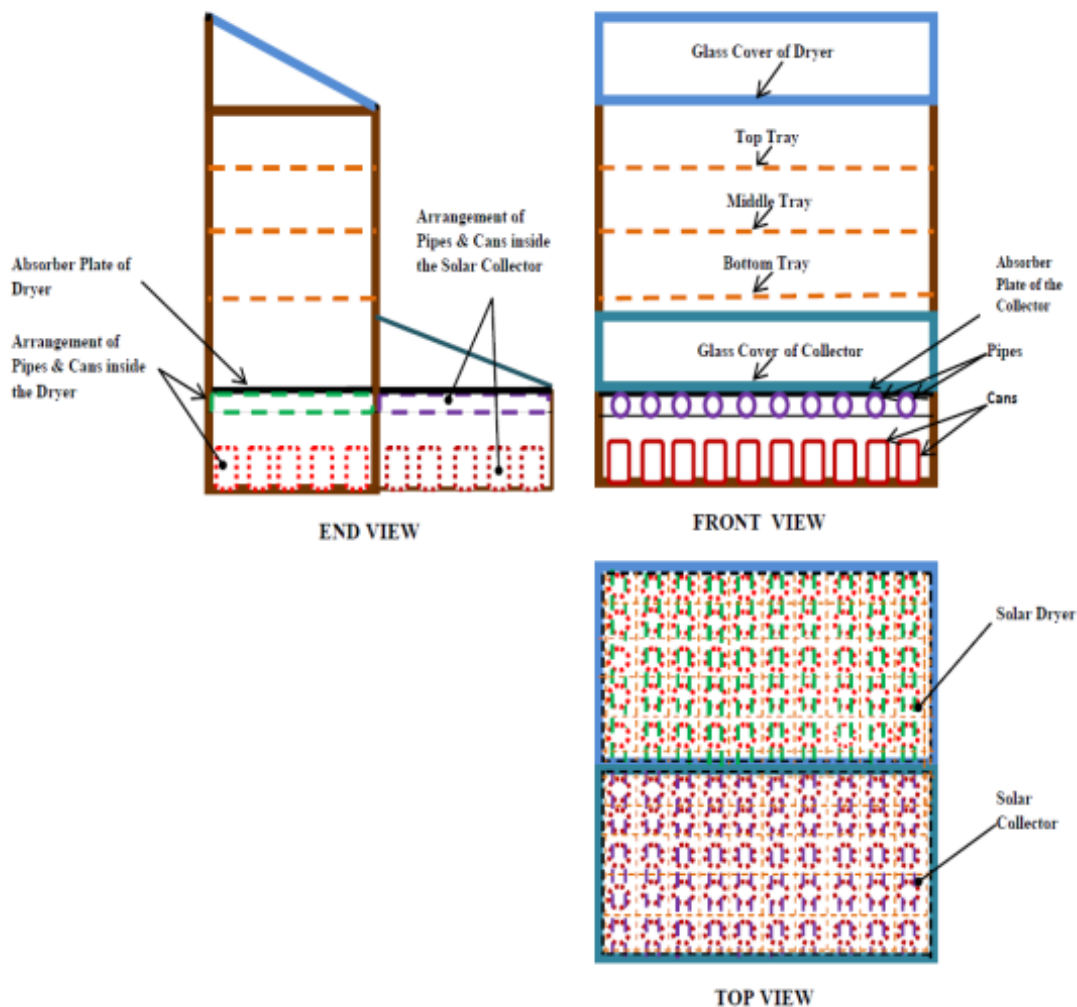


Fig. 2. Illustration of arrangement of PCM cans and tubes in the thermal storage unit.

5. RESULTS AND DISCUSSIONS

Experiments were conducted on the dryer to find out the difference in temperature of its cabinet with and without thermal storage. It was tested in no load condition. The experiments were conducted in the month of April when the sunshine remains considerable in Annamalai Nagar located at 11.39° N Latitude and 79.69° E Longitude at an altitude much closer to sea level. Experimental observations were recorded from 10 am onwards until it reached the atmospheric condition. Experiments were done for 6 consecutive days. The dryer was kept without thermal storage from day 1 to day 3 for 3 days and the temperature at different vital locations was recorded from 10 a.m. onwards until the cabinet temperature falls to that of atmospheric condition. Similarly, the experiments were done on the dryer with thermal storage from day 4 to day 6 for 3 days.

In this study, a paraffin-kerosene composite material was used as the thermal storage material in the solar cabinet dryer. This PCM is economical as well as highly effective. The paraffin used in this work was n-docosane. Paraffin (n-docosane) is available on the market commercially. Its melting point can be adjusted to the required level by mixing kerosene suitably. It has a high latent heat of fusion of around 194 kJ/kg. To establish the performance of the PCM, mixture of

paraffin and kerosene with the mass ratio of 2:1 which has desired temperature range was tested. The mixture was filled into aluminum pipes and aluminum cans. The PCM in the cans was allowed to solidify completely. The experiments were focused on the melting and solidification of the mixtures. The PCM mixture near the can wall solidified sooner than the mixture at the centre of the can. The mix ratio suited well for the application since it melts at a temperature much suitable for solar dryer application in this geographical area. The absorber plate, cans and pipes were made of aluminum. The heat storage unit was arranged under the absorber plate. It consisted of aluminum pipes and cans. The pipes were arranged at the bottom side of the absorber to increase heat transfer. The dryer and thermal storage unit were insulated using polyurethane foam. The mass flow rate of air during experimentation varied between 0.001-0.003 kg/m²s. The use of thin PCM cans and pipes allowed the storage and dissipation of thermal energy from the composite phase change material relatively quickly when compared with the normal phase change timing of a paraffin based composite. Thus it was clear that the thickness of the container plays a key role in improving the thermal diffusivity and the storage capacity of the phase change material.

Experimental and theoretical convection rates were calculated and compared in order to ensure the accuracy of experimental outcomes. The effect of thermal storage was tested by determination of convective heat transfer coefficient using appropriate Nusselt number correlations based on geometric parameters and experimental results. Conduction and radiation heat transfer effects were neglected and the convective heat transfer in the direction normal to the surface was taken into account. The physical properties of the solid and fluid phases were assumed as same and constant over the entire temperature range. The volume changes were neglected. When phase change occurred both solid and liquid portions were present which were separated by a moving interface between them. It was assumed that the solid and liquid phases are in local thermal equilibrium and the length of the test portion was long enough to assume that it was a semi-infinite medium. The heat transfer characteristics of the thermal storage unit were analyzed using standard heat transfer correlations. Physical properties of the fluid were considered based on the bulk mean temperature at atmospheric pressure. The heat transfer coefficient was considered constant throughout the length. The experimental convection rate was calculated based on Newton's law of cooling. Theoretical convection rate was calculated based on heat

transfer coefficients found through non-dimensional approach by Nusselt number correlations.

During solidification process, the solidification front is moving towards outer surface whereas heat transfer occurs in the opposite direction inwards through the already solidified portion. Thus, during solidification the thermal resistance of wax increases. Hence it is considered as heat transfer through a semi-infinite surface. This has been proven by the variations in temperature gradient during the discharging process. The fluid motion through the absorber has been considered as flow over a flat plate and width of the absorber has been chosen as the characteristic length as the flow occurs in that direction. During the phase change, the wax melts over a temperature range and it is difficult to find the fraction of wax that melts at a particular temperature. Hence it is assumed that the wax melts linearly over the entire melting temperature range. Thus the phase change occurs in fractions and the process is non-isothermal. The pipes and cans are considered as long horizontal cylinders undergoing natural convection. The Rayleigh number has been calculated based on Grashoff number and Prandtl number. The Nusselt numbers have been correlated using Rayleigh number.

Table 1. Nusselt number correlations used for theoretical analysis.

| Component | Average Nusselt Number | Restrictions |
|----------------|--|----------------------------|
| Absorber Plate | $0.54 * (Ra_L^{0.25})$ | $10^4 \leq Ra_L \leq 10^7$ |
| Pipes and Cans | $\left(\frac{(0.6) + 0.387 * (Ra_D^{0.167})}{\left(1 + \left(\frac{0.559}{Pr}\right)^{0.568}\right)^{0.3}} \right)^2$ | $Ra_D \leq 10^{12}$ |

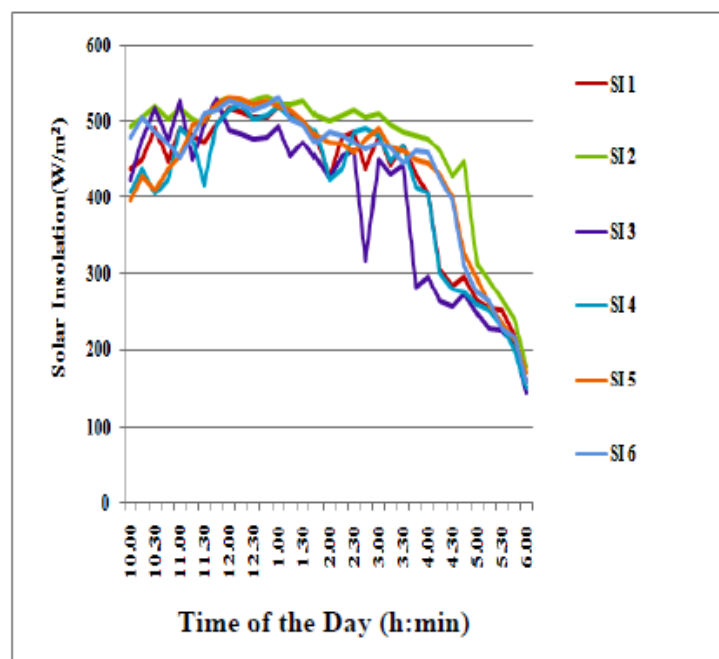


Fig. 3. Solar insolation on the days of experimentation.

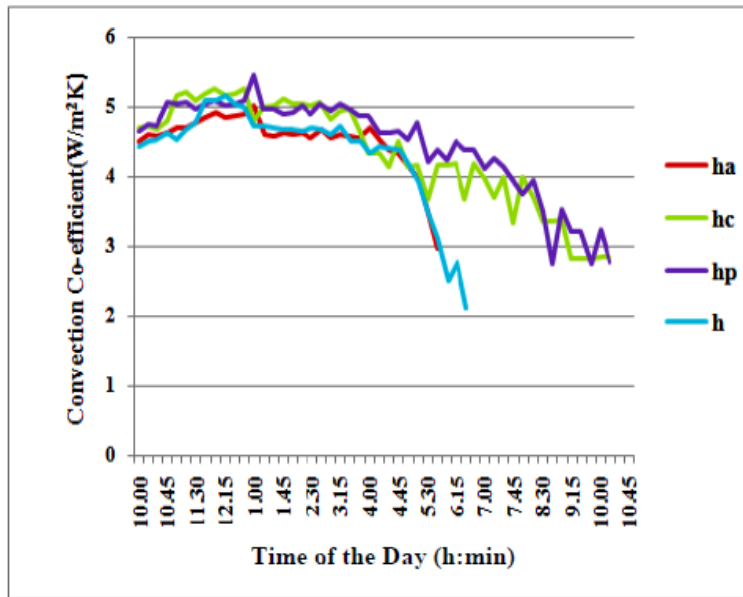


Fig. 4. Time Vs convection co-efficient on a typical day with and without thermal storage.

Figure 3 shows the variation of solar insolation with respect to time during the 6 days of experimentation. The curves SI 1 to SI 6 indicate the solar insolutions observed from day 1 to day 6 of experimentation. From the plot, it can be found that the insolation had a considerable value from 10 am to 4 pm, thereon it fell gradually and extended up to 6 pm. The peak insolation of around 525 W/m² had been recorded around 12 noon and the minimum value was around 150 W/m² around 6 p.m.

Figure 4 shows the variation of convection coefficient of absorber plate (h_a), PCM can (h_c) and PCM pipe (h_p) on a typical day of experimentation. The convection coefficient without thermal storage (h) has been shown separately. The convection coefficient of pipe varied between 5.45W/m²K and 2.75 W/m²K. Similarly, the convection coefficient of can varied

between 5.25 W/m²K and 2.77 W/m²K. The convection coefficient of absorber plate varied between 5.17 W/m²K and 2.95 W/m²K on the day when the observations were made without thermal storage. Whereas, the convection coefficient of absorber plate varied between 5.02 W/m²K and 2.12 W/m²K on the day when the observations were made with thermal storage.

The reduction in convection coefficient of the absorber, when compared with that of the PCM pipes and cans had been due to the heat conducted to the PCM pipes which were located below the absorber plate and touching the lower surface of it. As the cans were not in direct contact with the absorber or pipe they are getting only the heat convected to the bottom side. But they played a major role in reducing the bottom side heat loss.

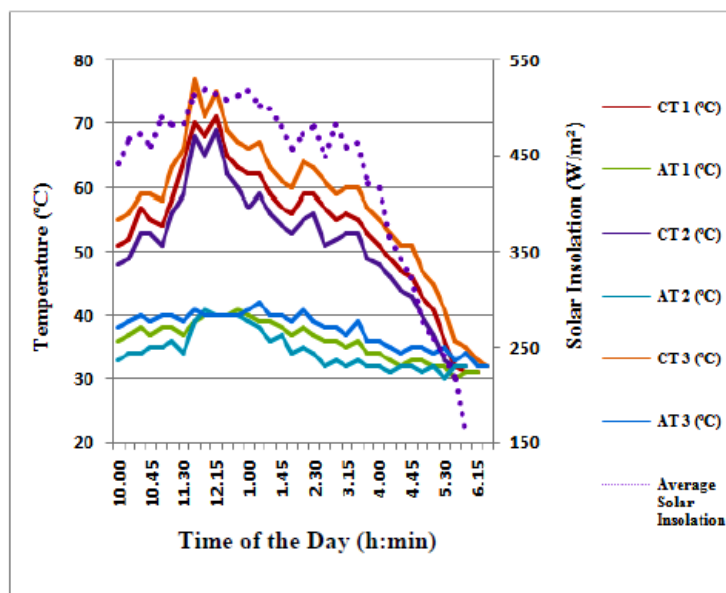


Fig. 5a. Time Vs temperature and average solar intensity on the days of experimentation.

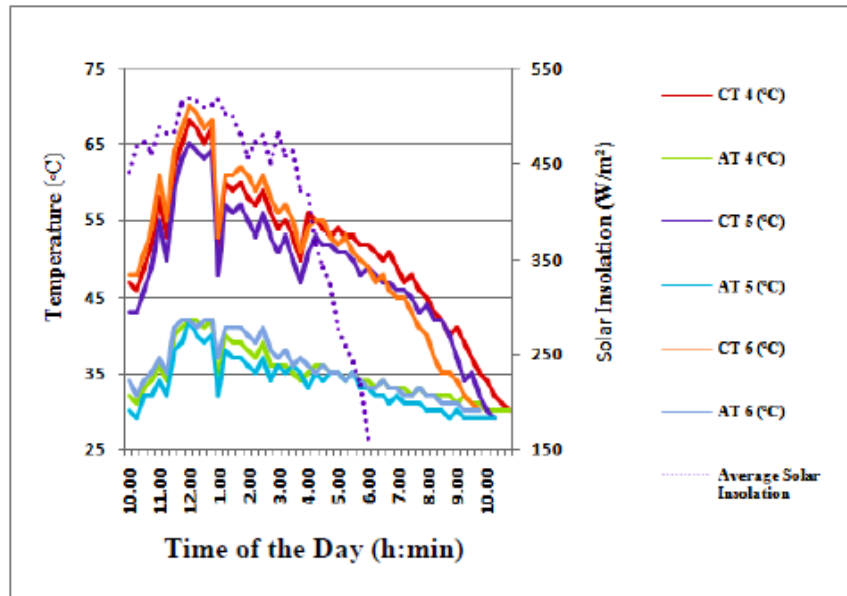


Fig. 5b. Time Vs temperature and average solar intensity on the days of experimentation.

Figures 5a and 5b shows the variation of atmospheric temperature and cabinet temperature with respect to time on the experimental days. The curves CT 1 to CT 3 indicate the cabinet temperatures from day 1 to day 3 and curves AT 1 to AT 3 indicate the atmospheric temperatures from day 1 to day 3 of experimentation without thermal storage. Likewise, the curves CT 4 to CT 6 indicate the cabinet temperatures from day 4 to day 6 and curves AT 4 to AT 6 indicate the atmospheric temperatures from day 4 to day 6 of experimentation with thermal storage. During this time the atmospheric temperature varied between 29°C and 41°C. Meanwhile, the cabinet temperature varied between 29°C and 75°C. Atmospheric temperature of all

the 6 days remained almost same without much variation. The temperature of the cabinet had been found as considerably higher than that of atmosphere but it fell with the declination of solar insolation on the days without thermal storage. Whereas it remained higher by 10-20°C even after peak sunshine hours on the days of experimentation with thermal storage. The variation of atmospheric air flow because of velocity changes created mass flow rate variations marginally and due to it, uneven temperature rise occurred inside the solar drier. As the temperature deviations were not so considerable it did not affect the overall performance of the dryer.

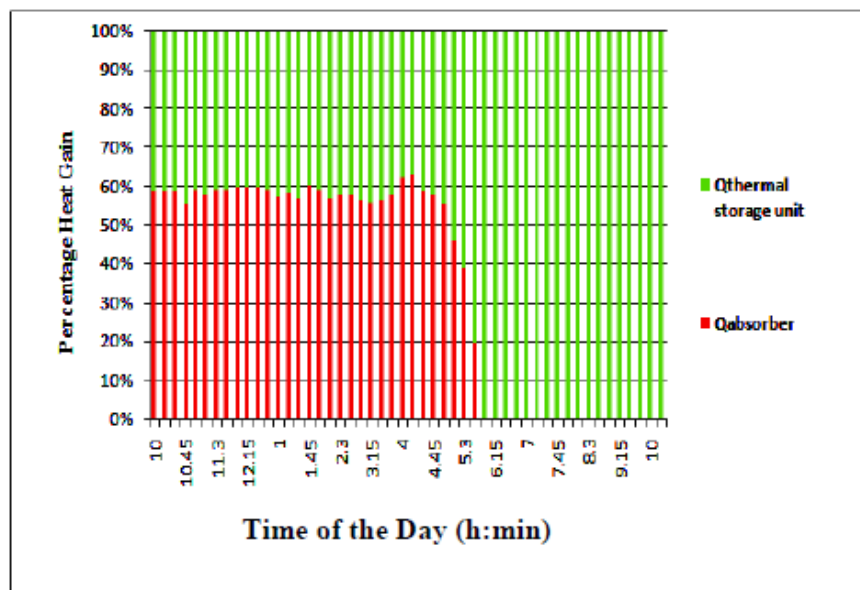


Fig. 6. Time Vs percentage heat gain on a typical day.

Figure 6 shows the percentage of heat gain from the thermal storage unit and absorber out of the cumulative heat gained by the dryer on a typical day during experimentation. It is clear from the plot that up to 60% of heat gain during the peak sunshine hours is from the absorber and the balance of up to 40% is from the PCM cans and pipes. Instantaneous heat gain depends on the thermal lag. The thermal lag or time lag

depends on the time difference between peak temperature of the outside environment and the peak temperature inside the dryer cabinet. As the solar insolation declines the thermal energy dissipated by the absorber reduces and the PCM dissipates the stored thermal energy considerably even after the sunset thus extending the drying process for hours.

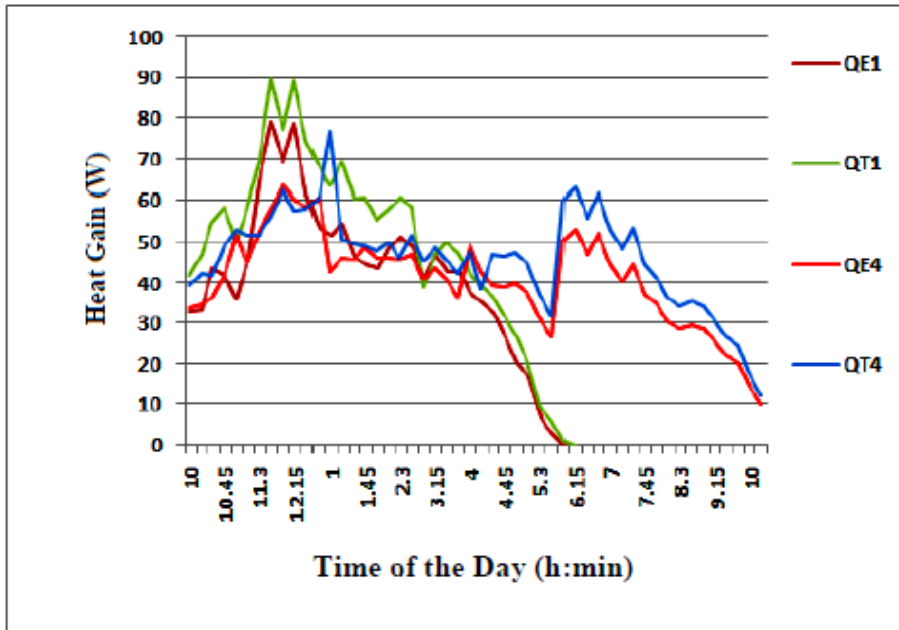


Fig. 7. Time Vs experimental and theoretical heat gain with and without thermal storage.

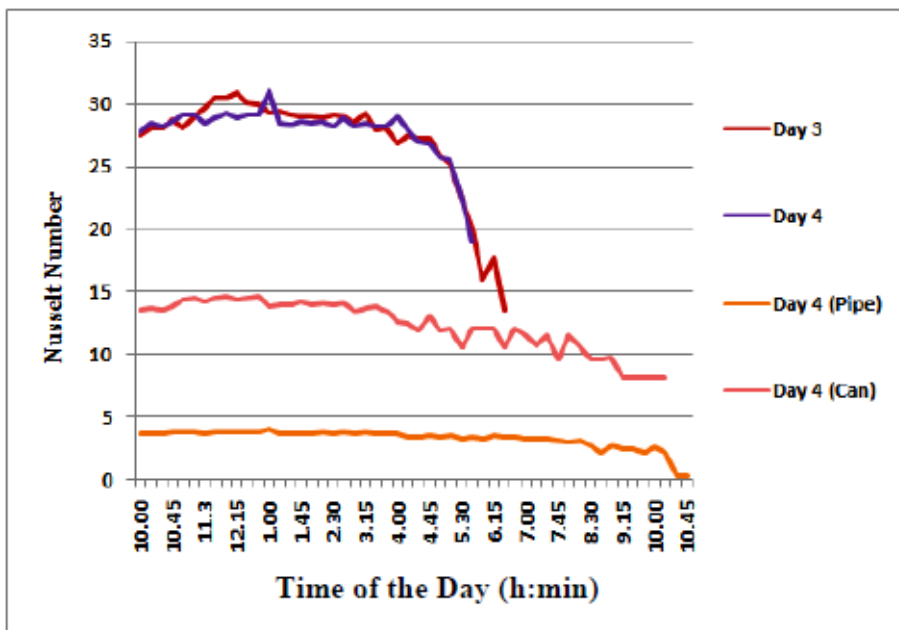


Fig. 8. Time Vs Nusselt number variation on a typical day of experimentation.

Figure 7 shows the heat gain in the dryer with respect to time on the days of experimental analysis. Curve QE1 indicates the experimental heat gain on the first day of investigation without thermal storage. Similarly, QE4 indicates the experimental heat gain on the fourth day of investigation with thermal storage.

Curve QT1 indicates the theoretical heat gain on the first day of investigation without thermal storage. Likewise, curve QT4 indicates the theoretical heat gain on the fourth day of investigation with thermal storage. The formation of heat flow network is the key factor for thermal conductivity in the phase change material.

The melting time of the PCM depends on the change in thermal conductivity of the composite material based on the heat flow network. It has been found that the peak heat gain was around 90 W on the day without thermal storage when compared with 76 W for the day with thermal storage. This may be due to the heat conducted by PCM pipes that were fixed below the absorber plate touching its bottom surface. But the heat gains extended for hours after peak sunshine on a day when the experimental set up had thermal storage. Even though the heat gain came down for some time due to non-availability of considerable solar insolation after 4 pm, it picked up due to the dissipation of stored latent heat from the storage material. No heat gain had been obtained by 6 pm on the days when experiments had been done without thermal storage.

Figure 8 shows the variation of Nusselt number with respect to time on 3rd and 4th day of experimentation. The curve Day 3 and Day 4 shows the

variation of Nusselt number for heat convected from the absorber plate on the 3rd day without thermal storage. The curve NU4 shows an almost similar trend for the Nusselt numbers of heat convected from absorber on the 4th day with thermal storage. Both the curves clearly show the rise and fall of convection from absorber during the day time. The curves Day 4(Pipe) and Day 4(Can) indicate the Nusselt number variation for convection from pipes and cans on the 4th day of experimentation with thermal storage which extended even after hours of peak sunshine. This indicates that the thermal energy has been partially dissipated from PCM with the decline of solar insolation. The Nusselt number values of the pipes are greater than that of the cans. This indicates that the thermal energy dissipated by PCM pipes that are in contact with the bottom side of the absorber are higher when compared with the cans placed at the base of the storage unit to avoid bottom side thermal losses.

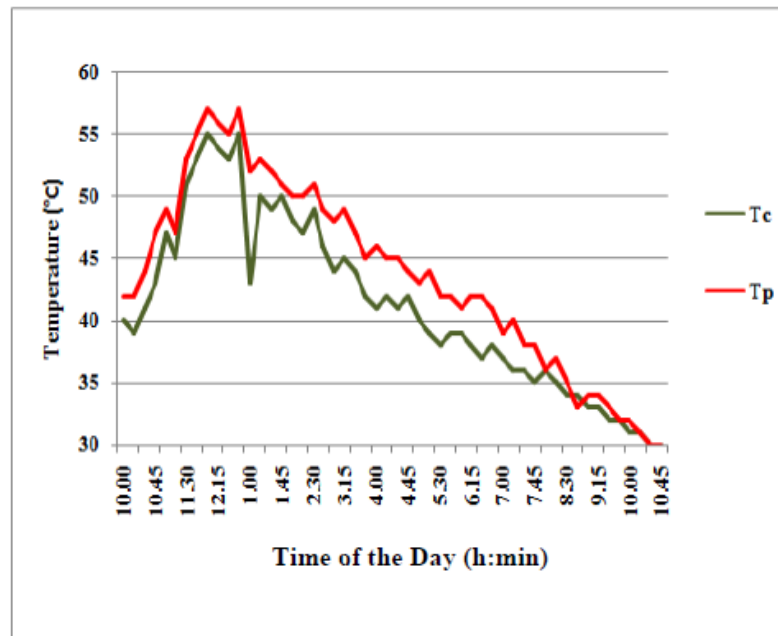


Fig. 9. Time Vs temperature of PCM cans and pipes in the thermal storage unit.

Figure 9 shows the variation of temperature with respect to time for the PCM cans (Tc) and pipes (Tp) on a typical day of experimentation. The rise in temperature between 10 am and 12.15 pm indicates the thermal charging process, thereafter the dissipation of heat from PCM started and extended for hours after the decline of sunshine. The melting time of PCM depends on the mass flow rate and inlet temperature of air, the heat transfer fluid. It has been clear from the experimental results that the thermal storage process gets affected by the motion of the solid–liquid interface of the PCM with time along axial and radial directions of the thermal storage unit because of resulting variations in the thermal resistance at different locations of the PCM container. The heat transfer at the interface depends on the instantaneous location of the moving boundary. The experimental findings indicate the gradual decrement of instantaneous heat storage until it reaches a constant value. The heat storage depends on the solar exposure

with respect to time and instantaneous inlet temperature. It is also clear from the experimental outcomes that the thermal lag depends on the duration of heat flow cycle based on the thermal mass of the storage material. The sudden undulations in the curves are indications of the partial phase change that occurred during the day with fluctuations in atmospheric temperature and mass flow rate of air.

The pipes and cans arranged below the absorber plate stored heat dissipated to the bottom side thus reducing the bottom side thermal loss. It has been found that the pipes which were arranged at the bottom side of absorber plate get a good amount of heat through conduction and convection whereas the cans arranged at the bottom were getting lesser heat only through convection as there was no contact with the absorber. Also, the comparatively smaller cross-section of pipes enhanced the heat transfer effect.

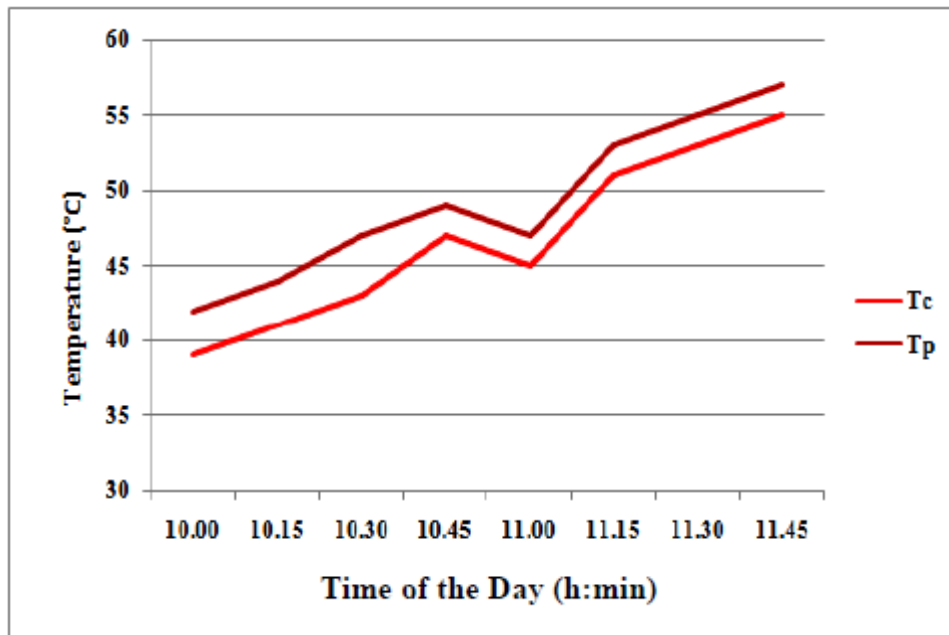


Fig. 10. Phase change during charging process.

Figure 10 shows the partial phase change that occurred in the PCM cans and pipes during the charging process. The curves T_c and T_p indicate the temperature variations in the PCM cans and pipes with respect to time respectively. The sudden dip and rise of temperature between 42°C and 53°C indicate the heat absorption by PCM and resulting phase change. It is clear from the observations that the system performance purely depended on the availability of solar energy as the wall temperatures reduced with the decline of solar intensity accompanied by entry of cold inlet air from the surrounding. The PCM temperature increased until it reaches the melting point, and it settled or slowly reduced until the wax melts fully. During this time, wax phase change ensured high thermal energy storage in addition to sensible heat it stored after melting. The liquid wax temperature started to increase above melting point during the charging process. After 12.15 pm the discharging process started, the PCM temperature reduced slowly thus losing its sensible heat. At this point, it reached phase change, settled for some time and the solidification of wax occurred. After this, the

temperature reduction was considerable due to drop in solar intensity and passing of the cold air. In general, paraffin consists of a combination of straight-chain hydrocarbons which have melting point between $23\text{--}67^\circ\text{C}$. The melting temperature and heat of fusion depends on the average length of the hydrocarbon chain. The experimental outputs indicate the variation of thermal absorption and storage depending on air velocity, temperature gradient, and solar intensity.

It has been noticed that the air temperature reached its peak around noon. Also, the cabinet temperature remained $25\text{--}30^\circ\text{C}$ higher than that of atmospheric temperature during mid-day. Because of the heat released from PCM during late evening hours, the cabinet temperature remained considerably higher even 3 hours after peak sunshine hours. This indicates the ability of storage unit to retain the thermal energy. The PCM worked as a damper by leveling the temperature and sustaining it close to its melting temperature. This aspect of stabilizing temperature near the melting point proves beneficial for solar dryer application.

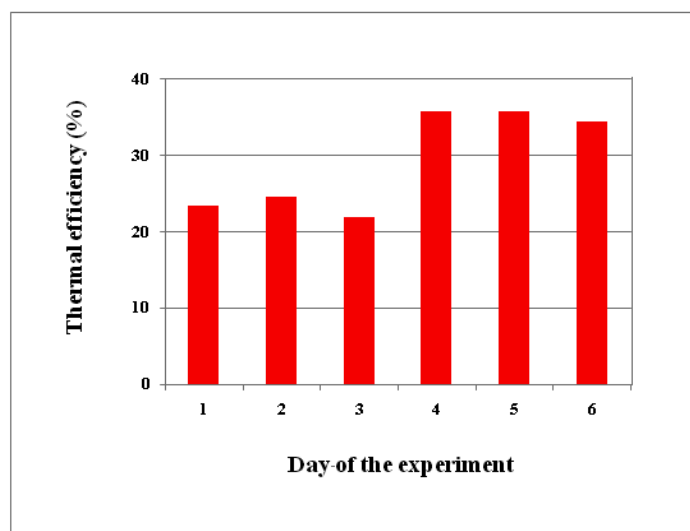


Fig. 11. Average thermal efficiency of the system.

Figure 11 shows the average system thermal efficiency for each day of the experimentation. The efficiency has been found as less than 30% on the first three days when the system performance has been investigated without thermal storage. The efficiency has been found as more than 30% on the days of experimentation with thermal storage. On an average the thermal efficiency of the system with thermal storage improves by 50% of its efficiency without thermal storage unit.

6. CONCLUSIONS

The following conclusions have been arrived based on the analysis of experimental results:

The paraffin n-docosane is suitable for thermal storage in a solar cabinet dryer. The PCM released its sensible heat very rapidly, and longer time was needed to transfer the latent heat due to frozen layer formation. As the solidification extended, the amount of latent heat transferred to heat transfer fluid became smaller. The melting and solidification of PCM occurred in a phased manner and so heat transfer cycle extended for longer duration. The PCM mixture near the can and pipe walls solidifies sooner than the mixture at the centre of the can. This is due to the thermal resistance offered by the PCM. During solidification process, the solidification front is moving towards outer surface whereas heat transfer occurs in the opposite direction inwards through the already solidified portion. Thus the thermal resistance of wax increases. The composite PCM mix ratio of 2:1 suited well for the application since it melts at a temperature much suitable for solar dryer application in this geographical area. During the phase change the wax melts over a temperature range and it is difficult to find the fraction of wax that melts at a particular temperature. Thus the phase change occurs in fractions which have been proven by the variations in temperature gradient during the thermal cycle. The PCM cans arranged at the base store the heat convected to the bottom side from the absorber thus reducing the bottom side heat loss. The variation of atmospheric air flow because of velocity changes created mass flow rate variations marginally and due to it, uneven temperature rise occurred inside the solar dryer.

It had been found that much of the heat gained by the working fluid (air) during the peak sunshine hours was from the absorber thereafter it decreases and the PCM dissipates the stored thermal energy. The reduction of peak heat gain on a day when the experiments were conducted with thermal storage is due to the heat conducted by PCM pipes that were fixed below the absorber plate touching its bottom surface. The heat gain after peak sunshine hours comes down for some time due to non-availability of solar insolation then it picks up due to the dissipation of stored latent heat from the thermal storage material. The partial phase change of the storage material occurs due to the fluctuations in atmospheric temperature and mass flow rate of air. The density and specific heat of the composite material can be adjusted to suit the thermal capacity requirements of the solar dryer by adjusting the mix ratio thus reducing

heat loss to the environment. Thus heat entering the storage unit can remain for several hours until it flows out to the cool incoming air after sunset provided conducive weather conditions prevail. It has been found that the pipes which were arranged at the bottom side of absorber plate get a good amount of heat through conduction and convection whereas the cans arranged at the bottom were getting lesser heat only through convection as there was no contact with the absorber. Also, the comparatively smaller cross-section of pipes enhanced the heat transfer effect.

The experimental outputs indicate the variation of thermal absorption and storage depending on air velocity, temperature gradient and solar intensity. Because of the heat released from PCM during late evening hours, the cabinet temperature remained considerably higher even 3 hours after peak sunshine hours. This indicates the ability of storage unit to retain the thermal energy. The PCM worked as a damper by leveling the temperature and sustaining it close to its melting temperature. This aspect of stabilizing temperature near the melting point proves beneficial for solar dryer application. Thus this paraffin based composite material can be considered as one of the efficient materials suitable for low-cost thermal storage in a solar cabinet dryer.

REFERENCES

- [1] Abhat A. 1983. Low temperature latent heat thermal energy storage: heat storage materials. *Solar Energy* 30 (4): 313-331.
- [2] Lane G.A. 1983. Solar heat storage: latent heat materials, background and scientific principles. *Vol. I. Florida: CRC Press Inc.*
- [3] Himran S., Suwono A. and Mansoori G.A., 1994. Characterization of alkanes and paraffin waxes for application as phase change energy storage medium. *Energy Source* 16:117-28.
- [4] Zalba B., Marin, J.M., Cabeza L.F. and Mehling H., 2002. Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. *Applied Thermal Engineering* 23:251-283.
- [5] Dincer I. and M.A. Rosen. 2002. *Thermal energy storage, Systems and Applications*. John Wiley & Sons, Chichester UK.
- [6] Sari. 2004. Form stable paraffin/high density polyethylene composites as solid-liquid phase change material for thermal energy storage: preparation and thermal properties. *Energy Conversion & Management* 45: 2033-2042.
- [7] So-namting W., Jareonvai A. Pisut A. and Holasut K., 2005. *Scaling up a herb solar energy dryer prototype for agricultural product drying application*. Industrial Research Project for Undergraduate students (IRPUS): I4813012 (unpublished). Khon Kaen University, Thailand.
- [8] Sharma S.D. and K. Sagara. 2005. Latent heat storage and systems a review. *International Journal of Green Energy* 2:56-62.

- [9] Arkar C., Vidrih B. and Medved S., 2007. Efficiency of free cooling using latent heat storage integrated into the ventilation system of a low energy building. *International Journal of Refrigeration* 30: 134-143.
- [10] Benmansour A., Hamdan M.A. and Bengueuddach A., 2006. Experimental and numerical investigation of solid particles thermal energy storage unit. *Applied Thermal Energy* 26: 513-518.
- [11] Srichompoo T., Mounsumpaw T.; Chaiamnant A.; and Holasut K., 2007. *Phase change material for retaining heat energy in solar dryer*. Industrial Research Project for Undergraduate students (IRPUS): I250C13007 (unpublished). Khon Kaen University, Thailand.
- [12] Felix Regin A., Solanki S.C. and Saini J.S. 2008. Heat transfer characteristics of thermal energy storage system using PCM capsules: A review. *Renewable and Sustainable Energy Reviews* 12: 2438-2458.
- [13] Holasut K., Wongvijitsook W., Kerpimai V. and Tunritarj S., 2009. Prolonging heat energy storage in a solar dryer by using suitable PCM. The 1st National Conference on Industrial and Research. March 27-29. 5th floor Siam Paragon Hall, Thailand (in Thai). Project for undergraduate Students: IRPUSCON-01.
- [14] Jegadheeswaran S. and S.D. Pohekar. 2009. Performance enhancement in latent heat thermal storage system: A review. *Renewable and Sustainable Energy Reviews* 13: 2225-2244.
- [15] Eze J.I. 2010. Evaluation of the efficacy of a family sized solar cabinet dryer in food preservation. *American Journal of Scientific and Industrial Research*: 610-617.
- [16] Agyenim F., Hewitt N., Eames P.C. and Smyth M. 2010. A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage systems (LHTESS)", *Renewable and Sustainable Energy Reviews* 14: 615-628.
- [17] Zhang P. Xia L. and Wang R.Z., 2011. The thermal response of heat storage system with paraffin and paraffin/expanded graphite composite for hot water supply. *World Renewable Energy Congress* 2011-Sweden. 8-13th May.
- [18] Klux S.A., Sane N.K. and Gawali B.S., 2011 Experimental investigation of phase change of paraffin wax inside a capsule. *International Journal of Engineering Trends and Technology* 2. 67-71.
- [19] Karunamurthy K., Murugumohankumar K., and Suresh S., 2012. Use of CuO nano-material for the improvement of thermal conductivity and performance of low temperature energy storage system of solar pond. *Digest Journal of Nanomaterials and Biostructures* 7(4): 1833- 1841.
- [20] Kokate D.H., Ghorpade S.R., Deshmukh S.P. and Pandit A.B., 2012. Thermal energy storage: its prospects of demand side energy management. *International Journal of Innovative Research & Development* 1(7): 277-286.
- [21] Rai A.K. and A. Kumar. 2012. A review on phase change materials and their applications. *International Journal of Advanced Research in Engineering and Technology* 3(2): 214-225.
- [22] Jesumathy S.P., Udayakumar M. and Suresh S., 2012. Heat transfer characteristics in latent heat storage system using paraffin wax. *Journal of Mechanical Science and Technology* 26(3): 959-965.
- [23] Oya T., Nomura T., Okinaka N., Akiyama T., 2012. Phase change composite based on porous nickel and erythritol. *Applied Thermal Engineering* 40: 373-377.
- [24] Wang N., Zhang X., Zhu D., Gao J., 2012. The investigation of thermal conductivity and energy storage properties of graphite/paraffin composites. *Journal of Thermal Analysis and Calorimetry* 107. 949-954.
- [25] Zhang Z., Zhang N., Peng J., Fang X., Gao X., Fang Y., 2012. Preparation and thermal energy storage properties of paraffin/expanded graphite composite phase change material. *Applied Energy* 91: 426-431.
- [26] Jeon J., Lee J., Sea J., and Jeong S., 2013. Application of PCM thermal energy storage system to reduce building energy consumption. *Journal of Thermal Analysis* 2(1): 279-288.
- [27] Chen Y., Nguyen D. Shen M. Yip M. and Tai N., 2013. Thermal characterizations of the graphite nanosheets reinforced paraffin phase-change composites. *Applied Science* 44: 40-46.
- [28] Chen Z., Gao L., Fang G. and Shan F. 2013. Synthesis and characterization of microencapsulated paraffin microcapsules as shape-stabilized thermal energy storage materials. *Nanoscale and Microscale Thermophysical Engineering* 17: 112-123.
- [29] Li B., Liu T., Hu L., Wang Y., and Ga, L., 2013. Fabrication and properties of micro-encapsulated paraffin phase change composite for thermal energy storage. *ACS Sustainable Chemistry and Engineering* 1: 374-380.
- [30] Jeong S., Lee J., Seo J., and Kim S., 2014. Thermal performance evaluation of bio-based shape stabilized PCM with boron nitride for energy saving. *International Journal of Heat and Mass Transfer* 71, 245-250.
- [31] Rathod M.K. and J. Banerjee. 2014. Experimental investigations on latent heat storage unit using paraffin wax as phase change material. *Experimental Heat Transfer* 27, 40-55.
- [32] Basakayi J.K. and C.P. Storm. 2014. Potential use of phase change materials with reference to thermal energy systems in South Africa. *International Journal of Advances in Engineering & Technology* 7(3): 692-700.
- [33] Jeong S., Chang S.J., We S., and Kim S., 2015. Energy efficient thermal storage montmorillonite with phase change material containing exfoliated graphite nanoplatelets. *Solar Energy Materials* 139: 65-70.
- [34] Zhang P., Xiao X., and Ma Z.W., 2016. A review

- of the composite phase change materials: Fabrication, characterization, mathematical modeling and application to performance enhancement. *Applied Energy* 165, 472-510.
- [35] Miro L., Barreneche C., Ferrer C., Sole A., Martorell T., and Cabeza F., 2016. Health hazard, cycling and thermal stability as key parameters when selecting a suitable Phase Change Material (PCM). *Thermochim. Acta* 627-629: 39-47.

