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Original Article

Mass transfer analysis during drying of *Capsicum annum* L. (Chili) in a packed bed dryer with intermittent mixing

B. M. K. Premanath[1], M. N. Rajapakshe[1], B. M. W. P. K. Amarasinghe[1,*] and G. K. Jayatunga[2]

[1]Department of Chemical and Process Engineering, University of Moratuwa, Bandaranayaka Mawatha, Moratuwa, 10400, Sri Lanka; [2]Division of Polymer and Chemical Engineering Technology, Institute of Technology, University of Moratuwa, Diyagama, Homagama, Sri Lanka.

ABSTRACT

This study investigates the fluid flow dynamics within packed beds containing fresh and dried chili (*Capsicum annum* L.) and investigates the impact of temperature on the drying process within an intermittently mixed packed bed dryer. The primary aim is to devise an effective drying technique to mitigate post-harvest losses. Experiments were conducted using a pilot-scale packed bed of 0.15 m diameter. The pressure drop (ΔP) across the chili bed at various airflow velocities (v) was measured, revealing a proportional relationship, $\Delta P \propto v^n$. Fresh chili exhibited a higher-pressure drop compared to dried chili, with respective exponents 'n' of 1.54 and 1.43. The proportionality constant in the equation relating ΔP and v depends on the specific surface area and the porosity of the bed and chili density. The constants were 1782 and 1549 for fresh chili and dried chili, respectively. Reynolds number ranges indicated transitional and turbulent flow regimes during operation. Physical characteristics of chili pods and the packed bed were assessed for both fresh and dried chili. Drying investigations focused on temperature effects, utilizing hot air temperatures of 50 °C, 55 °C, and 60 °C, while maintaining a constant airflow velocity of 1.11 m/s. The initial moisture content of fresh chili (433% dry basis) decreased to 22% over a drying period of 7 hours for 50 °C and 55 °C, and up to 5 hours for 60 °C. Constant drying rates were observed, increasing with temperature: 6.5×10^{-3}, 9.4×10^{-3}, and 12.3×10^{-3} kg of moisture/kg of dry material per minute for 50 °C, 55 °C, and 60 °C, respectively. The gas phase mass transfer coefficient increases with temperature, ranging from 4.6×10^{-3} to 6.4×10^{-3} kg/m^{2}s for temperatures between 50 °C and 60 °C. These findings provide valuable insights for developing efficient drying techniques for chili, facilitating the design and optimization of packed bed dryers to minimize post-harvest losses.

KEYWORDS: chili, packed bed, drying, moisture content, mass transfer.

INTRODUCTION

Annual global post-harvest losses of food produced amount to approximately 1.3 billion tons which is approximately one-third of the food produced [1]. In Sri Lanka losses of agricultural products are at a very high level and it is estimated that the country loses around 20% to 40% of vegetables and 30%-40% of fruits annually due to poor post-harvest operations [2]. Therefore, minimizing post-harvest wastage is vital for solving world food scarcity problems and for improving the economic status of farmers and the country.

Capsicum annum L. (Chili pepper) holds significant importance as a widely utilized spice in various culinary traditions. Effective drying

*Corresponding author: padma@uom.lk

techniques for chili are essential to minimize post-harvest losses, to increase the shelf life and to improve the product quality. In Sri Lanka, open sun dying is commonly used for drying of many agricultural products. However, this method causes several problems due to non-uniform sunshine during the day and low sunshine during rainy season. Improper drying of the products leads to growth of mold and lower the product quality.

Several researchers have conducted experiments on chili drying using different techniques, such as solar drying, fluidized bed drying and hot air drying on a tray dryer or a cabinet dryer [3-6]. Fudholi *et al*. and Kyi *et al*. in their two different studies have compared open sun drying of chili with solar drying and found that the time required for solar drying is 49% and 30% less compared to open sun drying, respectively [3, 4]. Normal Fluidized bed dryers and Fluidized bed dryers with different modifications have been tested for chili drying by many investigators [6-9]. Charmongkolpradit *et al*. dried Jinda chili in a continuous fluidized bed dryer and found that air temperature was a significant factor in the drying process. However, high air velocity of 4 m/s is required for fluidizing [7]. Dongbang *et al*. have conducted experiments on chili drying in a rotating fluidized bed and observed that high temperatures (> 90 °C) adversely affect the color of the final product [8]. Zulkarnain *et al*. compared open sun drying with swirling fluidized bed (SFB) drying of red chili and found that the drying time reduced to 4 days in the SFB dryer compared to 13 days in the open sun dryer [9]. Tasirin *et al*. in their experiments on bird's eye chili in a fluidized bed dryer observed that the optimum temperature for drying is 70 °C [10].

Many researchers have conducted investigations on chili drying in tray or cabinet dryers using hot air [11-14]. Nimrotham experimented on combined sun drying during the daytime and low temperature drying at night and observed bright color and aroma in the final product [11]. Agarry *et al*. conducted experiments on chili drying in a cabinet dryer using hot air and developed a model to predict drying kinetics, energy, and exergy parameters [14]. Arslan *et al*. in their study on drying of sweet red chili in a hot air tray dryer have found that 70-80 °C is the best temperature range to retain the bright color of the chili [12].

Packed bed dryers are commonly used for many applications such as grain, seed and coffee drying [14-17]. Prado and Satori studied heat and mas transfer in drying of seeds in a packed bed dryer [15]. Chen and Pan developed a model for heat transfer in drying walnuts in a packed bed using hot air [16]. Drying characteristics of parboiled paddy in a packed bed was studied by Anuththara *et al*. [17]. Packed beds are suitable for drying of high-density sticky materials which are difficult to fluidized. However packed bed dryer leads to non-uniform moisture content of the final product due to non-mixing and this effect can be overcome by mixing of the material at regular intervals.

Research results on drying of chili in a packed bed dryer are not readily available. Further, information on the flow of air through the packed bed of the material and physical properties of the bed material such as equivalent diameter, sphericity, surface area, bed voidage and density are of vital importance for the design of packed bed columns and for heat and mass transfer analysis during drying. Therefore, the three main objectives of this study are to investigate the packed bed behavior of fresh and dry chili, to determine the physical properties of chili and to study the drying characteristics and perform mass transfer analysis of chili in a packed bed dryer with intermittent mixing.

MATERIALS AND METHODS

Dried red chili was supplied by a local store in Moratuwa, Sri Lanka and stored in an airtight polythene bag at room temperature. Mature fresh red chili was provided by a local farmer and stored in a refrigerator at 5-10 °C to prevent spoilage.

Experimental setup of the packed bed dryer is shown in Figure 1. The setup consists of a cylindrical column, an air blower operated at 2.2 kW motor, an air heater with 12 kW capacity and a cyclone separator for retention of fine particles. The bottom of the column has a perforated plate to prevent chili from entering the air inlet. The column diameter and the total height

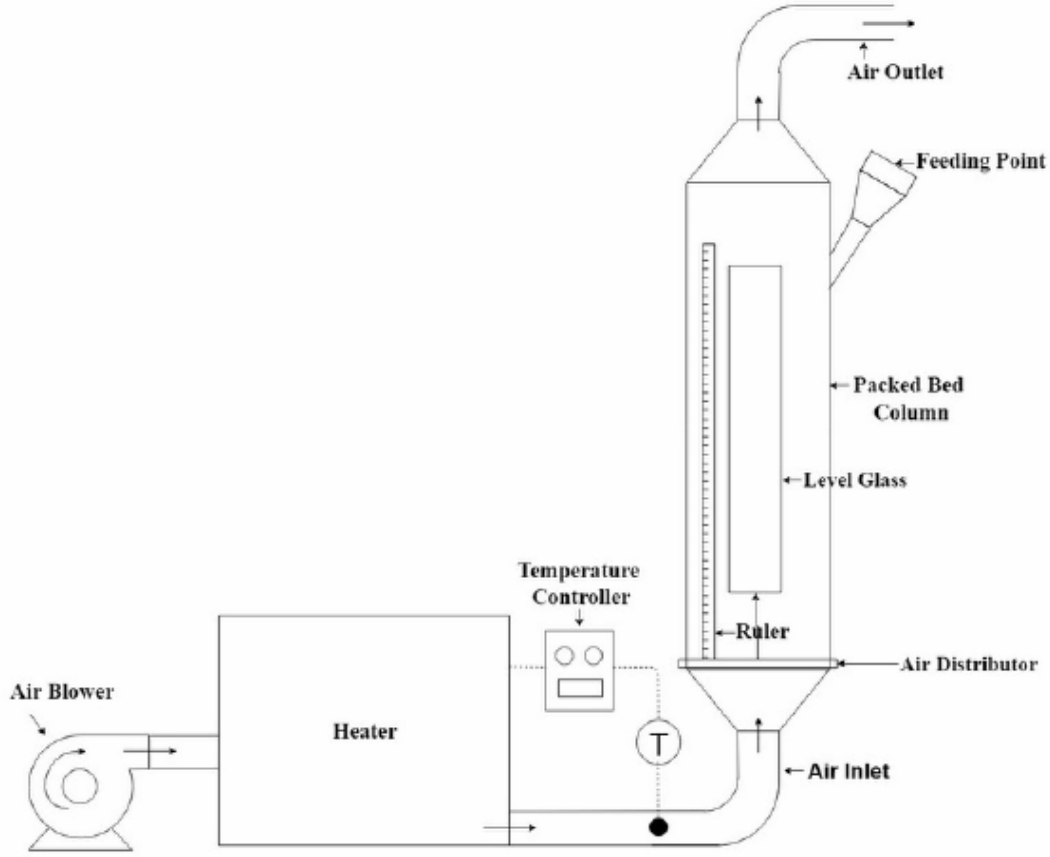

Figure 1. Schematic diagram of the experiment set up.

of the packed bed column are 0.15 m and 1 m, respectively.

The pressure measurement was performed using a U-tube water manometer on the bottom and top of the column. To measure the air inlet flowrate, EXTECH CFM thermo-anemometer model 407113 was fixed to the air inlet. A thermo-hygrometer was used for measuring the humidity of air at inlet and outlet.

Packed bed behavior was studied for both dried chili and fresh chili. The bed was filled with the material up to the required height (0.10 m to 0.30 m) and air at room (ambient) temperature was passed through the bed. Air velocity and the corresponding pressure drop across the bed were measured. Series of pressure drop versus air velocity results were obtained by gradually increasing the air velocity. Then the air velocity was gradually decreased, and pressure drop values were recorded.

Our experiments on packed bed behavior described above showed that 0.30 m height is the minimum height required for the packed bed operation for smooth flow of fluid without channeling. Therefore, drying experiments were conducted for the bed of materials of height 0.3 m.

Drying experiments were carried out to study the effect of hot air temperature on drying kinetics. Known weight of fresh red chili was filled to the bed and hot air was passed through the bed. The bed height and the air flow rate were maintained constant at 0.30 m and 1.111 m/s, respectively. The bed weight was measured, and the bed material was mixed every one-hour. Temperature and relative humidity of inlet air and outlet air were measured. The absolute humidity of the air entering the bed was 0.015 kg moisture/kg of dry air. The moisture content of chili was determined as a function of time using oven drying method. The maximum temperature that can reach without

losing the nutrient level of the red chili is 70 °C [8, 10]. Therefore, the drying experiments were conducted for the temperatures of 50 °C, 55 °C and 60 °C. Each experiment was duplicated to confirm the results.

Physical properties of the chili: equivalent diameter, surface area and sphericity were determined as explained by Hawa *et al*. and Kaleemullah *et al*. using measurements of randomly selected 50 chili peppers assuming cylindrical shape of chili [18, 19]. The true densities (ρ_s) of both dried and fresh red chili were obtained using the density meter GF-200. The porosity (ε) of the bed was calculated using Equation 1, where A, L and W are the cross-sectional area of the bed, bed height and the weight of material, respectively.

$$\varepsilon = \frac{AL - W/\rho_s}{AL} \qquad \text{(Equation 1)}$$

RESULTS AND DISCUSSION

Results obtained from the experiments were analyzed to study the flow of air through the packed bed of fresh and dry chili and to study drying characteristics of chili and are discussed below.

Packed bed behavior of chili

Results of pressure drop across the bed per unit bed height were plotted against the air velocity on the log-log scale. Results obtained for 0.10 m and 0.20 m height beds showed irregular behavior of the plots indicating improper fluid flow and possible channeling due to low bed height. Therefore, 0.30 m bed height was selected as the minimum bed height required to maintain uniform fluid flow through the bed. The pressure drop across the bed versus air velocity results analyzed for the 0.30 m bed height is described below.

Pressure drop vs air velocity results plotted on a log-log scale for fresh chili and dry chili are shown in Figures 2 and 3. The plots are linear and the pressure drop values during decreasing air velocity are slightly less compared to those during increasing velocity. This is due to the fact that bed material expands gradually when the high velocity is reached and the resistance to flow is less during decreasing velocity [20, 21]. This effect is clearer in dry chili results as the bed reached fluidization state at the highest velocity.

Fluid flow through the packed bed of materials is commonly expressed by the Ergun's equation, Carman-Kozeny equation, Burke-Plummer equation and Forchheimer equation [20, 21]. Pressure drop across the bed and superficial air velocity results obtained for fresh chili and dry chili were fitted to above equations using Excel solver 365 and the parameters were obtained. The results are shown in Table 1. Coefficient of variation confirms good fit to the Ergun's equation, and this is acceptable as the Ergun's equation is valid for the whole range of Reynolds numbers. However, the first parameter k_1 in the Forchheimer equation becomes zero for both chili types and fits with a higher Coefficient of variation (R^2). Therefore, results confirm that for fresh and dry chili the packed bed behavior is best explained by Equation 2. The parameters k_1, k_2 and n in the equations for fresh and dry chili are given in Table 1. Figures 4 and 5 show the pressure drop vs air velocity results and the fitted line for Equation 2.

$$\frac{\Delta P}{L} = k\, v^n \qquad \text{(Equation 2)}$$

Physical properties of chili and the packed bed

Equivalent diameters and shape factors of fresh and dry chili pods were determined using the average diameter and the average length of the pods assuming cylindrical shape [18]. Voidage values of the loosely packed bed were calculated using Equation 1. Physical characteristics of the chili pods and the packed bed of chili are given in Table 2. As the moisture content of chili decreased from 433% (d.b) to 21%, the average diameter and the average length of the chili pods decreased by 4.9% and 5.6%, respectively. Similarly, true and bulk densities of chili decreased by 54% and 69% respectively during drying. These changes in dimensions and other parameters agree with results obtained by other workers on chili drying [18].

Fluid pattern and the Reynolds number

The fluid flow condition through the packed bed, namely laminar, transitional or turbulent are distinguished by the Reynolds number for the

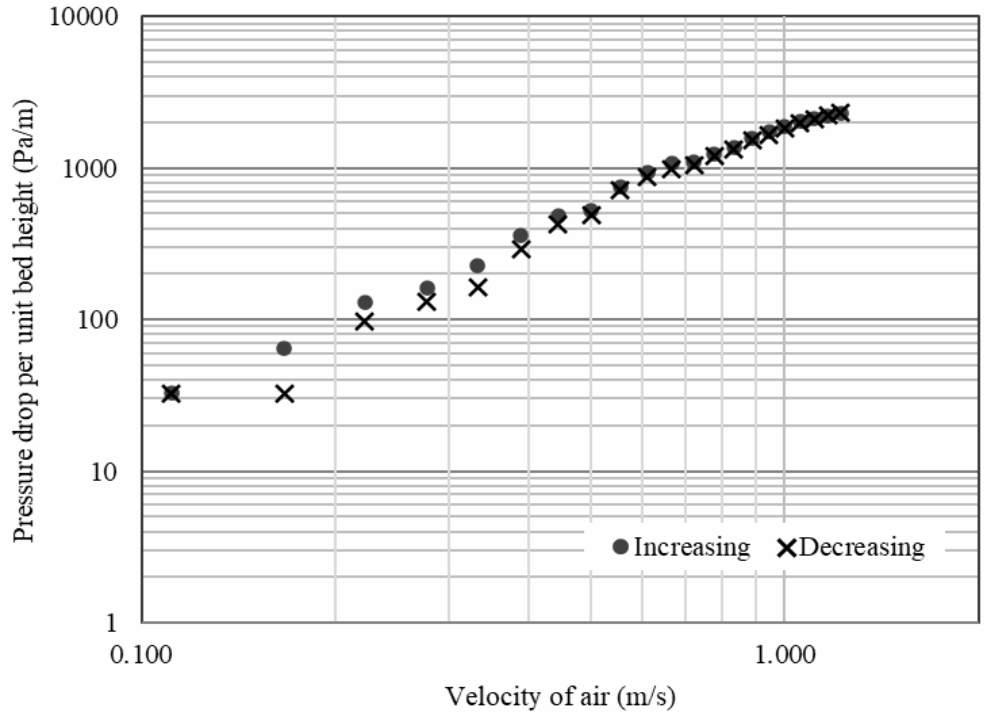

Figure 2. Pressure drop per unit bed height as a function of increasing and decreasing air velocity for fresh chili.

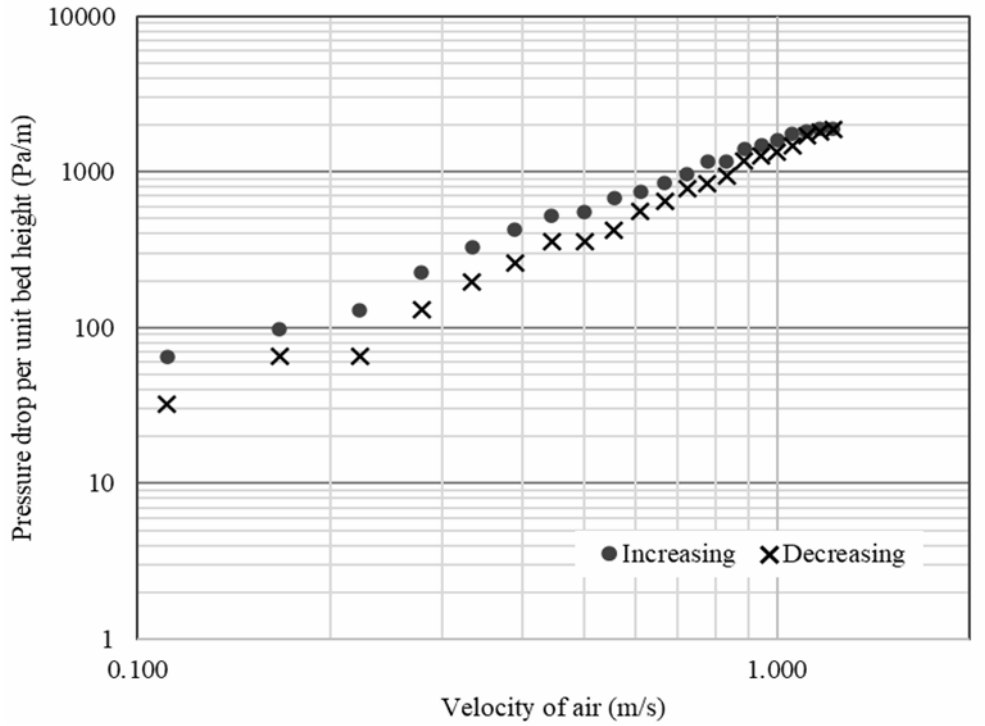

Figure 3. Pressure drop per unit bed height as a function of increasing and decreasing air velocity for dry chili.

Table 1. Pressure drop and superficial air velocity relationships for fresh and dry chili.

Fresh chili					
Equation		k_1	k_2	n	R^2
Carman-Kozeny	$\frac{\Delta P}{L} = k_1 v$	1701.88	-	-	0.9756
Ergun	$\frac{\Delta P}{L} = k_1 v + k_2 v^2$	675.42	1095.16	2 (fixed)	0.9884
Burke-Plummer	$\frac{\Delta P}{L} = k_2 v^2$	-	1771.02	2 (fixed)	0.9739
Forchheimer	$\frac{\Delta P}{L} = k_1 v + k_2 v^n$	0	1782.17	1.5413	0.9923
This study	$\frac{\Delta P}{L} = k_2 v^n$	-	1782.17	1.5413	0.9923
Dry chili					
Carman-Kozeny	$\frac{\Delta P}{L} = k_1 v$	1491.38	-	-	0.9804
Ergun	$\frac{\Delta P}{L} = k_1 v + k_2 v^2$	777.73	761.41	2 (fixed)	0.9917
Burke-Plummer	$\frac{\Delta P}{L} = k_2 v^2$	-	1539.64	2 (fixed)	0.9723
Forchheimer	$\frac{\Delta P}{L} = k_1 v + k_2 v^n$	0	1549.12	1.4255	0.9941
This study	$\frac{\Delta P}{L} = k_2 v^n$	-	1549.12	1.4255	0.9941

bed (Re_b). The Reynolds for a packed bed is defined by equation 3 [20];

$$Re_b = \frac{d_p v \rho}{(1-\varepsilon)\mu} \quad \text{(Equation 3)}$$

where, v is the superficial fluid velocity, d_p is the effective particle diameter or the Sauter mean diameter, ε is the bed voidage, μ is the fluid viscosity and ρ is the fluid density.

Range of bed Reynolds number (Re_b) values calculated for fresh and dry chili beds are 262 to 2648 and 383 to 3868, respectively. The operating range is out of the laminar region and hence justifies the invalidity of Carmon-Kozeny equation which is applicable for low Reynolds numbers (<10) [20]. The first and second term in the Forchheimer equation are due to the viscous drag component and due to turbulent eddies

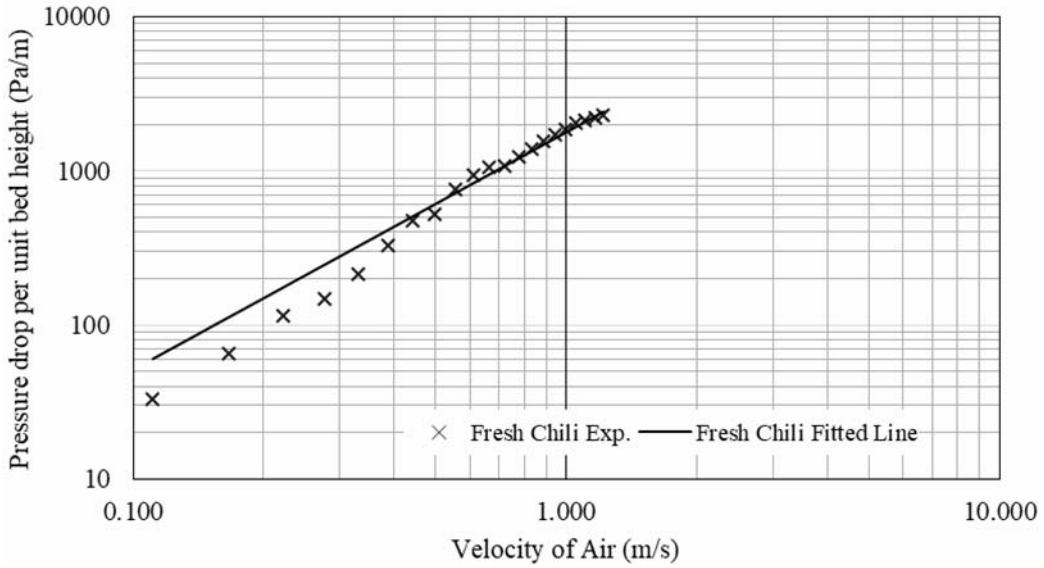

Figure 4. Pressure drop per unit bed height as a function of velocity of air for fresh chili.

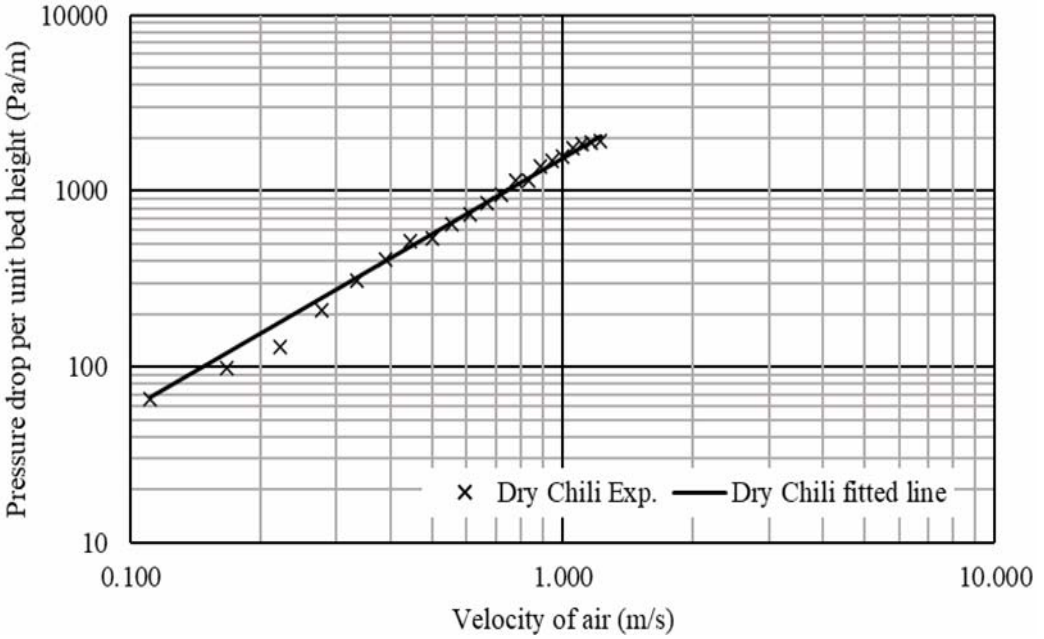

Figure 5. Pressure drop per unit bed height as a function of velocity of air for dry chili.

respectively [20]. The empirical equation developed in this study corresponds with the Forchheimer equation when the first term is neglected. The Reynolds number ranges in the study confirm that the flow region is beyond the laminar region and hence the Carman-Kozeny equation is not applicable. Therefore, as explained in the previous section the best equation to describe the flow behavior of air through a packed bed of chili is the empirical equation developed in this study. However, Ergun's equation which is valid for all three regions, Laminar, Transitional and Turbulent, also shows reasonably good agreement with the results obtained.

Table 2. Physical characteristics of fresh and dry chili pods and the packed beds of chili.

Parameter	Fresh chili	Dry chili
Average diameter of a pod (m)	0.00934	0.0089
Average length of a pod (m)	0.1067	0.1010
Equivalent volume diameter (m)	0.0241	0.0229
Sphericity	0.5570	0.5580
Equivalent surface diameter (m)	0.0323	0.0306
Specific surface area (m^{-1})	0.4469	0.4693
Voidage of the bed	0.6380	0.7640
Surface area available for Heat and mass transfer per unit bed volume (a) (m^2/m^3)	161.81	110.75
Sauter mean diameter (m)	0.0134	0.0128
True density (kg/m^3)	737.80	342.00
Bulk density (kg/m^3)	267.06	80.83
Moisture content (dry basis)	433%	21%

Drying characteristics of chili

The moisture content of a material expressed on dry basis as a percentage is given by Equation 4.

$$MC = \frac{(W_w - W_d)\,100}{W_d} \qquad \text{(Equation 4)}$$

where MC, W_w, W_d are the moisture content, weight of the wet solid and the weight of the dry solid, respectively.

Moisture content values obtained as a function of time for drying experiments are shown in Figure 6. The results show constant rate of drying over the complete drying period of 7 hrs for 50 °C and 55 °C and up to 5 hrs for 60 °C air temperature. Rate of drying (N) expressed in kg of moisture evaporated/kg of dry material/min was calculated using the gradient of the straight-line section of the moisture content versus time plots. The rate of drying values thus calculated as a function of temperature are given in Table 3. According to the results in Table 3 rate of drying increases linearly with the temperature at a rate of 0.0006 kg/kg/min per °C.

Mass transfer coefficient (MTC) is an important parameter for analysis of moisture transfer in a drying process. The driving force for mass transfer in drying chili is the difference between the humidity at the surface of the chili pod and the bulk air humidity (Y). The surface of the drying material is saturated with water during the constant drying rate period (Y_{as}). Rate of mass transfer is proportional to the area available for mass transfer. For a differential height dz of the packed bed rate of moisture transfer can be expressed by the following equation for constant drying rate period. The proportionality constant k_y in the equation is the mass transfer coefficient [22].

$$G\,dY = k_y\,a\,dz\,(Y_{as} - Y) \qquad \text{(Equation 5)}$$

where

k_y - gas phase mass transfer coefficient or mass evaporated/area time humidity difference (kg/m^2 s).

a - area available for heat and mass transfer in the packed bed per unit bed volume (m^2/m^3).

Z - bed height (m).

G - dry air mass flow rate per unit bed cross section (kg/m^2 s).

Y_{as} - adiabatic saturation temperature of air.

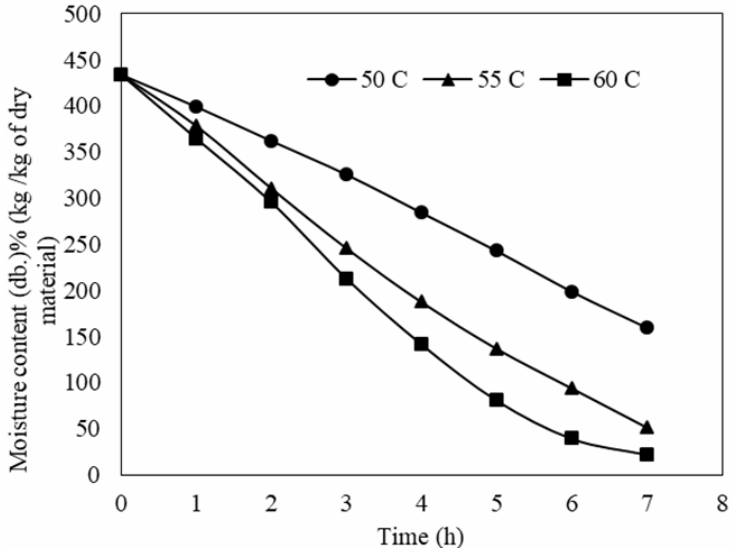

Figure 6. Moisture content (dry basis) % as a function of time for chili drying.

Table 3. Rate of drying and mass transfer coefficient values for chili drying.

Temperature °C	Relative humidity %	Drying rate (N) kg of moisture/kg of dry material/min	Mass transfer coefficient (k_y) kg/m^2 s
50	18	6.52 x 10^{-3}	4.603 x 10^{-3}
55	15	9.43 x10^{-3}	5.725 x 10^{-3}
60	12	12.30 x 10^{-3}	6.422 x 10^{-3}

By integrating Equation 5 over the packed bed of height z;

$$\frac{k_y a z}{G} = In\frac{Y_{as} - Y_1}{Y_{as} - Y_2} \qquad \text{(Equation 6)}$$

where Y_1 and Y_2 are the absolute humidity of the hot air at the inlet and exit, respectively.

Mass transfer coefficient values for the drying experiments were calculated from Equation 6 and the results are shown in Table 3 and Figure 7. MTC value ranges from 4.60 x 10^{-3} to 6.42 x 10^{-3} kg/m^2 s when the temperature increases from 50 °C to 60 °C. This increase of MTC with the temperature is in agreement with the results obtained by other workers for cabinet drying of chili [5, 13].

MTC depends on the air velocity through the dryer and the literature shows that MTC increases with the air velocity [5, 13]. However, in this study air velocity was kept constant for all the experiments and hence the effect of air velocity on the MTC was not investigated. Relative humidity of air is another parameter which affects the mass transfer coefficient. Low relative humidity of air provides a higher driving force for mass transfer and MTC decreases with the relative humidity. Ambient air was heated and used as the heating medium in this study. Therefore, despite the absolute humidity of air remained constant at 0.015 kg/kg for all three temperatures tested the relative humidity values were 18%, 15% and 12% at 50 °C, 55 °C and 60 °C, respectively. Hence the MTC decreases with the relative humidity as shown in Table 3. Agarry *et al*. and Getahun *et al*. have obtained similar behaviour for MTC during their studies on drying of Nigerian chili and Ethiopian chili in cabinet dryers [5, 14].

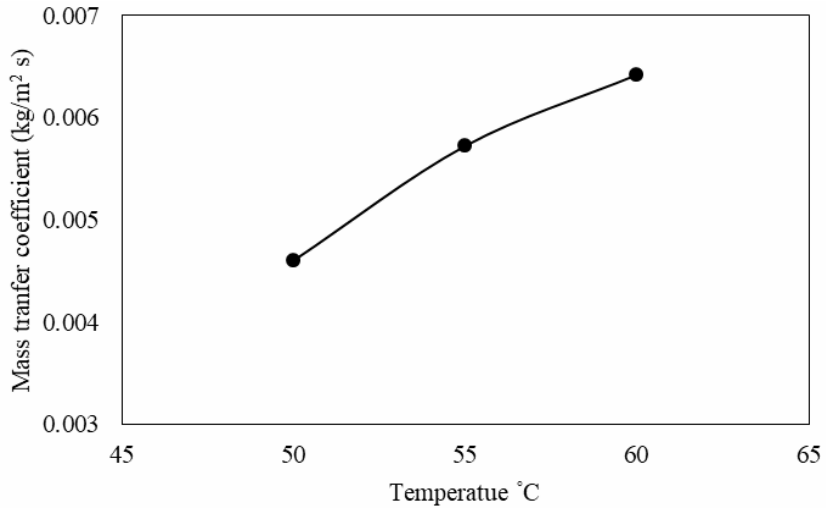

Figure 7. Effect of temperature on the mass transfer coefficient during chili drying.

CONCLUSIONS

Flow characteristics during flow of air through packed beds of fresh chili and dry chili were studied. Minimum bed height required for uniform air flow through the bed without channeling was 0.30 m. The flow condition was in the transitional and the turbulent region with high Reynolds numbers. Pressure drop across the bed can be related to the superficial air velocity through Ergun's equation and through the equation developed in this study where ΔP is proportional to the air velocity with an exponent n (v^n). Physical properties of fresh and dry chili pods showed that as the moisture content of chili decreased from 433% (d.b) to 21%, average diameter and the average length of the chili pods decreased by 4.9% and 5.6%, respectively. Similarly, true and bulk densities of chili decreased by 54% and 69 % during drying.

Drying of chili in the packed bed with intermittent mixing produces uniform moisture content in the final product. Constant drying rates were observed and the drying rate increased with the hot air temperature. Gas phase mass transfer coefficient was calculated and mass transfer coefficient is directly proportional to the hot air temperature and inversely proportional to the relative humidity of hot air.

Findings of the study: the packed bed behavior of fresh and dry chili, physical properties of chili and the drying characteristics and the mass transfer analysis are useful for the design of packed bed dryers with intermittent mixing for chili drying.

Drying characteristics and mass transfer rates depend on the hot air velocity through the bed. Future studies on the effect of air velocity on drying are proposed.

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CONFLICT OF INTEREST STATEMENT

Authors declare that there is no conflict of interest regarding the publication of this paper.

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