RESEARCH PAPER

An Experimental Investigation of Solar Cabinet Dryer with Thermal Storage Material

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ABSTRACT

A solar cabinet dryer integrated with heat storage material has been developed and tested for safed musli. Paraffin wax used as thermal storage material to stored solar energy in dryer to extent the drying time. The main parts of solar dryer are air heater and drying chamber. The solar cabinet dryer is used to dry safed musli having capacity of 10 kg. The drying experiment conducted at Department of Unconventional Energy Sources and Electrical Engineering, Dr. Panjabrao Deshmukh Krishi Vidyapeeth, Akola. The temperature inside air heater was in the range of 42.63 to 56.57°C with corresponding ambient temperature of 28.00 to 33.72°C.The collector thermal efficiency was 56.39 per cent at 9.00 h and reduced to 21.47 per cent at 11.00 h and shown increased trend onwards. Drying efficiency of solar dryer was highest at initial hours i.e. 45.92 per cent for Safed Musli and it was maximum i.e. 38.68 per cent during sunshine hours. Thermal energy storage efficiency was 70.18 per cent at 9:00 h and it reduced to 46.58 per cent at 16:00 h in, afterwards thermal energy storage efficiency increased gradually to 72.29 per cent at 22:00 h.

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INTRODUCTION

Solar energy is the most abundant form of energy available in the world can be utilized for the commercial as well as household purposes [1]. The lots of technology and devices are developed for the utilization of solar energy like solar dryers, solar pumps, solar cooker etc. [2]. Country like India with its geographical location and plenty of sunshine in most parts during the year, solar energy can be one of the most important alternative energy to meet energy needs [3]. India lies between 8°N and 38°S of the equator has a greater chance of utilizing this freely available source of energy. There are nearly 250-300 days per year available to get useful sunshine [4]. Since solar radiation is an inherently time-dependent energy resource, storage of energy is essential if solar is to meet energy needs at night or during daytime periods of cloud cover and make a significant contribution to total energy needs [5]. Radiant energy can be converted into a variety of forms and feasible to be stored such as; thermal energy, chemical energy, kinetic energy, or potential energy. Generally, the choice of the storage media is related to the end use of the energy and the process employed to meet this application [6].

Drying is a process of moisture removal from a product in order to reach the desired moisture content and is an energy intensive operation [7]. The prime objective of drying apart from extended storage life can also be quality enhancement, ease of handling, further processing and sanitation and is probably the oldest method of food preservation practiced by humankind [8]. Sun drying is common practice in many tropical and subtropical countries [9]. There are many types and designs of solar dryers available for drying of agricultural commodity, mainly includes natural convection cabinet dryer and forced circulation solar dryer based on array of flat plate air heaters [10]. The major drawbacks of natural convection dryer are higher drying time, uneven drying, comparatively low capacity, discoloration by the UV radiation and contamination by the foreign materials, insects and microorganisms [11]. Passive type of solar dryers is well realized and it get over the problems exist in

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open sun dryer and cabinet type dryers [12]. Indirect dryers are suitable for colour sensitive produce, as the produce is not exposed directly to the sun [13]. These are mainly coupled with the solar air heater or use the indirect solar energy. A solar air heater provides the hot air with a large variation in the temperature to the dryer only during sunshine hours [14]. Whereas, drying of many agricultural products like cereals and pulses are performed at the steady and moderate temperature and continuously for few days. In such a case, the thermal storage is required with a solar air heater for continuous drying. A thermal storage unit integrated with the solar air heater may be charged during the peak sun-shine hours and utilized (discharged) during sun- shine hours for supplying the hot air to the dryer [15].

Bhardwaj *et al*. (2019) investigated the indirect forced convection solar dryer for drying medical herb integrated with sensible heat storage material (SHSM) and phase change material (PCM). The iron scrap mixed with gravel is placed on absorber plate and copper tubes comprising of engine oil have been used as SHSM in the solar collector. The Paraffin RT-42 as a phase change material has been used in the drying chamber. Using SHSM and PCM simultaneously the overall drying rate observed was almost double as compared to with no use of thermal storage medium and traditional shade drying. The drying time to reach the saturation level of 9% was recorded as 120 h in comparison to 216 and 336 h, respectively and the dried rhizomes of good quality in terms of essential oil and bio-medical compounds are obtained. The solar collector without SHSM possess an average energy and exergy efficiency 9.8% and 0.14%, respectively. The respective energy and exergy efficiency achieved with SHSM are 26.10 and 0.81%[16].

Badgujar (2012) built and tested forced convection with desiccant integrated solar dryer. During sun shine hours the hot air from the flat plate collectors is forced to the drying chamber for drying the product and simultaneously the desiccant bed receives solar radiation directly and through the reflected mirror. Drying experiments were conducted with and without the integration of desiccant unit. With the inclusion of reflective mirror, the drying potential of the desiccant material is increased by 25% and the drying time is reduced. The drying efficiency of the system varies between 48% and 59% and the pick-up efficiency varies between 25% and 60%, respectively. Approximately in all the drying experiments 68% of moisture is removed by air heated using solar energy and the remainder by the desiccant. The inclusion of reflective mirror on the desiccant bed makes faster regeneration of the desiccant material [17].

Jain and Jain (2004) conducted the parametric study of an inclined multi-pass solar air heater with in-built thermal storage and attached with the deep-bed dryer. The effect of change in the tilt angle, length and breadth of a collector and mass flow rate on the temperature of paddy crop has been studied. The rate of moisture evaporation and humidity of the drying air have been analyzed with the drying time for different depth of the grain bed. It has been observed that the bed moisture content decreases with the time of the day. The humidity of the air and the drying rate increases with the increase in the depth of drying bed [18].

EXPERIMENTAL SET UP

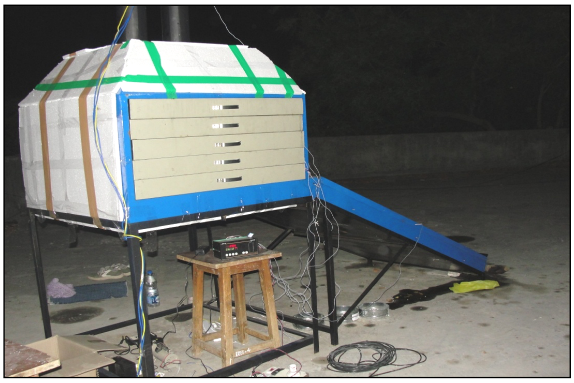

Figure 1: Experimental set up of solar cabinet dryer

Solar air heater with latent storage collector (SAHLSC) using spherical capsules as a packed bed absorber for drying of **10 kg/batch** tubular roots was designed, fabricated and installed at Department of Unconventional Energy Sources and Electrical Engineering, Dr. Panjabrao Deshmukh Krishi Vidyapeeth, Akola. It consists of solar air heater, heat exchanger and drying chamber with two chimneys. The air heater includes outer cover of GI sheet, above which the insulation of glass wool with thickness of 2.5 cm was sandwiched between absorber plate and outer cover. The absorber plate with thickness of 2 mm was painted black with selective coating having high absorptivity. Slit with flap was provided at one side of air heater and other side was connected with drying chamber. Heat exchanger unit consists of stand for aluminum capsules filled with phase change medium i.e. paraffin wax. It was used for providing stored heat during off sunshine hours. Thirty four (34) number of aluminum capsules spaced 2.5 mm apart were placed centrally in between absorber plate and glass cover. The drying chamber is directly connected to solar air heater (figure 1). The experiment for no-load and full-load test was undertaken for drying. For evaluating the performance of solar dryer, full load test by using tubular roots of Safed Musli was conducted. Also the experiment was conducted on open sun drying. An exhaust fan 12 V DC, 0.35 A, 4.2 W was fixed at upper part of chimney to ensure an even distribution of air and evacuate humidity of the product to surrounding for rapid release of moist air. Air flow of 1.0 m/s was maintained through a regulator to control the flow of air.

EXPERIMENTAL CALCULATION

The performance of system and the drying characteristics were calculated using the following equations.

A.) Determination of moisture content

Initial moisture content of sample was determined by the hot air oven drying method [19]. The percentage moisture content was determined by using following formula,

$$M.C.(wb)\% = \frac{(W_1 - W_2)}{W_1} \times 100 \quad ...1$$

$$M.C.(db)\% = \frac{(W_1 - W_2)}{W_2} \times 100 \quad ...2$$

Where,

W_1= weight of sample before drying, g

W_2= weight of bone dried sample, g

B.) Determination of drying rate

The drying rate (g $h^{-1}100g^{-1}$ of bone dry weight) of produce sample during drying period was determined using the following equation [20].

$$\text{Drying rate}\,(D_R) = \frac{\Delta W}{\Delta t} \quad ...3$$

Where,

ΔW= Weight loss in one hour interval (g $100g^{-1}$of bdm)

Δt = Difference in time reading (h)

C.) Determination of moisture ratio

The moisture ratio of the produce was computed by using the initial moisture content (IMC) and equilibrium moisture content (EMC) [21,22].

$$\text{Moisture Ratio (M.R.)} = \frac{(M - M_e)}{(M_0 - M_e)} \quad ...4$$

Where,

M = Moisture content (db), %

M_e = EMC, (db), %

M_0 = IMC, (db), %

D.) Collector Thermal Efficiency (η_c)

The drying efficiency of solar dryers was calculated by following formula [23].

$$\eta_c = \frac{m \times Ca\ (T_{out} - T_{in})}{Io \times A_C} \quad ...5$$

Where,

m= ρ.Q = Mass flow rate, kgs^{-1}

ρ = Density of air kgm^{-3}

Q = Volume flow rate m^3s^{-1}

C_a = Specific heat of air, kJkg $^{-1}$ °C^{-1}

I_o = Solar insolation, Wm^{-2}

T_{in} = Temperature at inlet, °C

T_{out} = Temperature at outlet of collector °C

A_c = Collector Area m^2

E.) Drying efficiency (η_d)

The drying efficiency is defined as the ratio of energy required to evaporate the moisture to the energy supplied to the dryer. The drying efficiency was calculated from following equation. (Kalbande ,2013)

$$\eta_d = \frac{(W_i \times C_f \times \Delta T) + (M_w \times C_w \times \Delta T) + (W_w \times \lambda)}{I_{sc} \times A_C \times N} \quad ...6$$

Where,

W_i= Initial weight of material, kg

C_f = Specific heat of material, kcalkg^{-1}K^{-1}

ΔT= Temperature rise

M_w= Mass of water evaporated, kg

C_w= Specific heat of water, 1 kcal kg^{-1}K^{-1}

λ = Latent heat of vaporization, 540 kcal kg^{-1}

I_{sc} = Solar radiation on collector, kcalm^{-2}h^{-1}

A_c = Drying area (80% of collector area)

N= Drying hours, h

The drying efficiency during non-sunshine hours was calculated from following equation.

$$\eta_d = \frac{m_w \times L}{mCp(Ti - To)} X100 \quad ...7$$

Where,

m_w = Mass of water evaporated ,kg

L = Latent heat of evaporation, kJKg^{-1}

m = Weight of Paraffin Wax, kg

Cp=Specific heat of Paraffin Wax,kJkg^{-1} °C^{-1}

T_i = Inlet hot air temperature at drying chamber, °C

T_o = Chimney exhaust temperature, °C

RESULT AND DISCUSSION

No load test for drying chamber

The temperature in the drying chamber was in the range of 39.50 to 59.20°C of solar dryer. The temperature of drying chamber was increased by 13.12°Cover the average ambient temperature, whereas average relative humidity was reduced by 13.93 per cent than average ambient relative humidity. The average ambient temperatures, relative humidity inside the dryer and solar insolation were 34.72 ºC, 15.14 per cent and 602.62 Wm^{-2} respectively. It was also observed that during non-sunshine hours of 18:00 to 22:00, the temperature inside the drying chamber was in the range of 38.70 to 49.60°C corresponding to ambient temperature in the range of 28.00 to 33.73°C. Even during non-sunshine hours, there was 12.40°C rise in temperature of drying chamber over ambient temperature (Figure 2). The average relative humidity inside drying chamber was found to be 15.14 per cent (Figure 3).

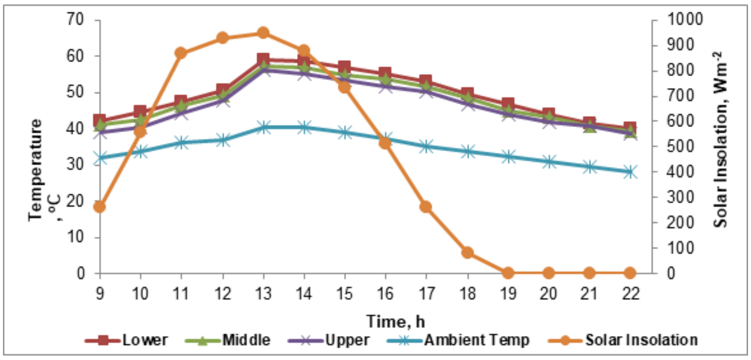

Fig 2: Average variation of temperature at different trays inside the drying chamber during no load test

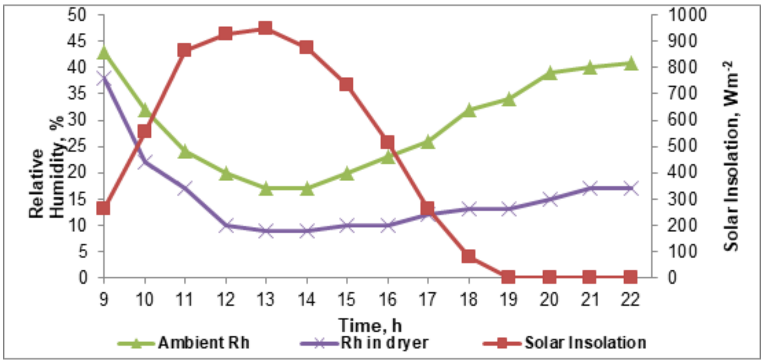

Fig. 3: Average variation of relative humidity inside the drying chamber during no load test

Full load test of solar dryer with PCM

Full load test of solar dryer was conducted by drying fresh roots of Safed Musli of known moisture content of 614.29 per cent (db) was loaded in drying chamber and distributed uniformly in thin layers for drying. The drying was continued till the moisture content reached to EMC [~10 per cent (db). The average temperature inside the drying chamber achieved its peak value at 13:00 hr and was found to be 58.07°C with corresponding ambient temperature, relative humidity and solar intensity of 39.02°C, 14.00 per cent and 905.12 Wm^{-2} respectively (Figure 4). It is observed that the temperature of drying chamber was increased by 12.64 °C over the average ambient temperature, whereas average relative humidity was reduced by 6.40 per cent than average ambient relative humidity. The average ambient temperature, relative humidity inside the dryer and solar insolation were 34.84°C, 18.00 per cent and 566.61 Wm^{-2} respectively. It was also observed that the weight of sample in all the five trays was reduced up to 18:00 h and was in the range of 15.44 to 15.69 g, further the weight of samples remained constant in all the trays. Time required for drying of Safed Musli was eight hours.

The minimum relative humidity inside drying chamber was achieved its lowest value of 10.00 per cent at 13.00 h of the day with corresponding ambient relative humidity of 14.00 per cent and solar intensity of 905.12 Wm^{-2}. The average relative humidity inside drying chamber was found to be 18.49 per cent (Figure 5). It was observed that the increase in temperature (36.75 to 58.07°C) inside the drying chamber correspondingly reduced the relative humidity to its lowest value (10.00 per cent) attributed to the stored heat in the thermal heat storage system of air heater. It is revealed from the above results that the temperature required for drying was maintained inside the solar dryer for the drying process because of PCM.

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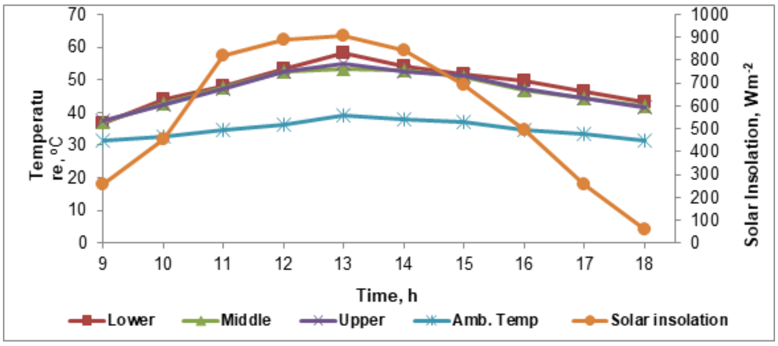

Fig 4 Average variation of temperature during full load test of dryer for Safed Musli

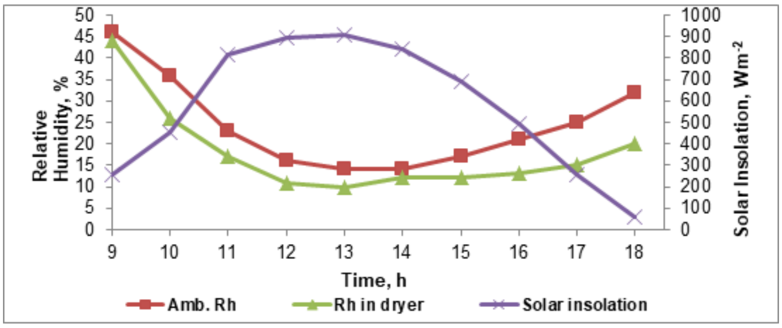

Fig 5: Average variation of relative humidity during full load test in dryer for Safed Musli

Drying characteristics of Safed Musli

The drying characteristics of Safed Musli dryed in solar dryer were studied and compared with open sun drying. The different drying characteristics in terms of moisture content per cent (db), drying rate (gm/100 gm of bdm /min) and moisture ratio were studied. The variation of moisture content, drying rate and moisture ratio with respect to drying time is presented graphically in Fig. 6 to 8. The drying rate decreased with increase in drying time (Fig. 7 and 8). There was rapid moisture removal from Safed Musli during initial 3 h of drying in solar dryer and 5 h in open sun drying. This was the first falling rate period during which the free moisture is removed. After 3h of drying in solar dryer, the drying rate further decreases slowly, this was second falling rate period during which bound moisture is removed. The drying results are in confirmation with the research findings recorded regarding drying rate and moisture content vs drying time for drying of onion in packed bed thermal storage natural convection solar crop dryer [12].

Fig. 6 revealed that the moisture content of Safed Musli was reduced from 614.29 per cent (db) to 12.85 per cent (db) in open sun drying in 12h, whereas moisture content was reduced to 10.71 per cent (db) in 8 h when dried in solar dryer with PCM. The drying time of Safed Musli was reduced by 4 h when dried in solar dryer as compare to the open sun drying. It was also observed that the maximum moisture removal had taken place from 614.29 to 87.14 per cent in 8 h in open sun drying whereas up to 73.71 per cent in 5 h in solar dryer and followed falling rate period.

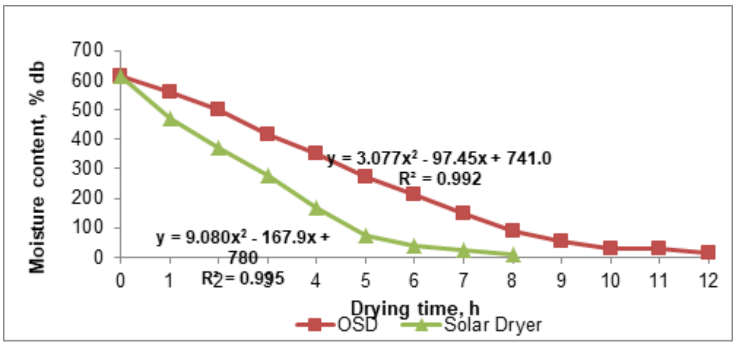

Fig 6: Variation of moisture content of Safed Musli in solar dryer and open sun drying

It is revealed that the drying rate varied from 0.578 to 0.0125 g/100g bdm/min and 1.498 to 0.0168 g/100g bdm/min in open sun drying, and solar dryer, respectively. The drying rate during initial hours was found to be higher in the solar dryer integrated with PCM (1.498 g/100g bdm/min) followed by open sun drying (0.578 g/100g bdm/min). The corresponding average moisture ratio for open sun drying and the solar dryer varied from 1.00 to zero.

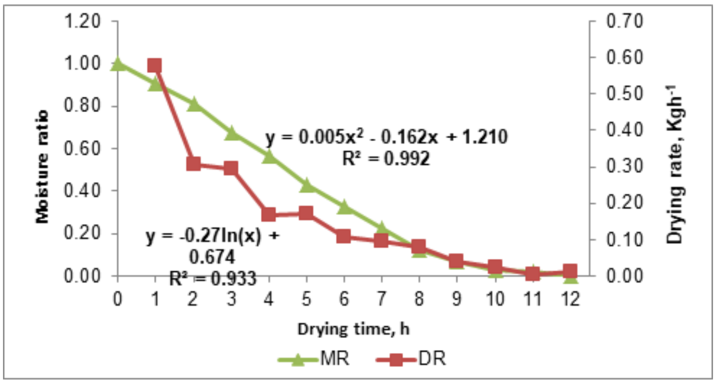

Fig 7: Variation of moisture ratio and drying rate of Safed Musli in open sun drying

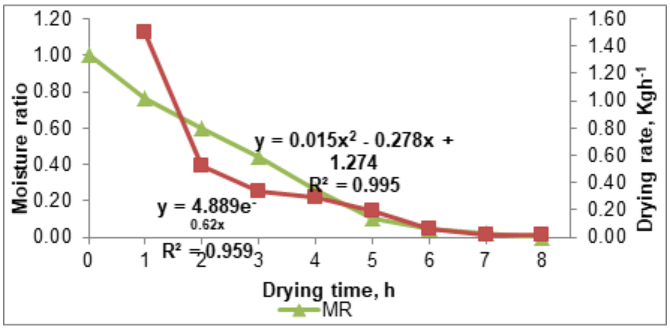

Fig 8: Variation of moisture ratio and drying rate of Safed Musli in solar dryer

Efficiencies of solar dryer with PCM

Collector thermal efficiency

The collector thermal efficiency was 56.38 per cent at 9:00 h and reduced to 22.45 per cent at 12:00 h and showed it increased trend onwards due to temperature developed in air heater. Similar ranges of efficiencies were reported by Fath (1991, 1994) by using paraffin wax as a phase change material. The outlet temperature was in the range of 51.90 to 61.63°C in the time zone of 13:00 to 18:00 h[25,26]. During this period the heat was stored in heat exchanger consists of paraffin wax as PCM which melts at 52.0°C. This stored heat was released from 18:00 h onwards and used to maintain the temperature from 41.00 to 48.47°C during night hours that were sufficient to dry the material during non-sunshine hours.

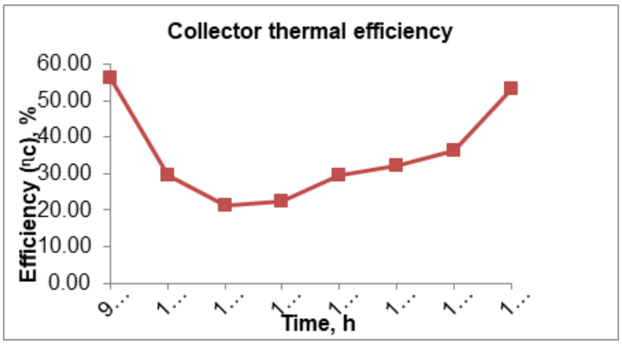

Fig 9: Variation in hourly collector thermal efficiency

Drying efficiency

The drying efficiency of solar dryer was highest at initial hours i.e. 45.92 per cent for Safed Musli for corresponding maximum removal of moisture 2 kg. Afterwards the drying efficiency showed decreasing trend up to 14:00 h and further increased till completion of drying in case of Safed Musli. The drying of Safed Musli was completed in 8 h as compared to open sun drying of 12 h. The results showed the drying efficiency values closer to the values reported by Kamble (2013) i.e. 34 per cent for solar cabinet dryer with thermal heat storage material for chilly drying. The similar trend of drying efficiency for turmeric was observed in tunnel dryer by Kalbande (2013)[27].

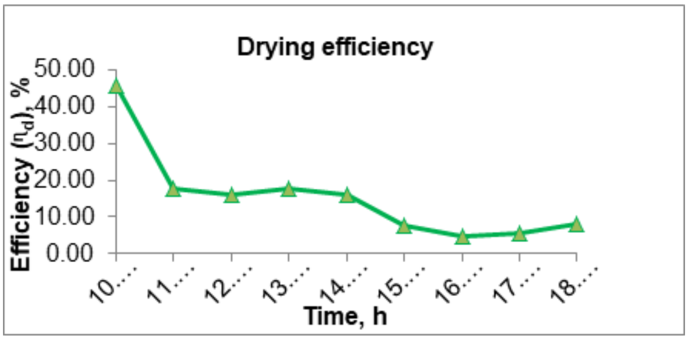

Fig 10: Variation in hourly drying efficiency

CONCLUSION

The drying time was extended by about five hours during non-sunshine hours in due to heat stored in phase change material during day time. The temperature inside air heater was in the range of 42.63 to 56.57°C with corresponding ambient temperature of 28.00 to 33.72°C.The collector thermal efficiency was 56.39 per cent at 9.00 h and reduced to 21.47 per cent at 11.00 h and shown increased trend onwards. Drying efficiency of solar dryer was highest at initial hours i.e. 45.92 per cent for Safed Musli and it was maximum i.e. 38.68 per cent during sunshine hours. Thermal energy storage efficiency was 70.18 per cent at 9:00 h and it reduced to 46.58 per cent at 16:00 h in, afterwards thermal energy storage efficiency increased gradually to 72.29 per cent at 22:00 h.

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