Modelling of vacuum drying of cherry pepper

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ABSTRACT

Drying is a complex phenomenon and study of drying kinetics and modelling is very important for describing the moisture movement with respect to time and predicting the dryer performance. Considering this fact, vacuum drying characteristics of cherry pepper was studied at different drying temperatures (50, 60 and 70°C). Cherry pepper were dried from initial moisture content of about 400% (dry basis) to 13 – 14.5% (dry basis) at different temperatures at 630 mm Hg vacuum. Time required to dry cherry peppers at 50, 60 and 70°C plate temperatures were 19 h, 9.75 h and 8 h respectively. Moisture reduction of cherry pepper at various temperatures was modelled using thin-layer models viz. Lewis, Page, Modified Page and Henderson & Pabis model. Based on highest value of coefficient of determination, lowest values of reduced chi square and root mean square error, Modified Page model was found to be the best fit. Moisture diffusivity increased from $6.27 \times 10^{-10}$ to $1.9 \times 10^{-9}$ m$^2$/s$^{-1}$ as plate temperature increased from 50 – 70°C. Activation energy was estimated to be 50.98 kJ/gmol$^{-1}$.

Key words: Cherry pepper, Effective moisture diffusivity, Thin-layer model, Vacuum drying.

INTRODUCTION

Cherry pepper (Capsicum frutescens var. cerasiforme) is a small, round shaped, mild to medium hot pepper that derives its name from its cherry like shape and appearance. Cherry pepper, locally known as Dalle Khorsani, is an important cash crop of Sikkim and Darjeeling hills in India and is very popular for its strong aroma and pungency. Due to higher moisture content (about 80% wet basis), drying can be employed to improve the shelf life of cherry pepper and increase the off-season availability at affordable prices.

Chillies are required to be dried to 8-11% (dry basis) moisture content for safe storage (Satyanarayana and Vengaiah, 2010). Sun drying takes about 14 – 21 days and is climate-dependent (Kaleemullah and Kaliappan, 2005). Moreover, the low drying rate, exposure to environmental condition, contamination by pathogens, rodents, birds and insects, manual labour requirement, poor product quality results in poor economic efficiency of the process (Aghbashlo et al., 2008).

Vacuum drying is another alternative drying method that can be effectively used for heat sensitive fruits and vegetables (Giri and Prasad, 2007). As the system temperature is kept below 75°C, products that are sensitive to oxygen and heat can be dried by vacuum drying (Jena and Das, 2007). Characteristics of this drying technique such as high drying rate, low drying temperature and oxygen deficient drying environment may help to maintain the qualities such as shape, color, aroma and flavor and nutritive values of the dried product (Alibas, 2007).

Mathematical modeling of thin layer drying is important for performance improvement of drying systems (Cihan et al., 2007). Drying kinetics models are essential for equipment design, process optimization and product quality improvement (Lee and Zuo, 2013). In recent years, thin layer drying behaviour of chillies has been studied by several researchers (Charmongkolpradit et al., 2010; Banout et al., 2011; Fadhel et al., 2014) which focussed on either sun, solar or hot air drying methods for drying of red pepper. Alibas (2012) investigated vacuum drying characteristics of red chilli pepper under varying temperature and pressure conditions. Artpansew et al., (2010a and b) developed a heat pump vacuum dryer for vacuum drying of Jinda chilli and Yodsun chilli. Very few researchers have worked on vacuum drying and heat pump drying of chillies (Alibas, 2012; Artpansew et al. 2010a and b). In light of the above, the following objectives were performed: to investigate vacuum drying characteristics of cherry pepper at different drying temperatures to evaluate several thin-layer drying models available in literature and to estimate effective moisture diffusivity.

MATERIALS AND METHODS

Materials: Fresh cherry pepper samples of local variety “Dalle” were procured from local market (Sikkim, India) during August, 2015 and stored at 4 ± 0.5°C in a refrigerator

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before use. Cherry pepper of relatively uniform size (average diameter and length of 2.2 ± 0.2 cm and 2.9 ± 0.2 cm respectively) was used in the tests. Moisture contents of fresh cherry peppers were determined by standard convective oven drying method at 105 °C for 24 h. The initial moisture content of the fresh cherry pepper samples was 80 ± 0.5% (wet basis).

Experimental setup: A laboratory model vacuum tray dryer (Fig. 1) was used for drying of cherry pepper. It mainly consisted of an insulated stainless steel drying chamber (49 cm × 49 cm × 38 cm) with three hollow stainless steel shelves for circulation of hot water, a water ring type vacuum pump, condenser, water chillers integrated with refrigeration unit (0.5TR), hot water tank with in-built PID controlled water heaters and stainless steel trays (40.5 cm × 40.5 cm).

Fig: 1 Schematic diagram of vacuum drying setup. 1. Drying chamber, 2. Hot water tank, 3. Hot water pump, 4. Condenser, 5. Water chiller, 6. Receiver, 7. Water ring vacuum pump, 8. Motor of the vacuum pump, 9. Sealing water tank.

Experimental procedure: About 230 g of fresh cherry pepper were used for each drying experiment. Weight loss of the drying samples was measured at one hour interval with a weighing balance (Shimadzu, model: BL2200H) having an accuracy of ± 0.01 g. Moisture content at different time intervals was calculated from the weight loss. Samples were dried till final moisture content of 13 – 15% (d. b.). The experiments were carried out at a vacuum of 630 mm Hg (i.e. 17.33 kPa absolute pressure) and 50, 60 and 70°C. Each experiment was replicated three times and the average values were used.

Mathematical modelling of drying curves: Dimensionless moisture ratio (MR) of samples was calculated using the experimental moisture reduction data taken at three different temperatures.

\[
MR = \frac{M_t - M_e}{M_i - M_e} \tag{1}
\]

Where, \(M_t\) is moisture content of cherry pepper at time \(t\), \(M_i\) is equilibrium moisture content at the drying conditions and \(M_e\) is initial moisture content.

The values of \(M_t\) for vacuum drying conditions are relatively small compared to \(M_i\) or \(M_e\) (Taniguchi and Nisshio, 1991). Thus according to Akgun and Doymaz (2005) and Arnasew et al., (2010b), the expression of moisture ratio (MR) can be reduced as:

\[
MR = \frac{M_t}{M_i} \tag{2}
\]

Four well-known thin-layer drying models as detailed in Table 1 were selected and fitted in the experimental data in their linear form using regression technique. The best fit model was selected based on the highest value of \(R^2\) and lowest values of \(\chi^2\) and RMSE.

\[
\chi^2 = \frac{1}{N - z} \sum_{i=1}^{N} (MR_{exp,i} - MR_{pred,i})^2 \tag{3}
\]

\[
RMSE = \left(\frac{1}{N} \sum_{i=1}^{N} (MR_{exp,i} - MR_{pred,i})^2\right)^{1/2} \tag{4}
\]

where, \(MR_{exp,i}\) is the experimental moisture ratio, \(MR_{pred,i}\) is the predicted moisture ratio, \(\chi^2\) is the reduced chi square, \(N\) is the number of observations and \(z\) is the number of constants in the model, \(RMSE\) is the root mean square error.

Estimation of effective moisture diffusivity and activation energy: Effective moisture diffusivity was calculated using Fick’s diffusion equation. Considering a spherical shape of the cherry peppers, the equation for radial diffusion of moisture is,

\[
\frac{\partial M(r,t)}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 D \frac{\partial M}{\partial r} \right) \tag{5}
\]

Assuming uniform initial moisture distribution in the spherical product and symmetrical radial diffusion of moisture, Eq. (5) was solved analytically as,

\[
MR = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp(-n^2 \pi^2 D . t) \tag{6}
\]

Assuming constant values of radius \(R\) and diffusion coefficient \(D\), Eq. (6) can be further simplified to only the

Table 1: Thin-layer drying models applied to vacuum drying of cherry pepper.

| Name of Model     | Model          | Reference               |
|-------------------|----------------|-------------------------|
| Lewis             | \(MR = \exp(-k \ t)\) | Alibas (2012); Arslan and Özcan (2011) |
| Page              | \(MR = \exp(-k \ t^a)\) | Arnasew et al. (2010b); Lee and Zuo (2013) |
| Modified Page     | \(MR = \exp(-k \ t)^a\) | Arnasew et al. (2010b); Alibas (2012) |
| Henderson and Pabis| \(MR = a \exp(-k \ t)\) | Alibas (2012); Lee and Zuo (2013) |
first term of the series (Eq. 7) for long drying periods (Aghbashlo et al., 2010; Domyaz and Ismail, 2011).

\[
\ln MR = \ln \left( \frac{6}{\pi^2} - \frac{\pi^2 D \tau}{R^2} \right) \tag{7}
\]

Where, \( MR \) is moisture ratio at drying time \( \tau \) in s, \( R \) is the radius of spherical cherry pepper in m, \( D \) is effective moisture diffusivity in m\(^2\)s\(^{-1}\).

\( D \) was determined by plotting experimental data in terms of \( \ln(MR) \) versus drying time \( \tau \). \( D \) was calculated from the slope of the best fit straight line as,

\[
slope = -\frac{\pi^2}{R^2} D \tag{8}
\]

\( D \) was related to drying temperature by Arrhenius equation as,

\[
D = D_o e^{\frac{E_a}{RT}} \tag{9}
\]

Where, \( D \) is effective moisture diffusivity in m\(^2\)s\(^{-1}\), \( D_o \) is the constant equivalent to the diffusivity at an infinitely high temperature in m\(^2\)s\(^{-1}\), \( E_a \) is the activation energy in kJkgmol\(^{-1}\), \( R \) is the universal gas constant in kJkg mol\(^{-1}\)K\(^{-1}\), and \( T \) is the absolute temperature in K. Eq. (9) was linearized as,

\[
\ln(D) = \ln(D_o) - \frac{E_a}{R} \left( \frac{1}{T} \right) \tag{10}
\]

The activation energy \( E_a \) and the constant \( D_o \) were determined by plotting \( \ln(D) \) versus \( 1/T \).

RESULTS AND DISCUSSION

Drying characteristics: The drying curve of cherry pepper under varying drying temperatures is shown in Fig. 2. It can be seen that the time required to dry cherry peppers from initial moisture content of 400 ± 0.5% (d. b.) to a moisture content of about 13 – 14.5% (d. b.) under vacuum at 50, 60 and 70°C was 19 h, 9.75 h and 8 h respectively. The drying time decreased with increase in drying temperature from 50 to 70°C. These results can be corroborated by the findings of Artnaseaw et al., (2010a and b) for vacuum heat pump drying of chillies where, drying time ranged from 9 – 17 h at temperatures of 50 – 65°C.

Fig. 3 shows variation of drying rate with moisture content of cherry pepper at different drying temperatures. It can be observed that vacuum drying of cherry pepper was entirely under falling rate drying period. During this period, the drying process was controlled mainly by diffusion mechanisms. This is in agreement with other reported literature for solar drying of chilli (Tunde-Akintunde and Afolabi, 2010), and for vacuum heat pump drying of Jinda chilli (Artnaseaw et al., 2010a) and for convective drying of strawberries (Domyaz, 2008). Drying rate was high at the initial stages of drying, when the moisture content of the samples was high. Drying rate decreased with decrease in moisture content and temperature. Similar results have been reported by Lee and Zuo (2013) for vacuum drying of Z. jujube miller.

Mathematical modelling of drying curves: The drying data were fitted to the selected models mentioned in Table 1. The values of constants \( k \) and coefficients \( a \) and \( n \) have been presented in Table 2. The statistical parameters for goodness of fit of the models, such as \( R^2 \), \( \chi^2 \), and RMSE were calculated using Eq. (3) and (4). Lowest \( \chi^2 \) and RMSE values and highest \( R^2 \) value indicate better goodness of fit. The details of analysis are shown in Table 2.

Table 2 reveals that both Page and Modified Page model showed similar \( R^2 \) values (0.9824-0.9939), which was the highest among all models at all drying temperatures. However, Modified Page model exhibited lowest values of \( \chi^2 \) (0.0004 – 0.0019) and RMSE (0.0165 – 0.041). Based on these criteria, Modified Page model may be assumed to be the best fit model.

Fig 4 shows the comparison of the predicted moisture ratios obtained by Modified Page model and the experimental MR values at various drying air temperatures 50, 60, and 70°C. The selected best fit model was validated by comparing the experimental MR ratio with the predicted ones as shown in Fig 4. It can be seen that, this model was in good agreement with the experimental results. This confirms that the Modified Page model could be suitably used to predict thin-layer drying behavior of cherry pepper.
Effective moisture diffusivity and activation energy:

Effective moisture diffusivity during vacuum drying of cherry peppers at different temperatures was calculated using Eq.(7) and (8). Values of effective moisture diffusivity $D$ at different drying temperatures are presented in Table 3.

From Table 3, it can be observed that effective moisture diffusivity values of cherry pepper were in the range of $6.274 \times 10^{-10}$ – $1.9 \times 10^{-9}$ m$^2$s$^{-1}$ for the selected drying temperature range of 50 – 70°C. These values lie within the general range $10^{-11}$–$10^{-9}$ m$^2$s$^{-1}$ for vacuum drying of food materials (Domyaz and Ismail, 2011; Lee and Zuo, 2013). The moisture diffusivity values increased steadily with increase in drying temperature. This behaviour may be explained due to the increased heating energy, which would increase the activity of the water molecules leading to higher moisture diffusivity at higher temperature (Lee and Zuo, 2013).

Effective moisture diffusivity was related to the temperature by Arrhenius equation as given in Eq. (9). Activation energy was calculated from the plot of ln ($D$) vs. reciprocal of absolute temperature (1/$T$) as shown in Fig. 5. The values of activation energy $E_a$ as calculated from Eq. (10) was found to be 50.98 kJ kg mol$^{-1}$. This value was higher than the reported activation energy values of 24.48 - 37.76 kJ kg mol$^{-1}$ for convective drying of chillies (Kaleemullah,

Table 2: Empirical constants and statistical results from selected thin-layer drying models.

| Model        | Temperature (°C) | Constant  | $R^2$ | $\chi^2$ | RMSE |
|--------------|------------------|-----------|-------|----------|------|
| Lewis        | 50               | 0.1116    | 0.8961| 0.0071   | 0.0819|
|              | 60               | 0.2676    | 0.8961| 0.0093   | 0.0921|
|              | 70               | 0.3417    | 0.9143| 0.0102   | 0.0952|
| Page         | 50               | 0.0538    | 1.2461| 0.9824   | 0.0019| 0.0410|
|              | 60               | 0.1326    | 1.3138| 0.9821   | 0.001 | 0.0278|
|              | 70               | 0.1545    | 1.4136| 0.9939   | 0.0137| 0.1033|
| Modified Page| 50               | 0.0958    | 1.2461| 0.9824   | 0.0019| 0.0410|
|              | 60               | 0.2148    | 1.3138| 0.9821   | 0.001 | 0.0278|
|              | 70               | 0.2668    | 1.4136| 0.9939   | 0.0003| 0.0165|
| Henderson and Pabis | 50 | 0.2754 | 1.3171 | 0.9284 | 0.0755 | 0.2607 |
|              | 60               | 0.3165    | 1.4039| 0.9269   | 0.0244| 0.1412|
|              | 70               | 0.4011    | 1.4003| 0.9436   | 0.0268| 0.1444|

Table 3: Effective moisture diffusivity at different temperatures.

| Temperature (°C) | Effective moisture diffusivity (m$^2$s$^{-1}$) |
|------------------|-----------------------------------------------|
| 50               | $6.274 \times 10^{-10}$                      |
| 60               | $1.45 \times 10^{-9}$                       |
| 70               | $1.9 \times 10^{-8}$                        |
and Kailappan, 2005 and 2006), within the range of the reported values of 49.73 – 54.54 kJ mol\(^{-1}\) for fluidized bed drying of chilli (Charmongkolpradit et al., 2010) and lower than the reported value of 51.26 kJ mol\(^{-1}\) for okra drying (Doymaz, 2005) and 54 kg mol\(^{-1}\) for grapes drying (Azzouz et al., 2002).

**CONCLUSION**

Vacuum drying characteristics of cherry peppers was investigated at different drying temperatures of 50, 60 and 70°C under vacuum of 630 mm Hg. An absence of constant rate drying rate period was observed during vacuum drying of cherry pepper. Drying time decreased with increase in drying temperature. Among the four thin-layer models, Modified Page model was found to be most suitable model for predicting the vacuum drying behaviour of cherry pepper. Effective moisture diffusivity of cherry pepper increased with increase in drying temperature from 50 – 70°C and exhibited Arrhenius behaviour. Activation energy of cherry pepper during drying was calculated as 50.98 kJ kg mol\(^{-1}\).

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