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Mathematical Modeling of Drying Characteristics of Chilies in a Rotating Fluidized Bed Technique

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Abstract: Problem statements: The present study investigates experimentally the thin layer drying of chilies in the Rotating Fluidized Bed (RFB) technique and its mathematical modeling. **Approach:** The layer's height was fixed at 4±0.5 cm. In addition, the drying air velocity and the centrifugal acceleration ratio were fixed at 2 m sec^{-1} and G = 2.5 (106 rpm), respectively. With 6 data sets for drying air temperature between 70 and 120°C, the samples were dried from 350±5%db down to 10±1%db. **Results:** The drying time is in the range of 69-257 min. The chilies from sunlight appear light red. On the other hand, from the RFB, they appear dark red but can be marketable. **Conclusion:** The comparisons of five outstanding models are predicted. The Modified Page model gives good agreement with prediction of change in moisture ratio.

Key words: Rotating fluidized bed, drying kinetics, chilies, drying models

INTRODUCTION

The Rotating Fluidized Bed (RFB) dryer is a new drying technology for several moist products. By rotating the bed container, the centrifugal force field takes place and causes an enhancement in heat and mass transfer (Dongbang *et al*., 2010). Drying using the RFB technique is found in only a few studies in the published literature, e.g., soybean, green bean and rice (Chen *et al*., 1999). They are almost spherical grains; on other hand, literature on different grains and mathematical models is scanty. The objectives of this work are (i) to investigate experimentally the drying kinetics of chilies (ii) and to develop the mathematical models.

MATERIALS AND METHODS

Materials: Fresh chilies (*Capsicum annuum* L.) obtained from the market (average length of 65±5 mm and average diameter of 7.8±2 mm) (Omar *et al*., 2008) were used in this study. The initial moisture contents was measured by the AOAC (2000) 930.04 method (Charmongkolpradit *et al*., 2010) at the Central Laboratory (Thailand) Co., Ltd., Khon Kaen Branch, Thailand, with ISO/IEC 17025.

Experimental apparatus: The Rotating Fluidized Bed (RFB) or so-called centrifugal fluidized bed is a relatively new fluidization concept. The centrifugal force generated from the rotating chamber is balanced by the particle drag force caused from the radial fluidization gas (Nakamura *et al*., 2009; Nakamura and Watano, 2008) as shown in Fig. 1. The variable r is the radius of the air-distributor (m) and ω is the angular velocity (rad/s). The air-distributor always rotates in the clockwise direction. When the annular particle bed rotates, the centrifugal acceleration, $r\omega^2$ takes place. At the same time, the particle drag force balanced to the centrifugal force takes place from the radial fluidized air (Ramli and Daud, 2008). The radial fluidization is generated by injecting gas through the porous wall and removing via a central chimney. The fluidized air velocity can be easily adjusted by varying the rotating speed. The centrifugal force can be increased by several gravity fields to increase the air-solid slip velocities for improving interphase mass and heat transfer through good contact efficiency (Brooks *et al*., 2008). Figure 2 shows a schematic diagram of the experimental apparatus. It consists of (1) blower of 5 HP, (2) electric heater of 5 KW, (3) U-tube manometer and orifice plate for measuring the air velocity, (4) air distributor with diameter of 0.4 m and depth of 0.3 m, (5) bed of

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particles, (6) air filter, (7) driven motor of 5 HP for driving air distributor, (8) high-speed camera, (9) U-tube manometer for measuring the bed pressure drop, (10) the exhaust pipe, (11) the recycling pipe and (12) the bypass pipe. The air-distributor with 400 mm diameter and 200 mm width can be rotated around a horizontal axis. The rotating speed can be adjusted for the optimal drying conditions by a frequency inverter and measured by RPM-meter (Tachometer Digital Meter, DTO6234N, Germany) with an accuracy of ±0.05%. Additionally, the dimension of the side surface of the air-distributor is 2.5 mm per hole and 38.5% of open area. For visualizing operation, transparent glass was installed and the fluidization behavior was viewed by high-speed video camera. For exhaust air, a filter of 100 mm diameter was located at the center of the air-distributor. The drying air was blown by a centrifugal blower of 5 HP which has its rotating speed adjusted by frequency inverter. The drying airflow was measured by an orifice meter with a U-Shaped manometer. The pressure drop through the bed was measured by a U-shaped manometer. The drying air was heated by an electric heater of 5 kW and adjusted by PID control (Suntree, SG6, USA) with an accuracy of ±0.1%. For temperature, a J-type iron-constantan thermocouple was used (NS, YB05C-A1, China) that indicated with an accuracy of ±0.05%.

Drying method: The procedure of the drying experiment was defined as follows. First of all, an electric heater was started with the drying air temperatures of 70, 80, 90, 100, 110 and 120°C. The drying air velocity of 2 m sec^{-1} was controlled by a blower. An experimental apparatus was operated with the operation time of 60 min for stabilizing the drying conditions. For the second, the 2 kg sample (estimated 4±0.5 cm of the bed layer height) was filled into the air-distributor which is the drying chamber in the RFB technique and this was the initial weight of the sample. Thirdly, the air-distributor was started with a rotating speed of 106 rpm based on the centrifugal acceleration ratio of G = 2.5. The “G” can be calculated by $G = r\omega^2/g$, where r is the radius of the air-distributor (Figure 1), n is the rotational speed (rps), ω is the angular velocity (rad/s) and g is the acceleration of gravity (m/s²). Finally, the moisture loss was recorded every 10 minutes during the drying process by a digital balance (OHAUS, PA512, USA) with an accuracy of ±0.01g. The samples were dried from the initial moisture content of 350±5%db down to a moisture of 10±1%db which is the safe storage level. The experiment was repeated three times and the average data was evaluated for analyzing.

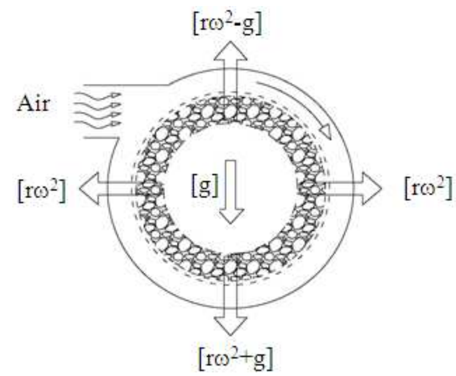

Fig. 1: Schematic diagram of balance forces

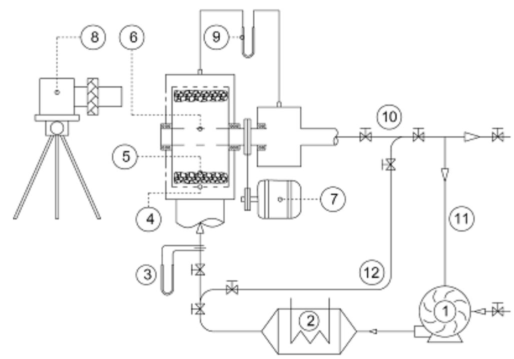

Fig. 2: Schematic diagram of apparatus

Table 1: Adaptable thin-layer drying models

Model name	Model equation
Newton	MR=exp (-kt)
Modified page	MR=exp [-(kt) ^{n}]
Henderson	MR=a exp (-kt)
Logarithmic	MR=a exp (-kt) +b
Two-term henderson	MR=a exp (-kt) +b exp (-gt)

Sunlit drying: A kilogram of chilies were exposed under sunlight. This drying method was done by placing on a steel tray in a thin layer. The sample was kept in a container at night. This process was conducted over a span of 12-14 days.

Drying models: Moisture ratios of samples during the thin-layer drying experiments were calculated (Alves-Filho and Eikevik, 2008). The temperature effect was modeled by the Arrhenius relationship (Mujumdar, 2000). Moisture ratios, MR, models have been proposed in the published literature, such as the Lawis or Nowton model, the Modified Page model, the Henderson and Pabis model, the Logarithmic model and the Two-term Henderson model (Goyal *et al*., 2008) as shown in Table 1. They were adapted to the experimental drying data for chilies at the different temperatures. The parameter, t, is the drying time. The parameters such as k, n, g, a and b were investigated.

Non-linear regression was utilized to determine each constant for the tested models. The effectiveness of model fit was evaluated via the statistical criteria such as coefficient of determination, R^2, Adj. R^2, reduced chi-square, X^2 and root mean square error, RMSE (Goyal *et al*., 2008). For the proposed model, the optimum condition with highest value of R^2 and the lowest value of X^2 and the lowest value of RMSE was selected. Analysis of variance was carried out to find the effect ($p<0.05$) of drying air temperature.

RESULTS

Fluidization behaviors: The optimal conditions of the particle fluidization behavior for drying can be seen by the high-speed camera. The fluidization behaviors are shown in Fig. 3. When the centrifugal force acting on the bed increases, the fluidization is restricted to the regions close to the wall of the air-distributor and the particle fluidization does not take place. It can be said that the drag force acting on the bed is smaller than the centrifugal force. When the radial air velocity increases, the inner particle's bed in the air-distributor begins to be fluidized. It can be said that when the air velocity increases, the centrifugal force at the inner surface is lower than the particle drag force. In this condition, the fluidization at the inner surface of the air-distributor takes place. So, this study investigates the optimal point for drying, such as drying air velocity 1.8 m/s and the centrifugal acceleration ratio of G = 2.5 which can be obtained at the rotating speed of 106 rpm.

Drying kinetics: The drying kinetics of chilies in the RFB dryer were investigated. The high temperature for drying can cause both physical and chemical damage to the produce (Theansuwan *et al*., 2008). For chili drying, the drying air temperature was set to 70, 80, 90, 100, 110 and 120°C, while the layer's height was fixed at 4±0.5 cm and the drying air velocity was fixed at 2 m/s. The six drying times required to dry chilies from 350±5%db of initial moisture content down to 10±1%db were 257, 163,131, 98, 78 and 69 min, respectively. The results show the effect of air velocity and operation temperature on the drying time. It can be said that after ventilating the gas velocity in the RFB technique, the turbulence and mixing of the fluidized particles were intensified. Then, the gas film on the particles becomes thin, so the gas-solid heat transfer was improved. The similar behavior has been reported. In addition, after the temperature is increased, then the latent heat is intensified and evaporation from the moist produce is improved (Aghbashlo and others, 2010).

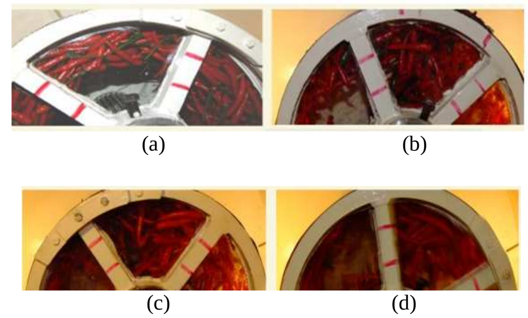

Fig. 3: Fluidization regimes in the RFB technique (a) Non fludization: (b) partial fludization: (c) uniform fludization; (d) turbulant fludization

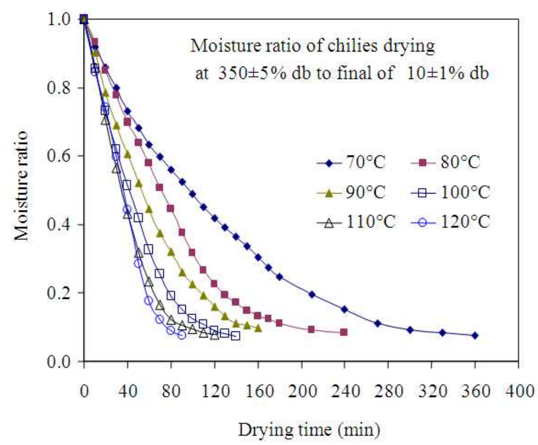

Fig. 4: Moisture ratio of chilies vs. drying time

Figure 4 shows the experimental drying curves of average Moisture Ratio (MR) versus drying time at 6 drying air temperatures, indicating the influence of drying temperature on the ability for moisture diffusion. In addition, the air velocity is an influential parameter which needs to be considered in the analysis of the drying process (Anwarul Huq and Arshad, 2010). Moreover, the drying air temperature affects the resistance of moisture movement at the surface. Researchers have recently reported the same phenomenon for other grain, such as Bird's chili (Mubarik *et al*., 2010) and red chili (Charmongkolpradit *et al*., 2010). As expected for RFB drying, the moisture content drops quickly in the early drying stage, but eventually this becomes nonessential when an equivalent moisture content occurs. Initially, the abundance of free water on the produce surface contributes to effortless moisture liberation.

Figure 5 shows the curve of drying rate against drying duration. As can be seen, a constant rate period is not observed in the RFB technique: the curve of the drying process presents a typical falling rate period at the start. The constant drying rate period is absent due to the quick moisture removal from the pericarp of chilies. In the beginning, when moisture is high, the drying rate is very high and as the moisture content approaches the equilibrium moisture content, the drying rate is very low (Brooks *et al*., 2008).

Table 2: Parameters for models in Table 1

Model	Equation
Newton	k=0.0000335T-0.016021
	k=0.0000323T-0.014879
Modified page	n=0.005755T+0.652561
	k=0.000365T-0.018003
Henderson	a=0.001431T+0.897117
	k=0.000317T-0.015382
Logarithmic	a=0.001394T+0.958332
	b=0.000609T-0.125766
	k=0.000365T-0.018003
Two-term Henderson	g=0.000365T-0.018003
	a=0.004416T+0.136752
	b=-0.003350T+0.802183

Table 3: Evolution of parameters for Table 2

Models	R^2	Adj.R^2	X^2	RMSE
Newton	0.985	0.984	0.00164	0.03422
Modified page	0.997	0.996	0.00036	0.01652
Henderson	0.990	0.989	0.00140	0.02979
Logarithmic	0.993	0.992	0.00087	0.02326
Two-term henderson	0.988	0.987	0.00181	0.02979

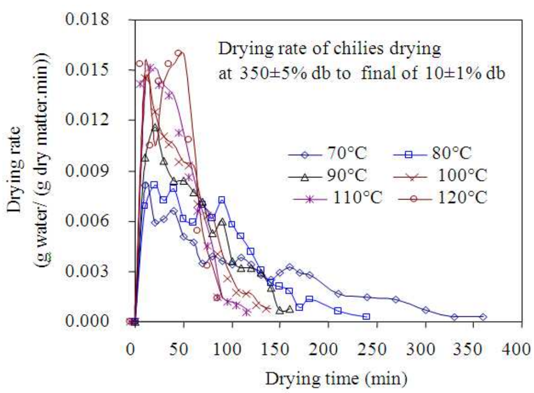

Fig. 5: Drying rate of chilies Vs. drying time

Fig. 6: The redness of dried chilies

Redness of chilies: The redness of chilies dried at different conditions is shown in Fig. 6. The results show the differences in redness between the two drying methods. The chilies dried by sunlight appear light red while the chilies dried by the RFB technique appear dark redness. When the drying air temperature is increased from 70-120°C, the redness is also affected adversely; notwithstanding, the dried chilies are marketable. This may be due to the oxidation of carotenoid pigments at the elevated temperatures (Simal *et al*., 2005).

DISCUSSION

Parameters of drying models: The average moisture ratios of chilies at drying air temperature ranging from 70-120°C based on the drying air velocity of 2 m sec^{-1}, were fitted to the best models. They were evaluated by the goodness of fit. Linear and non-linear regression analyses were performed by SPSS computer program. The model considered is the best one when the values of X^2 and RMSE are minimum values and the coefficient of determination R^2 and adjusted R^2 (Adj.R^2) are maximum values. The equations for all parameters are shown in Table 2.

The results from the Table 3 shown the highest value of R^2 in the Modified Page model; in addition, X^2 and RMSE are lower than other models. These equations can be used to predict the various parameters of models within a temperature range of 70-120°C.

CONCLUSION

The fluidization behavior, drying kinetics, redness and drying models in the drying processes were investigated. When the radial air velocity increases, the inner particles' bed in the air-distributor begins to be fluidized. It can be stated that when the air velocity increases, the centrifugal force at the inner surface is lower than the particle drag force. In this condition, the fluidization at the inner surface of the air-distributor takes place. When the air velocity increases continuously, the first layer at the inner surface is fluidized and then the bed is fluidized gradually layer by layer until the whole bed is fluidized completely at an air velocity of 2 m sec^{-1}. The six intervals of different drying air temperatures ranged from 70-120°C. As a result, the six drying times required to dry chilies from 350±5%db of the initial moisture content down to 10±1%db were 69-257 min. The air velocity is an influential parameter needing to be considered in the analysis of the drying process. Moreover, it can reduce the resistance of moisture movement at the surface. The differences in redness from the two drying methods were that the chilies dried by sunlight appeared light red while the chilies dried by the RFB technique appeared dark red. The comparison of models simulated from 70-120°C of drying air temperature showed that the Modified Page model can predict most accurately.

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