Experimental Investigation of Forced Convection Solar Dryer with Phase Change Material (PCM)

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Abstract. Solar dryer is an economical way of drying various agricultural products. The limitation of solar drying is that it available only during sunshine hours. An integration of phase change material (PCM) is one of the options to extend drying process after sunshine hours since it store heat in form of latent heat. In this work, an indirect, forced convection, single pass, batch type solar dryer with phase change material (PCM) was designed, constructed and experimentally investigated. Solar collector consists of rectangular pipe type absorber and it works as a PCM chamber. The experiments are carried out on solar dryer test rig under various loads, with PCM and without PCM. The main aim to carry out experiments is that to investigate the feasibility of using a solar dryer with PCM to store the solar energy in form of heat during the daytime, and to release it during the night or cloudy weather. Experiments were conducted to evaluate increments in cycle time, increment in collector’s and dryer’s efficiencies.

Keywords: Forced convection solar dryer, phase change material, cycle time, efficiency.

1. INTRODUCTION

Figure.1 Classification of PCM
The development and growth of renewable energy is increasing and projected to increase in the future. Solar energy is an essential source of renewable energy. Recently, the solar energy is utilized to generate electricity as well as heat in large scale. The main drawback of solar energy is an intermittent energy source and hence challenges associated with it will become more ambiguous. Consequently, there is a need to store energy during the bright sunshine hours and supply this stored energy during the night time or during cloudy atmosphere (low solar radiation) [1]. Conventional solar dryer is works only during day time or bright sunshine hours. By using PCM as energy storage (ES), it can be works during low solar radiation or night time. In other word, ES leads to increment in cycle time of solar dryer, increment in collector’s efficiency and increment in dryer’s efficiency.

There are main four ES methods noted from the literature as mechanical ES, chemical ES, thermal ES and electromagnetic ES. Each ES system has its own merits and demerits. They are suitable for the specific form of energy. [2]. In case of solar dryer, the thermal ES is viable.

The Thermal Energy Storage (TES) is classified as sensible and latent heat storage [3]. A material which changes phase while storing large energy is called Phase Change Material (PCM). PCM as TES is gaining a greater attention due to advantages of high storage capacity and nearly constant thermal energy [4]. Normally, PCM as TES is utilized mainly in solar energy system. A detail classification of various PCM is shown in Fig. 1 [1,5].

The PCM become good candidate for the energy storage if they satisfy the following conditions:

1. The melting point of the PCM should be match with working temperature of the device.
2. The material used as PCM should have sufficient phase change latent heat to absorb a large amount of thermal energy.
3. The coefficient of thermal expansion of PCM should be comparatively small to ensure the system work safely.
4. The PCM should have superb reversibility of phase transition.
5. The PCM should be non-poisonous, non-corrosive and produce no chemical reaction to the container and devices.
6. The PCM raw material should be readily available at economical rate.

2. Description of Experimental Setup

![Figure 2 Experimental Setup](image-url)
Forced convection, indirect type, single pass, batch type solar dryer is used for performance testing as shown in the Fig. 2. Technical details of experimental setup are given in Table No. 1. The various parameters such as temperature, velocity of air, humidity, weight, solar radiation are measured by K-type thermo-couple (10 °C – 150 °C), Anemometer (0 – 15 m/s), Thermohygrometer (0 – 100 % RH), digital scale (0.001 – 20 kg.) and Pyranometer (0 – 1000 W/m2) respectively during experiment work.

A fully refined paraffin wax was used as PCM. It satisfies selection criteria as given in introduction. Absorber pipes are works as PCM chamber, and hence paraffin was filled into absorber pipes (contains 11 kg of paraffin inside it, each pipe contains 1 kg). Paraffin wax was melting at 60 °C. Quantity of paraffin wax was decided as per the capacity of absorber pipes and based on excess heat available on absorber plates.

### Table 1 Specification of Setup

| Dimension of collector | 2 x 1 x 0.150 m³ |
|------------------------|------------------|
| No of poly carbonate sheet | 1 poly carbonate sheet |
| Poly carbonate sheet dimensions | 2 x 1 m² |
| Emissivity of poly carbonate sheet | 0.88 |
| Refractive index of poly carbonate sheet | 1.52 |
| Extinction coefficient of poly carbonate sheet | 16 m⁻¹ |
| Clearance between poly carbonate sheet and absorber plate | 0.05 m |
| Absorber plate | Aluminum Rectangular pipe |
| Dimension of absorber plate (total 11 no. of pipes) | 1.98 x 0.05 x 0.025 m³ |
| Selective coating on the absorber plate | Flat back powder coating |
| Emissivity of absorber plate | 0.17 |
| Absorptivity of absorber plate | 0.92 |
| Insulation material | Glass Wool |
| Insulation thickness inside the collector | 0.025 m |
| Dimension of the drying chamber | 0.6 x 0.6 x 0.6 m³ |
| Tray inside the chamber for drying | 5 (0.44x0.48 m²) |
| Loading from | Back |
| Material of chamber | 0.004 mm ACP sheet with 0.02 mm PUFInsulation |
| Material of chamber frame | MS fabricated |

### Table 2 Locations of Thermocouples

| Thermo- Couple | Location |
|----------------|----------|
| T₁ | Inside the PCM chamber |
| T₂ | Outside the pipe (on absorber surface) |
| T₃ | Inside the PCM chamber |
| T₄ | Outside the pipe (on absorber surface) |
| T₅ | Hot air at collector outlet |
| T₆ | Drying chamber exit |
| T₇ | Inside the chamber |
| T₈ | Air inlet in collector |

Where, T¹, T², T³, T⁴, T⁵, T⁶, T⁷, T⁸ = Temperatures at different locations (as per Fig. 2 and Table No. 2) as above mentioned in °C.

**Methodology**

A chopped potato fries were used for as drying product in the experiment work. A 8 kg chopped potato fries were placed, since potato fries have high weight per volume ratio. The experiment for drying process were carried out on 5 March 2020 to 7 March 2020 without PCM and from 13 July...
2020 to 15 July 2020 with PCM, dryer located at mechanical engineering department, B.V.M engineering college, Vallabh Vidyanyagar, Anand, Gujarat, India. The three experiments were carried out for different flow rates for each with PCM and without PCM. The flow rates of air are varied with help of fans used in the setup. In experiment no: 1, 2 and 3, single fan working (low flow rate), two fans working (moderate flow rate) and three fans working (high flow rate) respectively. The various parameters such as temperature, velocity of air, humidity, weight, solar radiation are measured during experiment work.

The following assumptions were made during the experiment work:

- Flow rate is remains constant throughout specified experiment on the solar dryer.
- Latent heat of vaporization of water is remains constant is 2250 kJ/kg for the temperature range of drying chamber.
- Thermal conductivity of glass wool varies in the range from 0.035 to 0.045 W/m-K. It is considered 0.04 W/m-K (average) at temperature of solar dryer.
- Thermal conductivity of ACP sheet is 0.415 W/m-K.
- Heat transfer coefficient of atmospheric air is considered constant 1.4 W/m²-K at 30 °C outside atmospheric temperature.

Mathematical Analysis

Overall Het Loss Coefficient \((U_L)\) W/m²-K

\[
U_L = U_p + U_t + 2 \times U_s
\]  (1)

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

\[
Q_u = A_c \times [I_t \times \beta \times \alpha - U_L \times (T_m - T_a)]
\]  (2)

Mass Flow Rate of Air \((m)\) kg/s

\[
m = Q \times \varphi
\]  (3)

Efficiency of Solar Collector \((\eta_c)\)

\[
\eta_c = \frac{m \times C_p \times (T_a - T_m)}{I_t \times A_c}
\]  (4)

Efficiency of Solar Dryer \((\eta_d)\)

\[
\eta_d = \frac{m \times L_d}{I_t \times A_c}
\]  (5)

Average Drying Rate \((m_{dr})\) Kg/hr

\[
m_{dr} = \frac{m_w}{\tau_d}
\]  (6)

Average Heat Required for Drying \((Q_r)\) KJ

\[
Q_r = m_w \times L_r
\]  (7)

Results and Discussions

The observed various parameters such as solar radiation \((I_t)\), average temperature on absorber pipe \((T_m)\) and average temperature inside the absorber pipe \((T_p)\) with respect to time for three set of experiment work are shown in Fig. 3, 4 and 5. Absorber pipes absorb solar radiation which emits by sun, and radiation trapped into solar collector in form of heat.
Solar Radiation and Temperatures of Absorber Plate and PCM chamber

Experiment No: 1

Solar Radiation W/m$^2$
Temperature (°C)
Time (hr)

Tm (Without PCM)
Tp (Without PCM)
Tm (With PCM)
Tp (With PCM)
It (Without PCM)
It (With PCM)

Experiment No: 2

Solar Radiation W/m$^2$
Temperature (°C)
Time (hr)

Tm (Without PCM)
Tp (Without PCM)
Tm (With PCM)
Tp (With PCM)
It (Without PCM)
It (With PCM)

Experiment No: 3

Solar Radiation W/m$^2$
Temperature (°C)
Time (hr)

Tm (Without PCM)
Tp (Without PCM)
Tm (With PCM)
Tp (With PCM)
It (Without PCM)
It (With PCM)
Solar Radiation and Temperatures of Absorber Plate and PCM chamber

In all radiation graphs sudden variations due to clouds which resist radiation coming from sun. In all temperature graphs initially, thermocouple indicated some temperature above the atmospheric temperature due to internal energy of absorber stored heat during idle period.

In case of experiment without PCM, radiation was decreased due to clouds, and hence temperatures of absorber plate and PCM chamber were decreased, since air starts to absorb stored heat from absorber during lower radiation. The temperature of absorber plate was decreased drastically at the end of the experiment, as solar radiation was absent; air starts to absorb heat from absorber plate.

In case of experiment with PCM, drops in radiation value did not affect temperature of absorber, because air absorbs heat from PCM.

In both case (With PCM and Without PCM), higher flow rate leads to lower system temperature. This is due to more amount of air came into contact with absorber at higher flow rate of air, which absorbs more amount of heat cause low system temperature. In case of solar dryer with use of PCM, air gets heated from PCM in absence of solar radiation (during cloudy weather or after sunset), as PCM contains heat which was already stored in it during bright sunshine hours. Experiments with PCM, the temperature of absorber plate (Tm) and temperature of PCM (Tp) remains almost same in all experiments since PCM absorbs or releases latent heats whenever temperature variation occur in absorber plate.

Inlet, Outlet Humidity and Temperature of Air

| Time (hr) | Experiment No: 1 |
|----------|------------------|
|          | Experiment No: 2 |
| Inlet %RH(in) | Outlet %RH(OUT) |
| Without PCM | With PCM |

Inlet, Outlet Humidity and Temperature of Air
Inlet, Outlet Humidity and Temperature of Air

The observed various parameters such as air temperature at collector outlet (T5), %RH (Inlet) and %RH (Outlet) with and without PCM with respect to time for three set of experiment work are shown in Fig. 6, 7 and 8. The air temperature at collector outlet (T5) was directly proportional to absorber plate temperature (Tm). In all experiments, at starting value of %RH (In) was higher and then decreased, because increment in air temperature leads to dehumidification of air.

In all experiments, difference between %RH (In) and %RH (Out) was decreased as flow rate is increased. Due to higher flow rate, air does not get sufficient time to absorb more moisture content. However, at higher flow rate more amount of air came into contact with product which causes better drying operation.

In experiments of with PCM, at the end of experiment value of %RH (In) and %RH (Out) became almost same. In other words, product was completely dried or ability of air to absorb moisture from the product is became zero. Outlet humidity %RH (out) was higher at starting and it was decreasing, since at starting of experiment product have more amount of moisture content and towards the end moisture content of product was less.
As shown in Fig. 9, 10 and 11, Qu is indicating heat gain by the absorber (from sun) and Qr indicates the heat required for drying operation.

From Figures, it is clear that the heat availability is higher than the requirement. It creates opportunity to use PCM with solar dryer. In this case main function of PCM is to absorb heat whenever heat available is higher than requirement; releases heat whenever heat requirement is higher than availability.

When heat available at absorber than requirement, the PCM was charged (PCM absorbs heat as latent heat). Similarly, PCM discharge heat when heat gain by absorber was less than requirement. In the graphs negative value of Qu indicates that no heat gained from sun (value of solar radiation was almost zero for particular time) or heat loss is higher than the heat gained from sun. The value of Qu is greater than Qr indicates charging of PCM and value of Qu is less than Qr indicates discharging of PCM.
It is clear from Fig. 12,13 and 14, efficiency of collector ($\eta_d$) increases with increasing the mass flow rate of air ($m$). There is rapid variation in efficiency of collector with respect to due to variation in solar radiation ($I_{t}$) and difference between the temperatures inlet ($T_8$) and outlet ($T_5$) of collector. In that case, it is difficult to conclude from observations. However, trend line indicates that efficiency of collector ($\eta_d$) increases with increasing the mass flow rate of air. Without PCM average efficiency of collector for experiment no. 1,2 and 3 was about 25%, 44% and 64% respectively.

In case of dryer with PCM, observations indicate clear idea that efficiency of collector ($\eta_d$) increases with increasing the mass flow rate of air. With PCM average efficiency of collector for experiment no. 1,2 and 3 was 32%, 53% and 67% respectively. It is also clear that the efficiency of collector with PCM for particular flow rate is higher than that of without PCM.
Mass Flow Rate and Efficiency of Collector

| Experiment No: | 1 | 2 |
|---------------|---|---|
| ƞc (Without PCM) |  |  |
| ƞc (With PCM) |  |  |
| $m$ (Without PCM) |  |  |
| $m$ (With PCM) |  |  |
Mass Flow Rate and Efficiency of Collector

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Fig. 15, 16 and 17, shows solar radiation ($I_t$) and dryer efficiency ($\eta_d$) with respect to time with and without the PCM. The dryer efficiency is decreases with increase in solar radiation in all cases. This indicates that heat available from radiation is not fully utilized for drying purpose. This is due to air getting saturated. The dryer efficiency has sudden increment in at beginning and ending as solar radiation comparatively very low, at that time the air is heated through stored heat of PCM chamber. Without PCM average efficiency of dryer for experiment no. 1, 2 and 3 was about 11%, 10% and 15% respectively. With PCM average efficiency of dryer for experiment no. 1, 2 and 3 was about 21%, 22% and 22% respectively. The average efficiency of dryer with PCM is comparatively higher than that of without PCM. This was the aimed to use PCM with dryer.
3. Conclusions

The experimental investigation on solar dryer is made for three air flow rates; dryer with PCM and without PCM.

The following findings are drawn from the experimental analysis:

The higher flow rate of air causes lower system temperature and reduced drying cycle time. Third flow rate air (three fans are running) is best among three in order to get better dried product and its quality.

It is clear from experiment that the heat availability is higher than the requirement. It creates opportunity to use PCM with solar dryer. In this case main function of PCM is to absorb heat whenever heat available is higher than requirement; releases heat whenever heat requirement is higher than availability. The use of PCM extends the drying process even during off sunshine hours. It is observed that dryer with PCM extends drying duration as about 1 hour, 2 hours, and 3 hours during experiments No: 1 (one fan is working), 2 (two fans are working), and 3 (three fans are working) respectively.

The use of PCM with dryer increases collector efficiency, i.e. average collector efficiency is increased about 6.99%, 9.84%, and 2.23% during experiments No: 1 (one fan is working), 2 (two fans are working), and 3 (three fans are working) respectively compared to dryer without PCM.

This work provides guide line to use PCM with the solar dryer to get optimum performance.
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