Performance analysis of a mixed mode forced convection solar dryer with and without thermal energy storage heat exchanger

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Abstract. A mixed mode forced convection solar dryer with and without thermal energy storage is developed for drying of different agricultural products. The drying kinetics of bitter gourd has been investigated under open sun drying and using solar dryer. The average drying efficiency of mixed mode solar dryer with thermal energy storage system was 32% and without thermal energy storage, it was found to be 24.5%. The bitter gourd slices were dried from initial moisture content of 90% (wb) to the final moisture content of 9% (wb) within 6 hr, 8 hr and 11 hr in solar dryer with thermal energy storage system, solar dryer without thermal storage and open sun drying conditions. The drying kinetics studies were performed for the three conditions and found that Midilli – Kucuk model was suited for the product dried in solar dryer and logarithmic model was found to fit for the open sun dried product. The color change values of the fresh, solar dried and open sun dried samples were 65.4, 56.8 and 46.8 respectively.

1. Introduction

Food is the basic need for a human being after water and air. Harvesting losses are more in developing countries like India due to lack of post harvesting techniques at rural places. In India, these losses are about 20-30% in fruits and vegetables and 5-10% in food grains [1]. To avoid these losses between harvest and consumption of the product, drying is necessary. Drying is defined as a process of moisture removal due to simultaneous heat and mass transfer operation. Open sun drying (OSD) is the most well-known technology used in many tropical countries. This type of drying does not fulfill the quality standards due to improper heating of the product, sudden rain, dust, rodents, etc. Further, OSD also requires large floor area and high labor cost. To overcome the above issues and also to utilize the solar radiation in an appropriate manner, solar dryers have been used widely. This technology enhances the quality of the product and also reduces the drying time period. Over the last three decades, many researchers have developed variety of solar dryers for drying of different agricultural products like mint, grapes, pepper, chili, ginger etc. [2-6]. The disadvantages of solar drying systems are the intermittent availability of solar energy and solar drying cannot be effectively during bad weather conditions. Solar drying with thermal energy storage is a promising solution for the continuous drying of agricultural products. An indirect natural convection solar dryer with sand as sensible heat storage material has been developed and tested for drying of grapes, figs and apples [2]. Shalaby and Bek [6] developed an indirect
forced convection solar dryer integrated with latent heat storage module for drying of thymus and mint. The storage heat exchanger placed separately and the accumulated heat released from the storage maintained the drying air temperature higher than the ambient temperature by 2.5 – 7.5 °C for 5 hr after the sunset. Forced convection solar dryer integrated with shell and tube based heat exchanger was developed for drying of red chili from initial moisture content 73.5% (w.b) to 9.7% (w.b) in 4 consecutive days and in case of open sun drying, the drying was completed in 10 days [8].

Drying kinetics of product is affected by drying air temperature, relative humidity, moisture content and sample size. Many drying kinetic studies were reported in the literature for drying of different agricultural products. Thin layer drying kinetics of ghost chili pepper was studied in a forced convection solar dryer by Rabha et al. [9]. The ghost chili pepper was dried from initial moisture 589.6%(d.b) to final moisture content 12% (d.b) in 123 hr and 193 hr in solar drying and open sun drying, respectively including night hours. An indirect forced convection solar dryer with pebble bed storage was developed by Vijayan et al [10] for drying of bitter gourd slices from initial moisture content of 92% to final 9% in 7 hr and 10 hr in solar and open sun drying conditions, respectively. Two term and page model was found best suited for solar and open sun drying conditions. From the literature, it is observed that there is no work reported on drying of bitter gourd in a mixed mode forced convection solar dryer integrated with thermal energy storage system. The drying kinetics of bitter gourd is studied by applying experimental moisture transfer data to 6 drying kinetic models available in the literature to find the best model. Further, effective moisture diffusivity of the product during drying process is also found for mixed mode solar dryer without thermal energy storage, mixed mode solar dryer with thermal energy storage and open sun drying conditions.

2. **Drying Kinetic Analysis:**

The moisture ratio of the product was calculated with the help of the following Eqs. 1 – 5[8].

\[
MR = \frac{M_t - M_e}{M_o - M_e} \quad (1)
\]

\[
MR = \frac{M_t}{M_o} \quad (2)
\]

The relative humidity fluctuated continuously during the experiment. So, the moisture ratio was calculated using Eq. 1 (neglecting the equilibrium moisture content \(M_e\)). \(M_t\) is the moisture content at time \(t\) and \(M_o\) is the initial moisture content. The mass of water evaporated from the product was calculated by employing Eq. 3. Where \(m_p\) is the mass of the product and \(M_i\) and \(M_f\) are initial and final moisture contents of the product on wet basis.

\[
m_w = \frac{m_p (M_i - M_f)}{100 - M_f} \quad (3)
\]

Energy input to the dryer is given by using Eq.4, \(A_{\text{SAH1}}, A_{\text{SAH2}}\) and \(A_{\text{dryer}}\) are areas of solar air heaters and dryer, \(I\) is the average solar radiation intensity and \(PB\) is power consumed by the blower.

\[
E_d = \left( A_{\text{SAH1}} + A_{\text{SAH2}} + A_{\text{dryer}} \right) \times I + PB \times t_{\text{mixed mode}} \quad (4)
\]

The dryer efficiency is defined as the ratio of amount of energy required to remove moisture from the product to energy input to the dryer.

\[
\eta_{\text{mixed mode}} = \frac{m_w \times h_{fg}}{E_d} \quad (5)
\]

The drying kinetic analysis was carried out using various drying kinetics models presented in Table 1. The regression analysis was done by using Excel-solver equation. The chi square distribution (\(\chi^2\)), RMSE (Root Mean Square Error) and coefficient of determination (\(R^2\)) were calculated. The model
which has highest $R^2$ value of coefficient of determination was considered as the best suited one.

Table 1. Drying kinetic models present in literature [7].

| Sl. No | Model name            | Model equation               |
|--------|-----------------------|------------------------------|
| 1      | Newton                | $MR = \exp(-k^*t)$          |
| 2      | Page                  | $MR = \exp(-k^*t^\prime)$   |
| 3      | Henderson and Pabis   | $MR = a^*\exp(-k^*t)$       |
| 4      | Logarithmic           | $MR = a^*\exp(-k^*t) + c$   |
| 5      | Two Term              | $MR = a\exp(-k_1t) + b\exp(-k_2t)$ |
| 6      | Midilli-Kucuk         | $MR = a\exp(-kt^\prime) + b't$ |

The effective moisture diffusivity can be calculated from Eq. (6) [11] by the method of slopes

$$MR = \frac{8}{\pi^2} \exp \left[ \frac{-D_{\text{eff}} \pi^2 t}{4L_s^2} \right]$$

Where $D_{\text{eff}}$ is the effective moisture diffusivity, $L_s$ is the product thickness and $t$ is the drying time. A curve is plotted between ln (MR) and $t$. The slope of the curve gives the rate constant $k = \frac{\pi^2 D_{\text{eff}}}{4L_s^2}$.

Color of fresh and dried bitter guard slices was measured in terms of the $L^*$, $a^*$ and $b^*$ values using a hunter lab colorimeter (D25 LT, Hunter lab, USA). The $L^*$ value is the degree of lightness, $a^*$ value is the degree of redness (+) and greenness (-), and $b^*$ value is the degree of yellowness (+) and blueness (-). Prior to determination, the colorimeter was calibrated with a standard white and black ceramic plates. The color change of bitter guard samples due to drying was characterized by the total color change ($\Delta E$), which was calculated by Eq.7 [12].

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

Where $\Delta L^* = L^* - L_0^*$, $\Delta a^* = a^* - a_0^*$, $\Delta b^* = b^* - b_0^*$

3. Experimental setup and Procedure: A schematic of mixed mode forced convection solar dryer with and without thermal energy storage system is shown in Fig.1. The setup mainly consists of two double pass counter flow solar air heaters which are connected in series, a mixed mode solar dryer with six trays and a thermal energy storage system (TES). Dimensions of two solar air heaters are 2 m long and 1m width and 20 mm depth. The two air heaters are connected in series; ambient air enters from the first air heater, passes initially over the absorber plate and then below the absorber plate of the solar air heater and thereafter enters into the second air heater. The solar air heater consisting of 1 mm black coated GI plate. The heated air passes from the collector to the TES system, if the system operates with thermal energy storage; which consists of 35 kg of paraffin filled in the shell side. The heated air passes through 10 copper tubes embedded in TES. By absorbing the heat from the HTF (heat transfer fluid), the paraffin wax starts melting (charging) and during off peak time, it delivers (discharging) the heat back to the HTF for continuous drying. The temperature at different locations of the air heaters is measured with the help of T-type thermocouples connected to a data logger. Solar radiation intensity was measured with the help of a pyrano meter on the hourly basis. Solar air heaters were positioned at 25° south to maximize the solar radiation intensity. Experiments have been performed under two different conditions (i) drying of bitter gourd slices without thermal energy storage and (ii) drying with thermal energy storage from morning 9 am to 6 pm and compared with the open sun drying.
The fresh bitter gourd was purchased from the local market and removed riped and rotten bitter gourd, and cleaned in the running water. After that, the water was removed by using a soft cloth. The bitter gourd slices were cut into 5-10 mm thickness and 45-50 mm length. Ten kg of slices were placed in the 6 trays, along with 200 g of the sample inside the dryer to study the drying behaviour. Simultaneously, another 200 g of sample was placed in open sun drying for comparing the quality and drying time. The position of trays was interchanged on hourly basis from top to bottom to get uniform drying.

4. Results and Discussion:

The experiments were performed during the month of January and February 2016 without and with thermal energy storage system. The hourly variation of collector outlet, ambient, dryer inlet and outlet temperature were measured at a fixed mass flow rate of 0.02 kg/s (Fig.2). The maximum collector outlet temperature was found to be 59.4°C at 12.15 pm with a corresponding solar radiation intensity of 720 W/m². The amount of moisture evaporated for drying 10 kg bitter gourd slices was 8.8 kg of water. The product was dried in 6 hr when the thermal energy storage was integrated. The energy consumed by the blower was 250 W and the average solar radiation intensity was measured as 500 W/m². Total glazing area of the dryer is 5.6 m². Based on these conditions, the average solar dryer efficiency with thermal energy storage was estimated as 32% (using Eq.5). Without thermal energy storage, the drying time was 8 hr and the average solar dryer efficiency was found to be 24.5%. By using thermal energy storage, the system efficiency can be improved by 25%. This is mainly due to the supply of air at near uniform temperature. While in case of dryer without thermal energy storage system, the drying air temperature is solely depending on the solar radiation. The hourly variation of moisture content on wet basis and moisture ratio of bitter gourd slices were measured with different conditions. As illustrated in Fig.3, the desired moisture content (9% on wet basis) was reached within 6 hr when dried in mixed mode dryer with thermal energy storage, 8 hr in solar dryer without thermal energy storage and 12 hr in open sun drying condition.
The thin layer drying models given in Table 1 were fitted to experimental moisture ratio with drying time by nonlinear regression analysis. The result of regression analysis is reported in Table 2. Based on the statistical parameters, the high value of correlation coefficient and low chi square distribution, it was found that Midilli-Kucuk model was best suited for solar drying with and without thermal energy storage and logarithmic model was suited for open sun drying conditions. The effective moisture diffusivity of the product was found with the help of graphical method and the values are $3.85 \times 10^{-5}$ (m$^2$/s), $2.65 \times 10^{-5}$ (m$^2$/s) and $4.18 \times 10^{-6}$ (m$^2$/s) respectively for the solar drier drying with and without thermal energy storage and the open sun drying.
Table 2: Various drying kinetic models used for analysis of bitter gourd slices drying

| Sl. No | Model name                | Mixed mode solar dryer with TES | Mixed mode solar dryer without TES | Open sun drying |
|--------|---------------------------|---------------------------------|-----------------------------------|----------------|
| 1      | Newton                    | \( k = 0.485 \), \( R^2 = 0.9967 \), \( \chi^2 = 0.000576 \) | \( k = 0.2397 \), \( R^2 = 0.9738 \), \( \chi^2 = 0.000305 \) | \( k = 0.2937 \), \( R^2 = 0.9738 \), \( \chi^2 = 0.0045 \) |
| 2      | Page                      | \( k = 0.4672 \), \( n = 1.0391 \), \( R^2 = 0.9954 \), \( \chi^2 = 0.000542 \) | \( k = 0.1876 \), \( n = 1.3434 \), \( R^2 = 0.9983 \), \( \chi^2 = 0.0008 \) | \( k = 0.19926 \), \( n = 1.188 \), \( R^2 = 0.9626 \), \( \chi^2 = 0.0046 \) |
| 3      | Henderson and Pabis       | \( a = 0.4889 \), \( k = 0.1876 \), \( n = 1.0391 \), \( R^2 = 0.9954 \), \( \chi^2 = 0.000542 \) | \( a = 1.0575 \), \( k = 0.3103 \), \( n = 1.3434 \), \( R^2 = 0.9773 \), \( \chi^2 = 0.002819 \) | \( a = 1.028 \), \( k = 0.2866 \), \( n = 1.188 \), \( R^2 = 0.9664 \), \( \chi^2 = 0.004089 \) |
| 4      | Logarithmic               | \( a = 0.9917 \), \( k = 0.5154 \), \( c = 0.01995 \), \( R^2 = 0.9956 \), \( \chi^2 = 0.00051 \) | \( a = 1.1576 \), \( k = 0.2446 \), \( c = -0.1197 \), \( R^2 = 0.9845 \), \( \chi^2 = 0.00290 \) | \( a = 1.028 \), \( k = 0.2866 \), \( c = 0.046 \), \( R^2 = 0.9993 \), \( \chi^2 = 0.004626 \) |
| 5      | Two Term                  | \( a = 0.5038 \), \( b = 0.5338 \) | \( a = 0.5287 \), \( b = 0.6528 \), \( k_1 = 0.310 \), \( k_2 = 0.285 \), \( R^2 = 0.9787 \), \( \chi^2 = 0.003955 \) | \( a = 0.5293 \), \( b = 0.5239 \), \( k_1 = 0.2527 \), \( k_2 = 0.2527 \), \( R^2 = 0.9636 \), \( \chi^2 = 0.0449 \) |
| 6      | Midilli-Kucuk             | \( a = 0.9921 \), \( k = 0.4537 \), \( n = 1.2268 \), \( b = 0.0117 \), \( R^2 = 0.9988 \), \( \chi^2 = 0.00055 \) | \( a = 0.9866 \), \( k = 0.1664 \), \( n = 1.5277 \), \( b = 0.00901 \), \( R^2 = 0.99762 \), \( \chi^2 = 0.000444 \) | \( a = 1.0193 \), \( k = 0.1546 \), \( n = 1.4815 \), \( b = 0.00109 \), \( R^2 = 0.9839 \), \( \chi^2 = 0.003819 \) |

Table: 3 Color analyses of bitter guard fresh, solar and open sun dried samples

| Parameters       | L*    | a*    | b*    | \( \Delta E^* \) |
|------------------|-------|-------|-------|------------------|
| Fresh Samples    | 59.567| -10.227| 25.07 | 65.467          |
| Dried Samples    | 52.11 | 0.736 | 22.803| 56.886          |
| Open sun drying  | 43.5  | 0.98  | 17.53 | 46.89           |

The effective moisture diffusivity of the solar dried product was found to be higher than that of the product dried in the open sun drying conditions. Color is one of the most vital sensory qualities of food product. In this study, color of the dried samples was measured using Hunter lab colorimeter. Mean surface color values (L*, a* and b*) of fresh, dried bitter guard under solar and open sun drying samples are presented in Table 3.
5 Conclusion: The mixed mode forced convection solar dryer has been developed for drying of bitter gourd with and without TES system. The following conclusions were obtained.

- The average drying efficiency of the mixed mode forced convection solar dryer with TES system was 25% more compared to the solar dryer without TES system.
- The bitter gourd slices were dried from initial moisture content 90% (wb) to 9% (wb) in 6 hr when the mixed mode solar drier was integrated with thermal energy storage system, in 8 hr without thermal energy storage and in 12 hr in open sun drying condition.
- Midilli –Kucuk model is best suited for presenting the drying kinetics in mixed mode solar dryer and logarithmic model is best for representing the drying of bitter gourd in open sun drying.
- The effective moisture diffusivity values of the product was found with the help of graphical method and the values are $3.85 \times 10^{-5}$ (m$^2$/s), $2.65 \times 10^{-5}$ (m$^2$/s) and $4.18 \times 10^{-6}$ (m$^2$/s) for the solar drier drying with and without thermal energy storage and the sun drying, respectively.

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