COMPARATIVE EXPERIMENTAL PERFORMANCE EVALUATION OF SOLAR DRYER WITH VARIOUS PHASE CHANGE MATERIALS

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Abstract: Solar drying techniques reduce post-harvest food spoilage due to its extra moisture content. Drying by fossil fuels is cause pollution, but solar is clean and green energy source, so the use of solar for drying does not harm the environment. In the past 2-3 decades, the researchers appreciate the thermal energy storage (TES) techniques in solar dryers as conventional solar dryers work only during sunshine hours. Researchers have tested a TES material on a particular dryer setup. As many different types of TES materials are available, in the present study three different TES materials namely sodium acetate trihydrate (SAT), ferrous sulfate heptahydrate (FSH), and stearic acid (SA) are tested and compared on indirect type solar dryer setup. In addition, the performance of TES materials is compared with solar dryer without TES material. A series of experiments were conducted to study the impact of mass flow rates. We found that the use of TES material is increased the drying rate, and the overall drying rate increases by increasing the flow rate of circulating air in the drying chamber. The experiments were carried out to dry potato fries in an 8kg batch. The batch size is fixed for all experiments. As results, we found FSH is not compatible with the system as it has corrosive effect, SA gives 7% more drying rate compared to SAT, but the SA material cost is seven times higher than SAT, so in the cost aspect, the SAT is considered as TES material.

Keywords: Solar dryer, PCM, Thermal Energy Storage, Salt hydrates, Fatty acid

1. Introduction

India is one of the world's most dominating food-producing countries. However, the amount of wastage of post harvested food is also very much due to lack of preservation. The main reason behind food spoilage is extra moisture content. Drying is one of the oldest methods for food preservation. Drying is the process of removing excess moisture from a product to store it for a more extended period without spoilage. Drying with fossil fuel causes pollution, and it is expensive; additionally, it requires more appliances. Sun is a source of light and heat energy. Solar energy is free of cost, readily available and pollution-free. For drying, solar energy can be used as it available free of cost from the sun.

Traditionally use of solar energy for drying is drying in open sunlight. It is a very economical and eco-friendly food preservation process. However, some limitations like dust contamination on a product, poor drying rate, poor product quality, inability to get the required moisture content, and many surrounding environmental elements also directly affect the overall drying process. So as compared to open sun drying in a closed system, it is more preferred because it protects the product from dust contamination and many environmental affecting factors also required moisture content to achieve with solar dryer system and excellent drying quality can achieve which fulfill all our requirements.

As solar dryer works only in the presence of direct sun energy is available because of this solar system are less reliable because at time of insufficient sunshine hours or after sunset, the system will stop working. To overcome this, researchers have working on technology for the storage of extra energy during the daytime. This concept is known as thermal energy storage (TES). The stored energy will use when the solar radiations are poor or during off sunshine hours. This TES will work as a thermal switch. Solar dryer systems integrated with TES will work more efficiently and continuously as compared to the conventional dryer.

The Solar dryer is classified according to nature of airflow as natural convection and forced convection. In forced convection system need blower or a fan to circulate air and in natural convection air will circulate naturally. Further, it is classified by mode of heat supply as direct mode, indirect mode and mix mode. In direct mode the solar energy is entered through transparent cover in closed box where the product for drying is placed. In case of indirect mode, collector preheats the air and heated air form collector is diverted to drying chamber where the product is placed. In mix mode, the hot air is supplied from the collector to drying chamber as well as direct solar energy (through transparent glass cover placed on drying chamber) is utilized for drying process. Thermal energy storage is classified as sensible heat storage and latent heat storage. The latent heat storage material will change its phase while storing and releasing heat energy. Latent heat storage materials have better performance than sensible heat storage materials, and they are classified as organic, in-organic and salt hydrates, fatty acid etc.

Nomenclatures

A_1	area at outlet pipe of drying chamber (0.008107 m^2)
A_2	effective cross section area of Solar collector (0.105 m^2)
A_c	area of absorber (1.089 m^2)
b_1	height of collector (0.150 m)
b_2	height of absorber pipe (0.025 m)
C_p	Specific heat of air (J/Kg-K)
D	Diameter of outlet pipe (0.1016 m)
H	heat transfer coefficient of hot air in collector (W/m^2-K)
h_a	Heat transfer coefficient of atmospheric air (1.4 W/m2-K)
I_t	Solar Radiation emitted on incline absorber (W/m^2)
K	thermal Conductivity of air (W/m-K)
K_{ACP}	thermal conductivity of ACP sheet (0.415 W/m-K)
K_g	thermal conductivity of glass wool (0.04 W/m-K)
l_1	width of collector (1 m)
l_2	width of absorber pipe (0.05 m)
L_c	characteristic length of collector duct (0.137975 m)
L_v	latent Heat for vaporization of water (2250 kJ/kg-K)
$\dot{m}$	mass flow rate of air in solar dryer (Kg/s)
M	number of glass cover (1)
m_w	mass of water is to be dried (Kg)
N_u	nusselt number
Q	constant flow rate of solar dryer (m^3/s)
Q_u	heat Gain by the Absorber Plate (J/s)
T_1	temperature Inside the TES chamber (°C)
T_2	temperature of Outside the absorber pipe (°C)
T_3	temperature of Inside the TES chamber (°C)
T_4	temperature of Outside the absorber pipe (°C)
T_5	temperature of hot air in collector (°C)
T_6	temperature of Air at Drying Chamber exit (°C)
T_7	temperature of Air at Inside the Drying chamber (°C)
T_8	atmospheric air temperature (°C)
T_a	atmospheric air temperature (°C)
T_{ACP}	thickness of ACP sheet (5 mm)
T_g	Thickness of glass wool Insulation (25 mm)
T_m	average temperature of absorber plate (°C)
U_b	bottom loss coefficient in (W/m^2-K)
U_L	overall heat loss coefficient (W/m^2-K)
U_s	side Loss Coefficient (W/m^2-K)
v_1	velocity of air at outlet of drying chamber (m/s)
v_2	velocity in Collector (m/s)
ϱ	density of air (Kg/m^3)
ε_c	emissivity of absorber plate (0.88)
ε_p	emissivity of absorber plate (0.17)
ß	angle of tilt of collector (23°)
α	absorptance of absorber plate (0.92)
σ	stephan boltzmann constant
Ꞇ	transmittance of glazing material (0.88)
PCM	phase change material
TES	thermal energy storage
SAT	sodium Acetate Trihydrate
FSH	ferrous sulphate heptahydrate
SA	stearic acid

2. Literature Review

D.K Rabha et al. (2017) [1] tested a forced convection solar dryer which is used to dry red chili in 20 kg batch capacity. The dryer is shell and tube type TES unit filled with paraffin wax (as TES material). They observed that during low solar radiation period, the TES unit increases the performance of the dryer. Kabeel et al. (2016) [2] conducted an experimental study on flat and V-corrugated plate solar collector with a built-in TES unit. They found that V- corrugated design collector with TES is 12% more efficient than without TES. A. Wadhawan et al. (2017) [3] used a lauric acid as TES material for experimental studies and CFC analysis. They predicted the different values of pressure drop and friction factor for various mass flow rates, and found that with an increase in mass flow rate of air, the output air temperature is decreased. A.H. Palaniappan et al. (2013) [4] conducted experimental study to know actual behavior of TES coupled with solar collector during charging and discharging. The experiment was carried out with different flow rates. They found that at high flow rates, the collector efficiency and value of heat transfer coefficient is higher and this will reduces overheating of air during the peak sunshine hours. Lalit M. et al. (2010) [5] summarized the past and current research in the field of TES technology. They listed and summarized the properties like temperature, density, and specific heat for different sensible and latent heat storage materials. Also, they added that solid-liquid transformation material is more compatible than liquid-gas and solid-gas transformation as the transformation involves less change in volume of 10%.

3. Experimental Setup

In this study, an indirect type forced convection solar dryer with TES as shown in Fig. 1 was used to dry potato slices. The system as shown in Fig. 2 is mainly divided into four parts as collector, TES chamber, fan arrangement, and drying chamber. The whole drying system is3.6m long and 1.02m wide. Solar drying experiment were conducted in the month of February and March of 2021 at Birla Vishvakarma Mahavidyalaya (BVM engineering collage Vallabh Vidyanagar). The setup has (2 m x 1m x 0.150m) box type solar collector, and the collector have 11 tubes for PCM storage of size (1980 mm x 50mm x 25mm). The collector tubes also work as absorber plates. The drying chamber of size 600mm x 600mm x 600mm as shown in Fig. 3 has five trays to place product. The air circulation in the system is followed by three fan arrangement. Fans are placed at the bottom of the drying chamber as shown in Fig. 4 and connected with the collector with a duct pipe. Each fan can work independently, and three different flow rates can be obtained by this fan arrangement as one fan working, two fan working, and three fan working. The collector and drying chamber are internally isolated with glass wool to avoid heat losses.

Fig 1 Schematic view of the solar dryer

Fig 2 Actual view of the solar dryer

Fig 3 Drying chamber

Fig 4 Fan arrangement

4. Instrumentation and Measurements

In the experiment work, temperature, humidity, airflow velocity, solar radiation and weight are measured. For temperature measurement 8 K-type thermocouple is placed on different location of the dyer setup. The Location of all thermocouples is shown in Table1. The inlet and outlet humidity of air circulating in the drying chamber is measured with a hygrometer. A digital anemometer and a pyrometer are used to measure air velocity at the drying chamber exit and solar radiation respectively. A digital weight scale is used to measure the product weight before and after drying process. All parameters are measured in interval of 15 minutes.

Table 1 location of thermocouple

Thermocouple	Location
T1	Inside the TES chamber
T2	Outside the absorber pipe
T3	Inside the TES chamber
T4	Outside the absorber pipe
T5	Air outlet at Collector
T6	Drying Chamber exit
T7	Inside the Drying chamber
T8	Air inlet at the collector

5. Operation

The solar dryer setup consists of TES unit used for storage of solar energy. During daytime when sufficient solar energy is available; the extra energy is stored in the TES unit, and when solar radiation is poor or insufficient, the energy which stored in TES available for drying purposes. The energy storing and releasing processes are done with the phase change process of TES material. The TES unit is working as a thermal switch.

The heated air from the collector is circulated in the drying chamber by fan arrangement. The experimental work is carried out with three various TES material and three different flow rates with help of fan arrangement. Each flow rate is tested for one day, and hence total of nine experiments with full nine days were conducted.

6. Selection of PCM materials

The main criteria for PCM material selection is that the melting temperature of PCM material should be just below the system operating temperature. The experiment was carried out without PCM material and no load to obtain the average collector temperature. It is observed that the average collector temperature was 76°C. The three PCM materials are selected based on the melting point, latent heat capacity and its availability in the market. The snapshot pictures of various TES/PCM materials are shown in Fig. 5, 6, and 7. The properties of PCM materials are shown in the Table 2.

Table 2 Properties of PCM materials

Name	**Chemical formula**	**Melting point (°C)**	**Latent heat (kJ/kg)**
Sodium Acetate Trihydrate	CH3COONa·3H2O	58	265
Ferrous sulphate heptahydrate	FeSO4·7H2O	64	200
Stearic acid	CH3(CH2)16COOH	70	199


Fig 5 Sodium Acetate Trihydrate


Fig 6 Ferrous sulphate heptahydrate


Fig 7 Stearic acid

7. Mathematical modeling

The performance parameters of solar dryer is calculated using following expressions and measured parameters.

(1) **Area at outlet pipe of solar dryer (A_1) m^2**

$$A_1 = \frac{\pi}{4} \times D^2 \quad [6]$$

(2) **Flow rate of solar dryer (Q) m^3/s**

$$Q = A_1 \times V_1 \quad [7]$$

(3) **Effective cross section area of Solar collector (A_2) m^2**

$$A_2 = [(11 - \{2 \times 50\}) \times (b_1 - 25)] - [11 \times l_2 \times b_2] = 0.105 m^2 \quad [8]$$

(4) **Velocity in Collector (v_2) m/s**

$$V_2 = \frac{Q}{A_2}$$ [9]

(5) **Characteristic length of Collector Duct (L_c) m**

$$L_c = 2\times\frac{[(l_1\times b_1)-11\times(l_2\times b_2)]}{[(l_1+b_1)+11\times(l_2+b_2)]}$$ **[8]**

(6) **Heat Transfer Coefficient of Air (h) W/m^{2}K**

$$h = \frac{N_u \times L_c}{k}$$ **[7]**

(7) **Heat Loss Coefficient (U) W/m^{2}K**

I. Bottom Loss Coefficient (U_b) W/m^{2}K

$$\frac{1}{U_b} = \frac{1}{h} + \frac{t_g}{k_g} + \frac{t_{ACP}}{k_{ACP}} + \frac{1}{h_a}$$ **[7]**

II. Side Loss Coefficient (U_s) W/m^{2}K

$$U_b = U_s$$ **[8]**

In bottom and side of collector same loss is there.

III. Top Loss Coefficient (U_t) W/m^{2}K

$$U_t = \frac{1}{\dfrac{M}{\left(\dfrac{C}{T_m}\right)\times\left(\dfrac{T_m - T_a}{M+F}\right)^{0.22}} + \dfrac{1}{h}} + \frac{\sigma\times(T_m^2 + T_a^2)\times(T_m + T_a)}{\dfrac{1}{\varepsilon_p + 0.05M(1-\varepsilon_p)} + \dfrac{2M+f-1}{\varepsilon_c} - M}$$ **[10]**

Where,

$$f = (1 - 0.04\times h + 0.0005\times h^2)\times(1 + 0.091\times M)$$

$$C = 365.9(1 - 0.00883\times\beta + 0.0001298\times\beta^2)$$

IV. Overall Het Loss Coefficient (U_L) W/m^{2}K

$$U_L = U_b + U_t + 2\times U_s$$ **[8]**

Here we were doing an addition of all losses from the top, bottom, and two sides of the collector.

(8) **Heat Gain by the Absorber Plate (Q_u) J/s**

$$Q_U = A_c \times \left[I_t \times \tau \times \alpha - U_L \times \left(T_m - T_a \right) \right] \quad [11]$$

(9) **Mass Flow Rate of Air ($\dot{m}$) Kg/s**

$$\dot{m} = Q \times \rho \quad [12]$$

(10) **Efficiency of Solar Collector (η_c)**

$$\eta_c = \frac{\dot{m} \times C_p \times \left(T_5 - T_1 \right)}{I_t \times A_c} \quad [13]$$

(11) **Efficiency of Solar Dryer (η_d)**

$$\eta_d = \frac{m_w \times L_v}{I_t \times A_c} \quad [14]$$

8. Result and dissection

(1) Solar radiation (input energy)

The solar intensity is the main input parameter for a solar dryer. As solar intensity changes, the output of the dryer will be changed. The solar intensity with respect to time is shown in Fig. 8, 9, and 10 for experiments with one fan working, two fan working and three fan working. For one fan working variation in solar intensity is higher for without PCM experiment compared to that of other experiments. Similarly, for two fan working, variation in solar intensity is lower compared to that of other experiments. It is clear that the input is quite similar for all experiment with two fan working. The variation in intensity for experiment with ferrous sulphate heptahydrate is much higher compared to other experiments with three fan working.

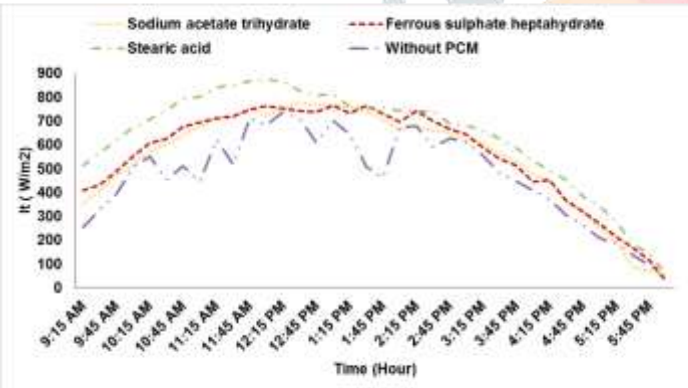

Fig 8 Solar radiation for one fan working

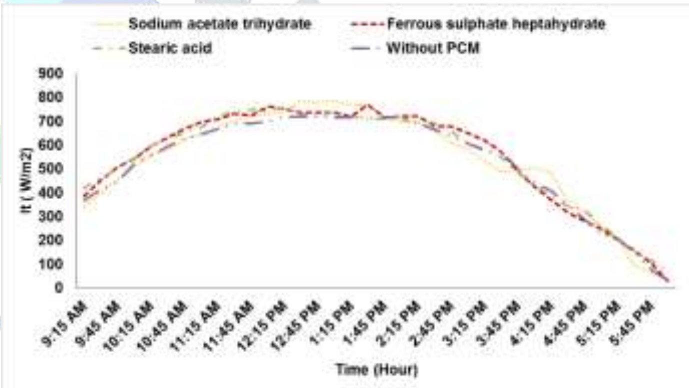

Fig 9 Solar radiation for two fan working

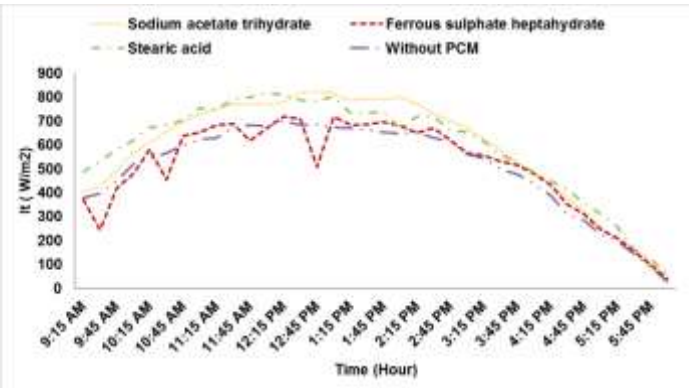

Fig 10 Solar radiation for three fan working

(2) Heat gain by absorber plate

The values of heat gain by absorber plate with respect to time are shown in Fig. 11, 12, and 13. The values of solar radiation are influencing the value of heat gain as it is directly proposal to solar radiation. The variation of heat gain is higher in case of without PCM as shown in Fig. 11, since that day variation in solar intensity was also noticed. the heat gain for all experiment with two fan working is shown in Fig 12, solar intensity values are near same for all experiments and heat gain in case of without PCM is lower between 10.30 am to 1.30 pm. The heat gain in case of ferrous sulphate heptahydrate with three fan working has more variation compared to other observations because the solar intensity on that day was not constant.

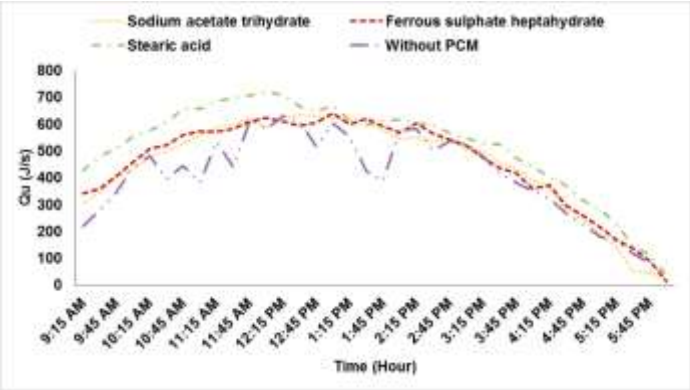

Fig 11 Heat gain by absorber plate for one fan working

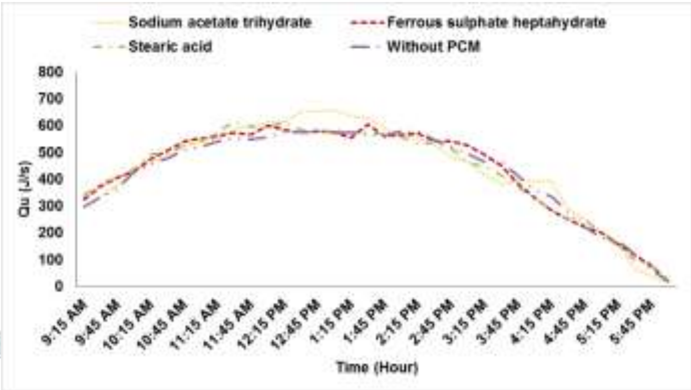

Fig 12 Heat gain by absorber plate for two fan working

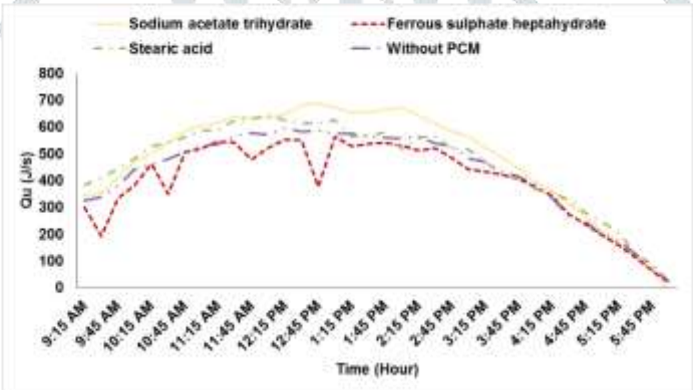

Fig 13 Heat gain by absorber plate for three fan working

(3) Solar dryer efficiency

The solar dryer efficiencies with respect to time are shown in Fig. 14, 15, and 16. Dryer efficiency is calculated as ratio of mass of water removed (equivalent energy) from the product to solar radiation. As solar radiation is in the denominator, the value of dryer efficiency is lower during daytime and as solar radiation decreases in the evening time the dryer efficiency will increases.

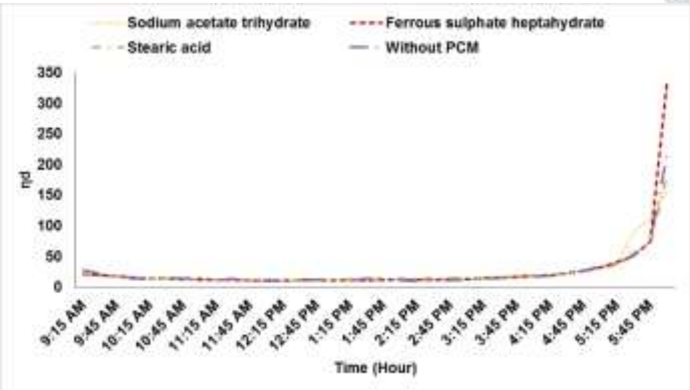

Fig 14 Solar dryer efficiency for one fan working

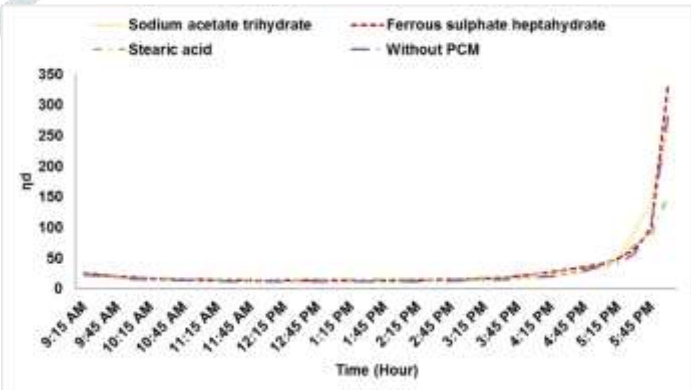

Fig 15 Solar dryer efficiency for two fan working

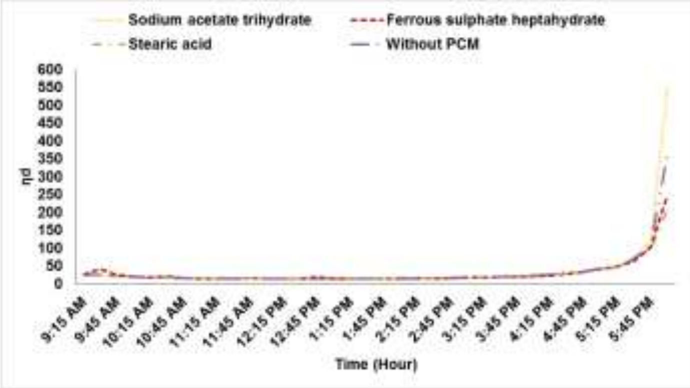

Figure 16 Solar dryer efficiency for three fan working

(4) Collector efficiency

The collector efficiency is calculated as ratio of useful energy and available energy. The collector efficiency with respect to time for one fan working, two fan working, and three fan working are shown in Fig. 17, 18, and 19 respectively. In case of one fan working, without PCM have lower collector efficiency due to lower solar radiation as noticed on that day. As shown in Fig. 18, collector efficiencies for two fan working are nearly same as solar intensity on that days for all experiments is nearly same. It is clear that with PCM as staeric acid, ferrous sulphate heptahydrate and sodium acetate trihydrate have better performance compared to without PCM. A ferrous sulphate heptahydrate for three fan working has higher efficiency as shown in Fig. 19 because the solar radiation on that day was poor, and PCM performs very well.

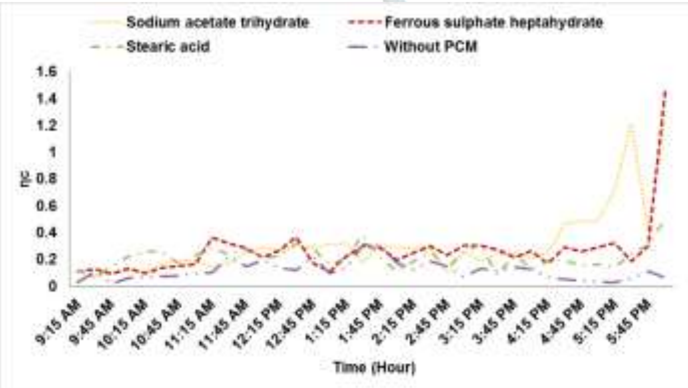

Fig 17 Collector efficiency for one fan working

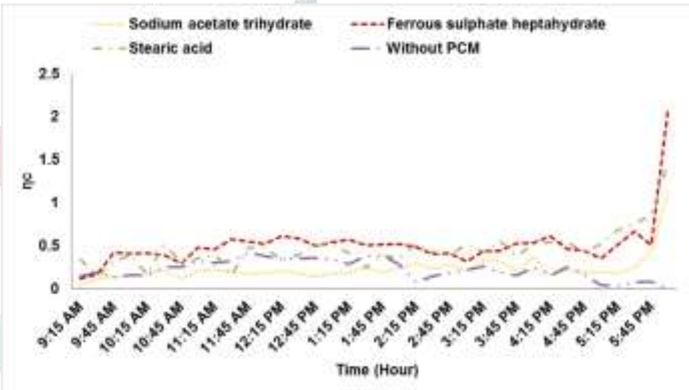

Fig 18 Collector efficiency for one fan working

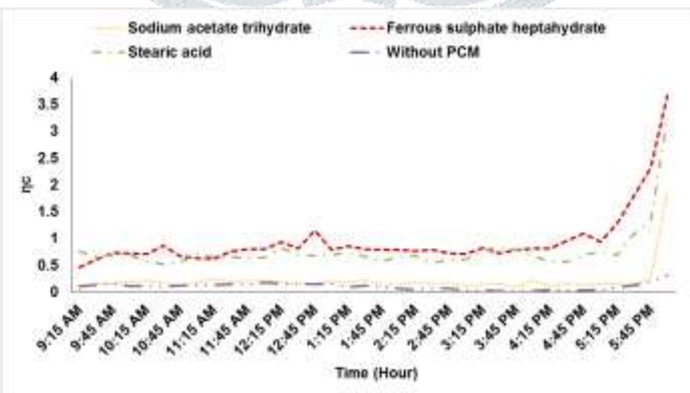

Fig 19 Collector efficiency for one fan working

(5) Summary of calculations

Name of PCM ►	Sodium Acetate Trihydrate			Ferrous Sulphate Heptahydrate			Without PCM			Stearic Acid		
Date of experiment ►	22-02-21 to 27-02-21			09-03-21 to 12-03-21			15-04-21 to 17-04-21			30-03-21 to 01-04-21		
parameters ▼	number of fan working			number of fan working			number of fan working			number of fan working		
	1	2	3	1	2	3	1	2	3	1	2	3
Average solar intensity	545.122	537.514	583.161	558.568	550.754	509.594	472.795	530.062	505.778	631.983	549.457	593.040
Average heat gain by absorber plate	445.692	439.764	484.230	455.927	434.851	397.913	406.397	427.436	432.843	516.347	432.671	461.731
Average efficiency of solar collector	0.313	0.234	0.211	0.265	0.509	0.951	0.116	0.223	0.782	0.219	0.464	0.767
Average efficiency of solar dryer	23.586	29.963	38.157	27.261	31.424	30.552	24.008	27.531	29.433	23.302	26.523	33.887
Ammount of water dryed from product (kg)	3.772	4.435	5.170	4.120	4.881	4.912	3.417	4.090	4.850	4.876	5.067	5.862

(6) Product Before and after the drying process

The snapshot of product (potato fries) before and after the drying process are shown in Fig. 20 and 21 respectively.

Fig 20 before drying

Fig 21 after drying

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(7) Effect of material on PCM chamber

It is found that the PCM's staeric acid and sodium acetate trihydrate are compatible with the aluminum storage container. However, Ferrous Sulphate Heptahydrate (FSH) is not compatible with the aluminum storage container. It has corrosive effect on the storage pipe for storing the material for only 5-6 days as shown in Fig. 22. Hence, ferrous sulphate heptahydrate is not recommended to use with an aluminum storage unit.

Fig 22 Corrosive effect of FSH material on PCM storage

9. Conclusion

- The solar dryer integrated with thermal energy storage (TES) will give a better drying rate compared to without TES.
- The drying rate is increased with increase in flow rate; however, system reliability optimization of flow rate is necessary.

- TES provides hot drying air at constant temperature and protect product against sudden temperature drop due to poor radiation.
- The amount of water dried with PCM materials such as stearic acid, ferrous sulphate heptahydrate, sodium acetate trihydrate and Without PCM in case of two fans working (moderate flow rate of air) is 63%, 61%, 55%, and 51% respectively.
- The material Ferrous sulphate heptahydrate is found corrosive with aluminum storage container.
- The PCM materials such as stearic acid and sodium acetate trihydrate are compatible with storage container. Stearic acid has 7% higher drying capacity compared to sodium acetate trihydrate, however it's cost is seven times higher than sodium acetate trihydrate.

10. References

[1] D. K. Rabha and P. Muthukumar, "Performance studies on a forced convection solar dryer integrated with a paraffin wax –based latent heat storage system," Solar Energy, vol. 149, pp. 214-226, 2017.

[2] E. Kabeel, A. Khalil, S. M. Shalaby and M. E. Zayed, "Experimental investigation of thermal performance of flat and v-corrugated plate solar air heaters with and without PCM as thermal energy storage," Energy Convers. Manag., vol. 113, pp. 264-272, 2016.

[3] Wadhawan, A. S. Dhoble and V. B. Gawande, "Analysis of the effects of use of thermal energy storage device (TESD) in solar air heater," Alexandria Eng. J., 2017.

[4] S.Esakkimuthu, Abdel Hakim Hassabou, C.Palaniappan, Markus Spinnler, Jurgen Blumenberg and R.Velraj, "Experimental investigation on phase change material based thermal storage system for solar air heating applications," Solar Energy, vol. 88, pp. 144-153, 2013.

[5] Lalit M. Bal, Santosh Satya and S.N. Naik, "Solar dryer with thermal energy storage systems for drying agricultural food products: A review," Renewable and Sustainable Energy Reviews, vol. 14, no. 8, pp. 2298-2314, 2010.

[6] D. R. K. Bansal, A Textbook of Fluid Mechanics and Hydraulic Machines First Addition..

[7] E. R. K. Rajput, Heat and Mass Transfer Fifth Revised Addition 2012..

[8] R. Rushikesh, "Experimental Studies of Solar Dryer with Phase Change Material," BVM engineering college affilited by Gujarat Technological University, gujarat, 2020.

[9] F. M. White, Fluid Mechanics Seventh Addition..

[10] S. P. Sukhatme and J. K. Nayak, Solar Energy Fourth Edition..

[11] C. A. Komolafe, Iyiola O. Oluwaleye, Omojola Awogbemib and Christian O. Osueke, "Experimental investigation and thermal analysis of solar air heater having rectangular rib roughness on the absorber plate," Case Studies in Thermal Engineering, vol. 14, 2019.

[12] C. Papande and M.A. Boda, "Design & Development of Indirect Type Solar Dryer With Energy Storing Material," IJIRAE, vol. 1, no. 12, 2014.

[13] Masoud Iranmanesh, Hadi Samimi Akhijahani and Mohammad Saleh Barghi Jahromi, "Cfd Modelling And Evaluation The Performance Of A Solar Cabinet Dryer Equipped With Evacuated Tube Solar Collector And Thermal Storage System.".

[14] Abhay Lingayat and V.P. Chandramohan, "Numerical analysis on solar air collector provided with artificial square shaped roughness for indirect type solar dryer," Journal of Cleaner Production, 2016.