Fluidized Bed Drying Characteristics of Soybeans

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ABSTRACT

The present study investigated the influence of air temperature and velocity on the drying kinetics and specific energy consumption during fluidized bed drying of soybean at 80, 100, 120 and 140ºC and airflow rates of 1.8, 3.1 and 4.5 m s^{-1}. Six mathematical models for describing the fluidized bed drying behavior were investigated. The value of the drying rate coefficient (k) increased with increasing air temperature and velocity and thus reduced the drying time. Although the Midilli model showed the best fit, the Page's model was selected, since it had almost a similar performance but the model is simpler with two parameters instead of four. The drying of soybean seeds took place in the falling rate period and was controlled by moisture diffusion. A third order polynomial relationship was found to correlate the effective moisture diffusivity with moisture content. Effective diffusivity increased with decreasing moisture content and increasing temperature and air velocity. It varied from 4.595×10^{-11} to 3.325×10^{-10} m^2 s^{-1} over the temperature and velocity ranges. Values of the activation energy for moisture diffusion were determined as 35.33, 32.85 and 30.73 kJ mol^{-1} for air velocities of 1.8, 3.1 and 4.5 m/s, respectively. It was found that decrease in energy of activation caused an increase in drying rate. The minimum and the maximum specific energy requirements for drying of soybean seeds were determined as 26.90 and 111.05 kWh kg^{-1} for 140ºC with 1.8 m s^{-1} and 80ºC with 4.5 m s^{-1} air velocity, respectively.

Keywords: Drying rate, Mathematical modeling, Moisture diffusivity, Energy consumption.

INTRODUCTION

Soybeans are harvested typically at moisture contents in the range of 20-25% wet basis (Soponronnarit *et al*., 2001). Safe storage requires rapid decrease in moisture to preserve quality. Fluidized-bed drying is one of the hot-air drying processes used for raw soybean drying during the last few years due to high heat and mass transfer rates between the hot-air and the soybean grains (Dondee *et al*., 2011; Li *et al*., 2002). Also, it is important to dry the product with minimum cost, energy, and time. In fluidized bed drying, drying time is shortened due to intensive heat and mass transfer between drying air and particles being dried while overheating is prevented. Moreover, it can reduce the anti-nutritional factors to the acceptable level for the animal feed and the human food industry (Abbasi Surki *et al*., 2010; Soponronnarit *et al*., 2001; Dondee *et al*., 2011).

Soponronnarit *et al*. (2001) studied the fluidized bed drying characteristics of soybeans at high temperatures (110-140°C) and moisture content of 31-49% dry basis, air speeds of 2.4-4.1 m/s and bed depths from 10 to 15 cm. They reported that the optimum conditions for cost and energy saving and maximum capacity coincided at a drying temperature of 140ºC, bed depth of 18 cm, air velocity of 2.9 m s^{-1} and 90% air recirculation in fluidized bed drying of soybeans. Also, they concluded that the Page's drying model could adequately describe the fluidized bed drying behavior of

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soybeans. Dondee *et al*. (2011) investigated the effect of infrared-fluidized bed drying method on the cracking and breakage of soybean, and reported that this method could reduce cracking and breakage of soybean seeds. The characteristic fluidization velocities, mixing mechanisms and fluidization quality of soybean seeds have been studied by Li *et al*. (2002). Kundu *et al*. (2001) repotted the effect of the drying air temperature, bed height, feed rate, and initial moisture content on drying rate of soybean seeds in fluidized bed dryer, and reported that the drying took place mainly in constant rate and falling rate periods.

Rafiee *et al*. (2009) reported that the Midilli model was the best model to describe the thin layer drying behaviour of soybeans in hot air dryer at 30-70ºC and 1 m s^{-1} air velocity. Freire *et al*. (2004) investigated drying kinetics of soybean seeds in fixed-bed and in the moving bed with cross flow, both being run under thin-layer conditions. Results showed that the effective diffusivity of the moving bed was 24 to 44% higher than that of the fixed-bed. Wiriyaumpaiwong *et al*. (2003) investigated soybean drying by two-dimensional spouted bed dryer. Results showed that the drying kinetics of soybean in a two-dimensional spouted bed dryer could be described by Newton thin layer drying model.

Most of the research work on drying of soybean seeds has been focused on the investigation of the influences of different variables such as air temperature, air velocity, drying method, and the type of dryer, on the breakage and cracking of soybean seeds (Duarte *et al*., 2004; Dondee *et al*., 2011; Pfeifer *et al*., 2010; Stewart *et al*., 2003; Abbasi Surki *et al*., 2010; Gowen *et al*., 2008. Sinnecker *et al*., 2005; Li *et al*., 2002; Kundu *et al*., 2001; Pfeifer *et al*. 2010; Felipe and Barrozo, 2003; Barrozo *et al*., 2006; Sinnecker *et al*., 2005; Kundu *et al*., 2001; Sangkram and Noomhorm, 2002). There are a limited number of reported studies on drying kinetics, effective moisture diffusivity, activation energy, and energy consumption in fluidized bed drying of soybean seeds. Therefore, the objectives of this study were to: (a) to evaluate the influence of air temperature and air velocity on drying kinetics of soybeans; (b) to select the optimal thin-layer drying model for the purpose of simulation; (c) to calculate the effective moisture diffusivity and energy of activation for fluidized bed drying of soybeans; and (d) to determine the effect of drying variables on energy consumption.

MATERIALS AND METHODS

Material

Fresh soybeans with initial moisture content of 25±0.5% (wb) were obtained from a soybean farm in the Gorgan region of Iran. Samples were stored in a refrigerator at 4±1°C before the experiments. A 100 g sample was used in each experiment and dried to around 10% moisture content (wb).

Fluidized Bed Drying System

The fluidized bed column was constructed from a Pyrex pipe, 90 mm inside diameter (100 mm outside diameter) and 380 mm height. The distributor plate, 1 mm thick, had 3 mm diameter holes on 6.2 mm triangular pitch. The distributor was tightly fixed to the bottom of the column. The column was connected to a fan by a 20 mm diameter plastic pipe. The temperature and relative humidity of the inlet and outlet air were measured with appropriate sensors (PT100 and HIH-4000) placed at the inlet and outlet section of the bed. Before each experiment, the temperature and velocity of the drying air were fixed and measured directly when there was no sample in the cylindrical chamber. Air velocity was measured using a digital anemometer (Extech's Model 45158 Anemometer, USA) with the accuracy of ±0.2 m s^{-1}. An open-end U-tube manometer containing water was connected between the fluidized bed and air fan, close to the entrance of the fluidized bed, to measure the pressure drop in the bed. Based on the mass and energy balance, the solids moisture can be calculated from the temperature (T_{out}) and relative humidity (RH) of the outlet air, which can be measured by the temperature and humidity sensors directly. The following steps can be followed for calculation (Wang *et al*., 2009):

First, the saturation vapor pressure in the air phase is defined as:

$$P_v = \sum_{i=0}^{s} \left(a_i \left(\frac{T_{out}}{100} \right)^i \right) \quad (1)$$

Where, P_v is the saturation vapor pressure (mbar), T_{out} is the temperature of the outlet gas (°C), and the coefficients a_i are shown in Table 1.

The humidity ratio at the inlet and outlet air of the dryer can be calculated as follows:

$$M_{w,in} = 0.62198 \frac{P_{w,in}}{p_0 - p_{w,in}}, \; p_{w,in} = \frac{RH_{in} P_v}{100} \quad (2)$$

and

$$M_{w,out} = 0.62198 \frac{P_{w,out}}{p_0 - p_{w,out}}, \; p_{w,out} = \frac{RH_{out} P_v}{100} \quad (3)$$

In the above equations, $M_{w,in}$ and $M_{w,out}$ are the inlet and outlet humidity ratios, RH_{in} and RH_{out} are the relative humidity of the inlet and outlet gas, respectively, and P_0 is the atmospheric pressure (mbar).

The total water loss from the solids phase can be integrated with the drying time and written as:

$$w = \int_{t=0}^{t} (M_{w,out} - M_{w,inlet}).M_f.dt \quad (4)$$

The inlet air flow rate (M_f) is given by:

$$M_f = 0.0006362 \times 0.9 \rho_a u_0 \quad (5)$$

Where, u_0 is the inlet air velocity (m^3 min^{-1}) and ρ_a is the density of the air (kg m^{-3}), which can be calculated as:

$$\rho_{air} = 1.24703 - 0.002787 T_{out} - 3.23518 \times 10^{-s} T_{out}^2 \quad (6)$$

Hence, the average moisture content of the sample can be calculated as:

$$X_p = \frac{W_0 X_0 - W}{W_0 - W} \quad (7)$$

Where, W_0 is the initial sample weight, and X_0 is the initial sample moisture content.

To avoid carryover of particles from a fluidized bed, the fluidization gas velocity must be kept between the minimum fluidization air velocity and the terminal air velocity. The minimum fluidization velocity of soybeans is defined as (Wang *et al*., 2009; Kunii and Levenspiel, 1991):

$$u_{mf} = \left(0.0494 \times \frac{g(\rho_s - \rho_a) D_s}{\rho_a} \right)^{\frac{1}{2}} + \left(8.61 \times 10^{-4} \times \frac{g(\rho_s - \rho_a) D_s^2}{\mu_a} \right) \quad (8)$$

Where, u_{mf} is the minimum fluidization velocity (m s^{-1}), ρ_s is the soybean grain density (kg m^{-3}), ρ_a is the air density (kg m^{-3}), D_s is the sample diameter (m) and μ_a is the viscosity of air (N s m^{-2}). The minimum fluidization velocity of soybean seeds was found to be 1.8 m s^{-1}.

Relation between the terminal velocity and minimum fluidization air velocity is defined as (Kunii and Levenspiel, 1991):

$$\frac{u_{mt}}{u_t} = 0.1175 - \frac{0.1046}{1 + 0.00373 Ar^{0.6}} \quad (9)$$

$$Ar = \frac{\rho_a g(\rho_s - \rho_a) D_s^3}{\mu_a^2} \quad (10)$$

Where, u_t is the terminal velocity (m s^{-1}) and Ar is the Archimedes number. The terminal velocity was calculated as 15.5 m s^{-1}. High air

Table 1. Coefficients in Equation (1).

a_0	a_1	a_2	a_3	a_4	a_5
6.415	7.265	-2.990	1.106	-0.318	4.764×10^{-2}

velocity in fluidized bed dryer caused an increase in cracking and breakage of soybeans seeds. Therefore, drying experiments were carried out with air velocities of 1.8, 3.1 and 4.5 m s^{-1} at temperatures of 80, 100, 120, and 140ºC. Each experiment was performed at a depth of 5 cm soybean at a relative humidity of 35±3.5% under laboratory conditions and in triplicate.

Mathematical Modeling of Drying Curves

For mathematical modeling, the equations in Table 2 were tested to select the best model for describing the drying behavior of soybean during fluidized bed drying. The moisture ratio and drying rate of soybean samples were calculated using the following equations:

$$MR = \frac{X_t - X_e}{X_0 - X_e} \quad (11)$$

$$DR = \frac{X_{t+\Delta t} - X_t}{\Delta t} \quad (12)$$

Where, X_t, X_0 and X_e are the moisture content at any time of drying, initial moisture content (and equilibrium moisture content (kg water kg^{-1} dry mater), respectively. The equilibrium moisture content was calculated using the equation proposed by Soponronnarit *et al.* (2001):

$$RH = \exp\left[\left(\frac{-21065}{R \times T}\right) \times X_e^{-1.25}\right] \quad (13)$$

Where, RH is the air relative humidity (%), T is the air temperature (Kelvin), and R is the gas constant (8.314 J mol^{-1} K^{-1}).

Non-linear regression analysis was performed using software package SPSS 18.0 to fit the experimental data to the selected mathematical models. In addition to R^2, reduced Chi-square (χ^2) and root mean square error (RMSE) were used to determine the goodness of fit. The higher the R^2 values and the lower χ^2 and $RMSE$ values, the better is the goodness of fit. Reduced Chi-square and RMSE can be calculated as follows:

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)^2}{N - z} \quad (14)$$

$$RMSE = \left(\frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)^2}{N}\right)^{0.5} \quad (15)$$

Where, N is the number of observations, z is the number of constants, MR_{exp} and MR_{pre} are the experimental and predicted moisture ratios, respectively.

Moisture Diffusivity

Fick's second equation of diffusion was used to calculate the effective diffusivity, considering constant moisture diffusivity, spherical geometry, and uniform initial moisture distribution (Duc *et al.*, 2011):

$$MR = \frac{6}{\pi^2}\sum_{n=1}^{\alpha}\frac{1}{n^2}\exp\left(-\frac{n^2\pi^2}{r^2}D_{eff}t\right) \quad (16)$$

Where, D_{eff} is the effective diffusivity (m^2 s^{-1}), and r is the radius of soybean seeds (m). The Equation (16) can be simplified by taking the first term:

$$MR = \frac{6}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff} t}{r^2}\right) \quad (17)$$

Table 2. Used mathematical drying models.

Model name	Model	References
Lewis	$MR = \exp(-kt)$	Doymaz and Ismail (2011)
Page	$MR = \exp(-kt^n)$	Jangam *et al.* (2008)
Henderson and Pabis	$MR = a\exp(-kt)$	Figiel (2010)
Logarithmic	$MR = a\exp(-kt)+b$	Kingsly *et al.* (2007)
Wang and Singh	$MR = 1+bt+at^2$	Wang *et al.* (2007)
Midilli	$MR = a\exp(-kt^n)+bt$	Midilli *et al.* (2002)

Where k is the drying constant and a, b, n are equation constants

Equation (17) is written in a logarithmic form as follows:

$$\ln(MR)=\ln\left(\frac{6}{\pi^2}\right)-\frac{\pi^2 D_{eff}t}{r^2} \qquad (18)$$

The effective moisture diffusivity was calculated from a slope of a straight line by plotting experimental drying data in terms of *ln(MR)* versus drying time.

Activation Energy

The temperature dependence of effective moisture diffusivity can be described by an Arrhenius type relationship (Duc *et al.*, 2011):

$$D_{eff}=D_0\exp\left(-\frac{E_a}{RT_{abz}}\right) \qquad (19)$$

Where, D_0 is the pre-exponential factor of Arrhenius equation in $m^2\ s^{-1}$, E_a is the activation energy (kJ mol^{-1}), R is the universal gas constant (J $mol^{-1}\ K^{-1}$), and T_{abs} is the absolute temperature (K).

Specific Energy Consumption

The energy consumed for evaporating a kilogram of water is calculated using Equation (20) (Motevali *et al.*, 2011):

$$E_s=\frac{A.u.\rho_a.C_a.\Delta T.t}{m_w} \qquad (20)$$

Where, E_s is the specific energy consumption to evaporate a unit mass of water from the product (kWh kg^{-1} water), A is the cross sectional area of column (m^2), ρ_a is the air density (kg m^{-3}), ΔT is the temperature difference of inlet and outlet air (ºC), u is the air velocity (m s^{-1}), C_a is the air specific heat (kJ kg^{-1} ºC^{-1}), t is the time (h), and m_w is the mass of evaporated water (kg).

RESULTS AND DISCUSSION

Fluidization and Drying Curves

The variation of the pressure drop with air velocity across the soybean bed is depicted in Figure 1, which shows that the minimum

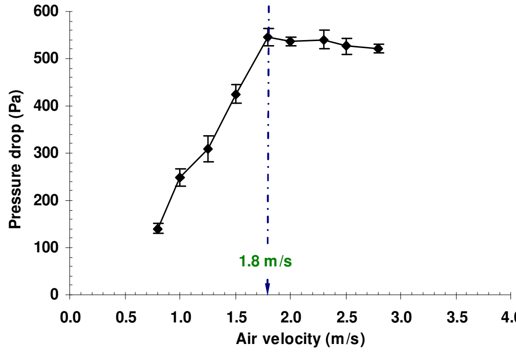

Figure 1. Fluidization characteristics of soybeans.

air velocity required for fluidization of soybean was 1.8 m s^{-1}. Typical fluidization behaviour was observed above the minimum fluidization velocity, with gas bubbles being formed above the distributor and moving to the bed surface.

The drying times involved in reducing the moisture content of soybeans from initial level to about 10% (wb), under various drying conditions, are presented in Figure 2. The drying time decreased with the increase in air velocity from 1.8 to 4.5 m s^{-1} at the same levels of air temperature. As expected, the drying time showed a substantial reduction as drying temperature was increased.

The drying times obtained in this study were low compared with the results obtained in the previous studies given in literature. Sangkram and Noomhorm (2002) concluded that during hot air drying of soybean seeds (80-140°C), drying time of 260 min (100°C)

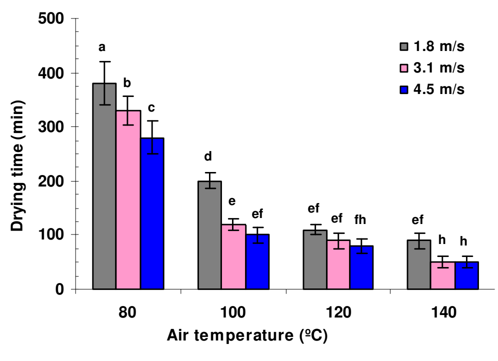

Figure 2. Drying time for soybeans under various temperatures and air velocities. Columns with different superscripts mean that the data are significantly different (P< 0.05).

would be most suitable for the hot air drying of soybean samples. The results obtained in the present work show that, as compared to hot air, the drying time can be shortened by 1.6- to 9-fold by working at 140ºC and 4.5 m s^{-1}, respectively. Besides, by performing fluidization drying at 140°C and 4.5 m s^{-1}, instead of hot air drying of soybean samples at 45-90ºC and air velocity of 1-2.5 m s^{-1} as reported by Boeri and Khatchatourian (2012), the drying time can be shortened about 2.4- to 9.5-fold, respectively.

The moisture ratio versus drying time curves for fluidized bed drying of soybean samples, as affected by air temperature and velocity, are shown in Figure 3. Statistical results for fitting of the models are summarized in Tables 3-5. Midilli model can be considered the most suitable drying model with the highest R^2 and lowest *RMSE* and χ^2 values for all air temperatures and velocities. The level of χ^2 as well as R^2 for the Midilli and the Page's models were always very close to each other. Although the Midilli et al. (2002) showed the best fit among the selected models, the Page's model was selected as the appropriate model for this research because it is simple with two parameters while Midilli model has four parameters. Values of drying constants were in the range of 0.011–0.106 min^{-1} in air temperature and velocity ranges of 80–140ºC and 1.8-4.5 m s^{-1}, respectively. The value of the drying constant increased with temperature and air velocity. The higher k values confirm the elevated moisture removal rates and indicate an enhancement of drying potential (Evin, 2011; McMinn, 2006). These results were in good agreement with the drying rate data, which follow a similar trend.

Figure 4 shows the comparison between experimental moisture ratios at different drying temperatures and air velocities and that predicted by the Page's model. As can be seen, the dots in Figure 4 are closely banding around a 45º straight line, showing a very good agreement between the calculated and experimental data, which indicates that the Page's model could adequately describe the drying behavior of soybean samples. To account for the effect of the drying air temperature and velocity on this model, constants *k* and *n* were regressed against those of drying air temperatures and velocities using regression analysis. The constant equations are as follows:

$$K = (0.1156 - 0.0087u) \times \ln(t) + 0.0432u - 0.4899$$

$$R^2 = 0.835 \qquad (21)$$

$$n = (-0.0004u^2 \times 0.0007u + 0.0011)T^2 - (0.0189u^2 - 0125u + 0.201)T - 0.424u + 2.739$$

$$R^2 = 0.908 \qquad (22)$$

Figure 5 shows how the drying rate of soybean seed samples changed with drying time under various drying conditions. The drying rate at the beginning of the process is higher because initially water for evaporation exists on the surface and comes

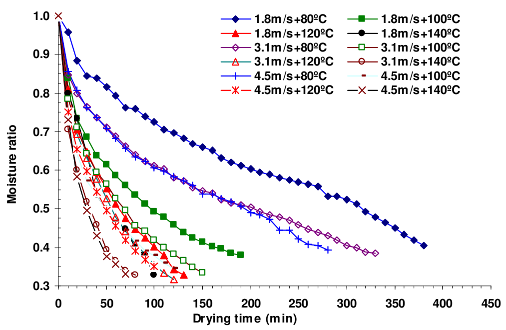

Figure 3. Influence of temperature and air velocity on the drying curves of soybean seeds.

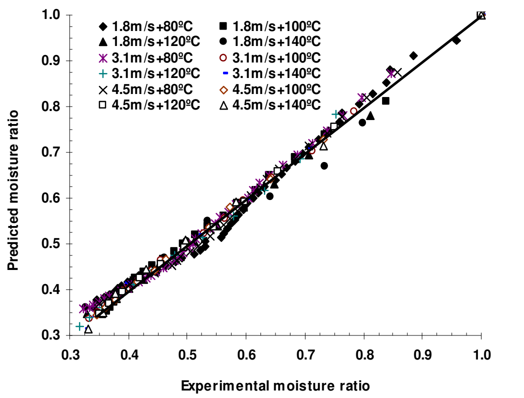

Figure 4. Comparison of the experimental moisture ratio with the data predicted by Page's model at various temperatures and air velocities.

Table 3. Statistical parameters and the coefficients of drying models at air velocity of 1.8 m s^{-1}.

Model	T (ºC)	Model constants	R^2	χ^2	RMSE
	80	k= 0.011; n= 0.741	0.988	0.00047	0.02116
Page	100	k= 0.062; n= 0.552	0.998	0.00010	0.00968
	120	k= 0.073; n= 0.569	0.995	0.00021	0.01328
	140	k= 0.080; n= 0.572	0.980	0.00094	0.02768
	80	k= 0.035; n= 0.409; a= 1.009; b= -0.001	0.994	0.00789	0.08485
Midilli	100	k= 0.050; n= 0.599; a= 1.001; b= 0.0002	0.999	0.00054	0.02125
	120	k= 0.065; n= 0.548; a= 1.007; b= -0.001	0.999	0.00201	0.03791
	140	k= 0.071; n= 0.527; a= 1.016; b= -0.001	0.991	0.00091	0.02403
	80	k= 0.002; a= 0.854; b= 0.070	0.982	0.00211	0.04445
Logarithmic	100	k= 0.016; a= 0.582; b= 0.359	0.984	0.00048	0.02060
	120	k= 0.021; a= 0.651; b= 0.312	0.988	0.00052	0.02028
	140	k= 0.024; a= 0.689; b= 0.293	0.99	0.00051	0.01930
	80	k= 0.0024; a= 0.9174	0.985	0.00053	0.02257
Henderson and Pabis	100	k= 0.0048; a= 0.7889	0.942	0.00330	0.05500
	120	k= 0.0082; a= 0.8709	0.967	0.00207	0.04387
	140	k= 0.0118; a= 0.8934	0.967	0.00201	0.04054
	80	a= 4×10^{-6}; b= -0.003	0.949	0.00189	0.04256
Wang and Singh	100	a= 3×10^{-5}; b= -0.0085	0.895	0.00449	0.06417
	120	a= 7×10^{-5}; b= -0.0135	0.958	0.00204	0.04353
	140	a= 1×10^{-4}; b= -0.0158	0.981	0.00166	0.03690
	80	k= 0.0027	0.959	0.00162	0.03986
Lewis	100	k= 0.0067	0.783	0.00871	0.09137
	120	k= 0.0112	0.908	0.00430	0.06316
	140	k= 0.0136	0.936	0.00288	0.05119

Table 4. Statistical parameters and the coefficients of drying models at air velocity of 3.1 m s^{-1}.

Model	T (ºC)	Model constants	R^2	χ^2	RMSE
	80	k= 0.046; n= 0.537	0.997	0.00019	0.01348
Page	100	k= 0.064; n= 0.592	0.999	0.00002	0.00448
	120	k= 0.079; n= 0.570	0.992	0.00015	0.01123
	140	k= 0.086; n= 0.663	0.999	0.00010	0.00868
	80	k= 0.053; n= 0.450; a= 1.001; b= -0.0003	0.998	0.00014	0.01108
Midilli	100	k= 0.067; n= 0.553; a= 0.999; b= -0.00007	0.999	0.00003	0.00483
	120	k= 0.073; n= 0.522; a= 0.994; b= -0.001	0.999	0.00026	0.01349
	140	k= 0.081; n= 0.638; a= 1.002; b= 0.001	0.998	0.00056	0.01765
	80	k= 0.006; a= 0.589; b= 0.298	0.971	0.00074	0.02627
Logarithmic	100	k= 0.021; a= 0.616; b= 0.333	0.982	0.00064	0.02276
	120	k= 0.022; a= 0.664; b= 0.284	0.979	0.00090	0.02624
	140	k= 0.043; a= 0.666; b= 0.317	0.992	0.00055	0.01917
	80	k= 0.0027; a= 0.8008	0.966	0.00130	0.03517
Henderson and Pabis	100	k= 0.0083; a= 0.8368	0.959	0.00694	0.07795
	120	k= 0.00111; a= 0.8720	0.972	0.00336	0.05334
	140	k= 0.0198; a= 0.8992	0.966	0.00517	0.06338
	80	a= 9×10^{-6}; b= -0.0047	0.848	0.00386	0.06060
Wang and Singh	100	a= 6×10^{-5}; b= -0.0129	0.933	0.00456	0.06320
	120	a= 1×10^{-4}; b= -0.0157	0.942	0.00319	0.05191
	140	a= 3×10^{-4}; b= -0.0272	0.969	0.02293	0.13354
	80	k= 0.0037	0.789	0.00653	0.07980
Lewis	100	k= 0.0104	0.869	0.00638	0.07736
	120	k= 0.0133	0.920	0.00437	0.06353
	140	k= 0.0227	0.936	0.00652	0.07611

Table 5. Statistical parameters and the coefficients of drying models at air velocity of 4.5 m s^{-1}.

Model	T (ºC)	Model constants	R^2	χ^2	RMSE
Page	80	k= 0.052; n= 0.524	0.994	0.00003	0.00486
	100	k= 0.088; n= 0.556	0.997	0.00001	0.00334
	120	k= 0.097; n= 0.536	0.996	0.00002	0.00427
	140	k= 0.106; n= 0.587	0.991	0.00022	0.01284
Midilli	80	k= 0.064; n= 0.401; a= 1.002; b= -0.001	0.998	0.00010	0.00941
	100	k= 0.078; n= 0.581; a= 0.991; b= 0.0006	0.999	0.00005	0.00560
	120	k= 0.084; n= 0.528; a= 1.001; b= -0.0003	0.999	0.00007	0.00684
	140	k= 0.096; n= 0.587; a= 1.014; b= 0.00004	0.995	0.00043	0.01464
Logarithmic	80	k= 0.006; a= 0.597; b= 0.302	0.973	0.00061	0.02357
	100	k= 0.025; a= 0.602; b= 0.321	0.968	0.00129	0.03155
	120	k= 0.031; a= 0.625; b= 0.342	0.985	0.00067	0.02210
	140	k= 0.046; a= 0.684; b= 0.310	0.999	0.00011	0.00815
Henderson and Pabis	80	k= 0.0034; a= 0.8425	0.979	0.00108	0.03181
	100	k= 0.0098; a= 0.7978	0.932	0.00482	0.06389
	120	k= 0.0112; a= 0.8615	0.959	0.00335	0.05235
	140	k= 0.0216; a= 0.9140	0.976	0.00479	0.05993
Wang and Singh	80	a= 1×10^{-5}; b= -0.0051	0.885	0.00237	0.04719
	100	a= 1×10^{-4}; b= -0.0169	0.901	0.00361	0.05529
	120	a= 1.3×10^{-4}; b= -0.0183	0.946	0.00263	0.04639
	140	a= 3×10^{-4}; b= -0.0277	0.988	0.00151	0.03361
Lewis	80	k= 0.0043	0.885	0.00389	0.06145
	100	k= 0.0130	0.782	0.00923	0.09231
	120	k= 0.0148	0.896	0.00538	0.06996
	140	k= 0.0241	0.957	0.00511	0.06685

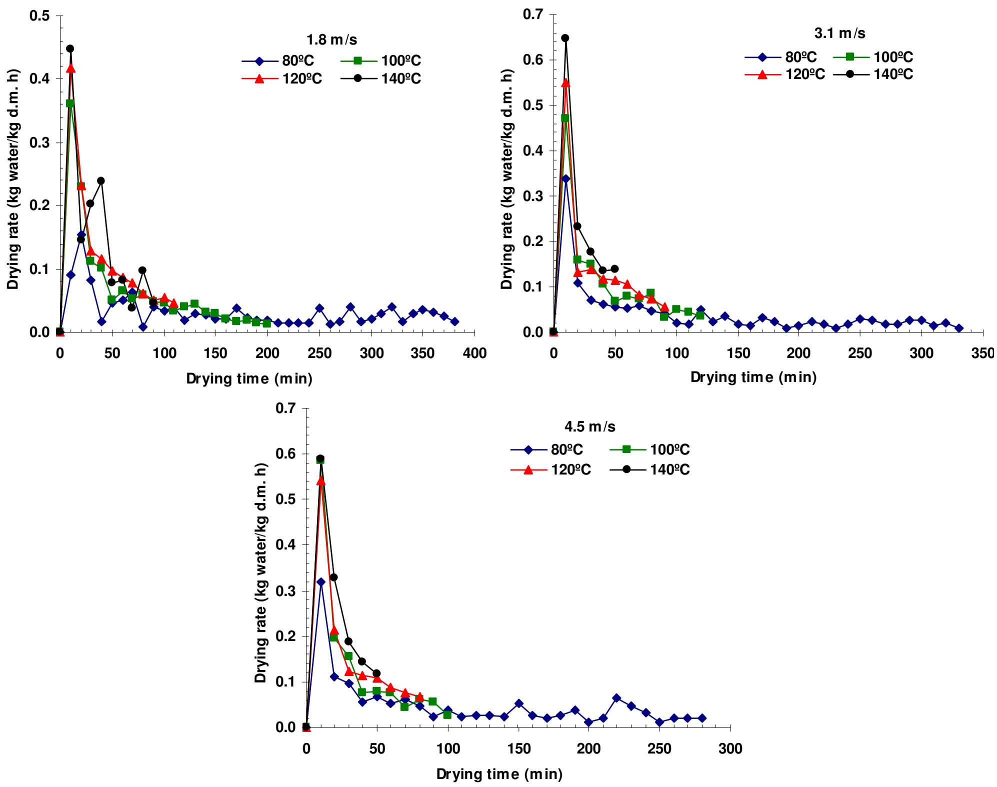

Figure 5. Variation of drying rate with drying time for the soybeans at various air temperatures and velocities.

from regions near the seed surface. Subsequently, the drying rate decreases with decreasing moisture content because water to be evaporated comes from parenchyma cells within the seed structure and must be moved to the surface. Therefore, it can be considered that the rate of moisture removal is limited by the diffusion rate of moisture from inside to the surface of the seeds. Drying of soybeans occurred in the falling rate period and no constant rate period was observed in any of the experimental runs for the entire duration. Drying in the falling rate period indicates that, internal mass transfer has occurred by diffusion. It was shown in Figure 5 that drying rate increases with air temperature. This can be explained by the increase in evaporation rate with temperature. Also, the drying rates increased with drying air velocity as shown in Figure 5. The increase in the drying rate was apparently due to the increased heat transfer potential between the surrounding air and seeds as well as higher moisture diffusivity, thus, enhancing the evaporation of water from the seeds. These experimental results are similar to others which have been published in the literature of the drying process of vegetables and agricultural products; for example, rapeseed (Duc *et al*., 2011), breadfruit seed (Shittu and Raji, 2011), olive cake (Akgun and Doymaz, 2005), and tomatoes (Celma *et al*., 2011).

Effective Moisture Diffusivity

The logarithm of moisture ratio values (lnMR) was plotted against average drying time (t) for different drying conditions of soybean seeds and is shown in Figure 6. It is noted that the relationships were non-linear in nature under all the drying conditions studied. This non-linearity in the relationship may be due to the reasons like shrinkage in the product, non-uniform distribution of initial moisture, variation in moisture diffusivity with moisture content, and change in product temperature during drying. The non-linearity of the curves is indicative of the variation in moisture diffusivity with moisture content.

Variation in effective moisture diffusivity of samples with moisture content at different air temperatures and velocities is shown against moisture content in Figure 7. The effective moisture diffusivity increased with decreasing moisture content. This may indicate that, as moisture content decreased, permeability to vapour increased, provided the pore structure remained open. Temperature of the product rises rapidly in the initial stages of drying, due to more absorption of air heat, as the product has a high loss factor at higher moisture contents. This increases the water vapour pressure inside the pores and results in pressure

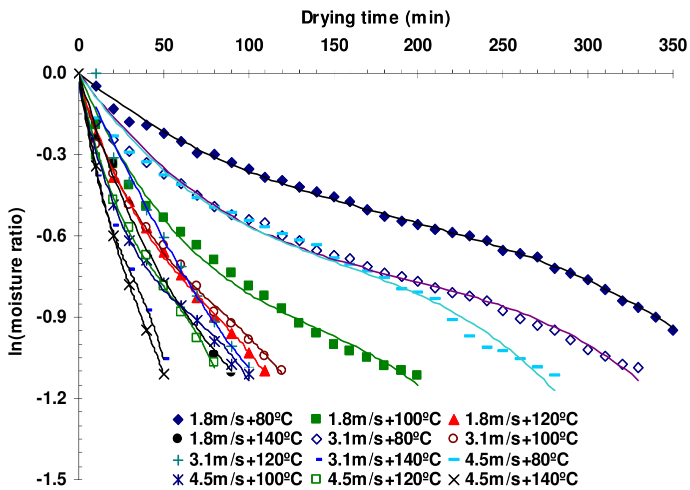

Figure 6. Variation in *ln(MR)* and drying time (min) for soybeans dried at different drying air temperatures and velocities.

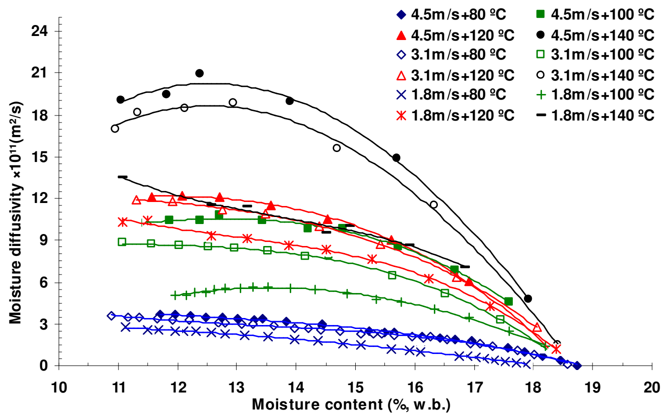

Figure 7. Effective moisture diffusivity as a function of moisture content, air temperature, and air velocity.

induced opening of pores. In the first stage of drying, liquid diffusion of moisture could be the main mechanism of moisture transport. As drying progressed further, vapour diffusion could have been the dominant mode of moisture diffusion in the latter part of drying. Sharma and Prasad (2004), Reyes *et al*. (2007) and Sharma *et al*. (2005) also reported similar trend in the variation of moisture diffusivity with moisture content. A third order polynomial relationship was found to correlate the effective moisture diffusivity with corresponding moisture content of samples and is given by Equation (23):

$$D_{eff} = (A + BX + CX^2 + DX^3) \times 10^{-11} \qquad (23)$$

Where, *A, B, C* and *D* are the constants of regression, and *X* is moisture content (%wb). Regression constants for fluidized bed drying of soybean samples under different air temperatures and velocities are presented in Table 6. The high values of R^2 are indicative of good fitness of empirical relationship to represent the variation in effective moisture diffusivity with moisture content of the samples.

The average effective moisture diffusivity $(D_{eff})_{avg}$ was calculated by taking the arithmetic mean of the effective moisture diffusivities that were estimated at various levels of moisture contents during the course of drying. Average values of D_{eff} for

Table 6. Regression coefficients of effective moisture diffusivity for different air temperatures and velocities.

V (m s^{-1})	T (ºC)	A	B	C	D	R^2
	80	16.902	-2.791	0.1987	-0.0055	0.999
1.8	100	-8.271	2.126	-0.0174	-0.0044	0.996
	120	39.08	-7.381	0.7026	-0.0235	0.999
	140	55.725	-9.636	0.7893	-0.0233	0.951
	80	45.904	-9.771	0.764	-0.0204	0.997
3.1	100	-14.388	4.779	-0.226	-0.00001	0.996
	120	28.782	-4.191	0.455	-0.0178	0.999
	140	203.43	-41.544	3.287	-0.0907	0.999
	80	25.051	-4.5073	0.3506	-0.010	0.996
4.5	100	9.919	-0.5793	0.2081	-0.0114	0.986
	120	47.075	-8.4015	0.8048	-0.0276	0.999
	140	82.973	-14.577	1.353	-0.0456	0.999

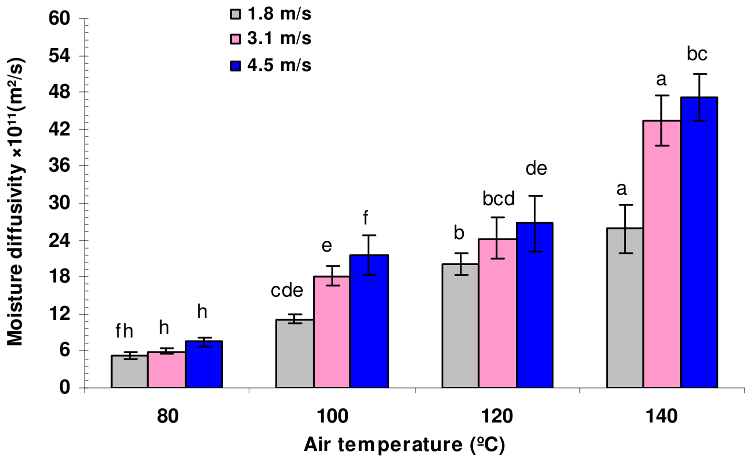

Figure 8. Average effective diffusivity as affected by temperature and drying air velocity.

different drying air temperatures and velocities are presented in Figure 8. The D_{eff} values of the samples were within the general ranges of 10^{-9} to 10^{-11} m^2 s^{-1} for biological materials (Wang *et al.* 2007). The values of D_{eff} are comparable with the reported values of 1.218×10^{-10} to 2.861×10^{-10} mentioned for wheat (Mohapatra and Rao, 2005), 2.78×10−11 to 3.06×10−11 m^2 s^{-1} for corn grain (Ajala *et al*., 2012), 1.1×10^{-11} to 3.1×10^{-11} m^2 s^{-1} for sesame seed (Khazaei and Daneshmandi, 2007), and 1.72×10^{-11} to 3.31×10^{-11} m^2 s^{-1} for rapeseed (Duc *et al*., 2011).

The increase in the average values of D_{eff} with air velocity might be due to the increase in outside heat transfer coefficient causing rapid heat transfer from air to the product. This might have caused an increase in vapour pressure within the seeds, hence a slight increase in moisture diffusivity with increase in drying air velocity up to a critical limit. Thus, there were fluctuations for higher seed bed depth with higher air velocities. A linear regression analysis on the average diffusion coefficient with the processing variables resulted in the following relationships:

$$(D_{eff})_{avg} = \left(47.268T^{0.259} + 5.712u^{-S.113} + 2.146\frac{T}{u}\right) \times10^{-11}$$

$$R^2 = 0.966 \quad (24)$$

Activation Energy

The ln D_{eff} as a function of the reciprocal of absolute temperature is plotted in Figure 9. The slope of the line is *($-E_a/R$)* and the intercept equals *$ln(D_0)$*. The results show a linear relationship due to Arrhenius type dependence. Then, the dependence of the effective diffusivity of soybeans on the temperature can be represented by the following equations:

1.8 m s^{-1}: $D_{eff} = 7.83\times10^{-6} \exp(-4193.9/T_{abs}$ $R^2= 0.967$ (25)

3.1 m s^{-1}: $D_{eff} = 4.48\times10^{-6} \exp(-3860.7/T_{abs})$ $R^2= 0.920$ (26)

4.5 m s^{-1}: $D_{eff} = 2.59\times10^{-6} \exp(-3594.5/T_{abs})$ $R^2= 0.934$ (27)

Values of activation energy of soybeans were found to be 34.87, 32.10 and 29.88 kJ mol^{-1} for air velocities of 1.8, 3.1 and 4.5 m s^{-1}, respectively. These are within the range of 15–40 kJ mol^{-1} for various foods as reported by Rizvi (1986).

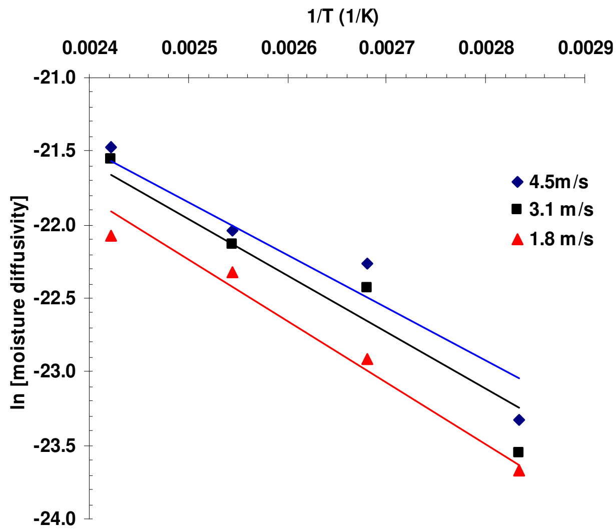

Figure 9. Arrhenius-type relationship between effective diffusivity and reciprocal absolute temperature.

Thermodynamically, activation energy is the relative ease with which the water molecules pass the energy hurdle when migrating within the product. Results showed that activation energy increased when drying air velocity decreased. The lower activation energy translates into higher moisture diffusivity in the drying process (Sharma and Prasad, 2004). Thus, the results indicate that higher drying rates were observed at 4.5 m s^{-1} as compared to 1.8 and 4.5 m s^{-1} during fluidized bed drying process, due to lower activation energy for moisture desorption. This value is higher than that for rapeseed (28.47 kJ mol^{-1}) (Duc *et al*., 2011), peanut grain (27.22 kJ mol^{-1} (Palacios *et al*., 2004); but lower than the value obtained for green pepper (51.4 kJ mol^{-1}) (Kaymak, 2002), green bean (35.43 kJ mol^{-1}) (Doymaz, 2005). A linear regression analysis on the activation energy with air velocity resulted in the following relationships:

$$E_a = 12.377 - 0.275u \qquad R^2 = 0.909 \tag{28}$$

Specific Energy Consumption

Figure 10 shows the specific energy consumption for drying of soybeans at

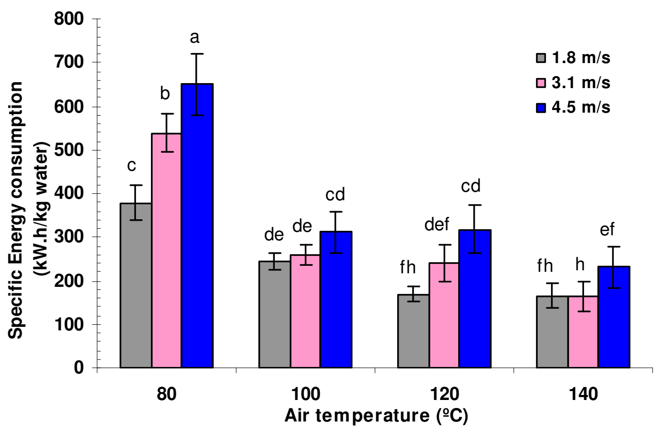

Figure 10. Specific energy consumption at different temperatures and drying air velocities.

various temperatures and air velocities. Specific energy consumption decreases with increasing temperature at all air velocities. At constant temperature, decreased air velocity reduces specific energy consumption. Minimum value of specific energy observed at 140ºC and 1.8 m s^{-1} air velocity was 26.90 (kWh kg^{-1}) while the maximum value was observed at 80ºC and 4.5 m s^{-1} air velocity to be 111.05 (kWh kg^{-1}). According to the results, it can be said that 140ºC temperature and 1.8 m/s air velocity should be selected for drying freshly harvested soybean seeds.

CONCLUSIONS

The minimum fluidized bed and terminal velocity of soybean seeds were found to be 1.8 and 15.5 m/s. The drying curves of soybean seeds took place in the falling rate period during drying process. As air temperature and air velocity increased, drying time decreased from 380 to 50 min. To explain the drying characteristics of soybeans, six drying models were applied and the model developed by Page showed good agreement with the experimental data. Effective moisture diffusivities varied between 4.595×10^{-11} to 3.325×10^{-10} m^2 s^{-1}, increasing with increase in temperature and air velocity, and decreasing with moisture content. The values of activation energy ranged from 35.33 to 30.73 kJ mol^{-1} and decreased with increase in air velocity. Specific energy consumption decreased with increase air temperature and decreasing air velocity. Air temperature of 140ºC and air velocity of 1.8 m s^{-1} for 90 minutes produced the least specific energy consumption and the energy requirement for drying was only 162.73 MJ kg^{-1} water.

REFERENCES

1. Abbasi Suraki, A., Sharifzade, F., Tavakkol Afshari, R., Majnoun Hosseini, N. and Gazor, H. R. 2010. Optimization of Processing Parameters of Soybean Seeds Dried in a Constant-bed Dryer Using Response Surface Methodology. *J. Agr. Sci. Tech.,* **12:** 409-423
2. Ajala, A. S., Ajala, F. A. and Tunde-Akintunde, T. Y. 2012. Study on Drying Kinetics of Fermented Corn Grains. *Food Sci. Quality Manag.* **5:** 10-18
3. Akgun, N. A. and Doymaz, I. 2005. Modeling of Olive Cake Thin-layer Drying Process. *J. Food Eng.,* **68:** 455–461.
4. Barrozo, M. A. S., Felipe, C. A. S., Sartori, D. J. M. and Freire, J. T. 2006. Quality of Soybean Seeds Undergoing Moving Bed Drying: Countercurrent and Crosscurrent Flows. *Drying Tech.,* **24:** 415-422.
5. Boeri, C. N. and Khatchatourian, O. 2012. Numerical Simulation to Describe the Soybean *Glycine max* (L.) Drying Process: Influence of Air Velocity, Temperature and Initial Moisture Content. *Int. J. Mech. Eng.,* **2(2):** 30-41.
6. Celma, A. R., Cuadros, F. and Lopez-Rodriguez, F. 2011. Convective Drying Characteristics of Sludge from Treatment Plants in Tomato Processing Industries. *Food Bioprod. Process.,* **90**: 224-234.
7. Dondee, S., Meeso, N., Soponronnarit, S. and Siriamornpun, S. 2011. Reducing Cracking and Breakage of Soybean Grains under Combined Near-Infrared Radiation and Fluidized-Bed Drying. *J. Food Eng.,* **104:** 6–13.
8. Doymaz, I. 2005. Drying Behaviour of Green Beans. *J. Food Eng.,* **69:** 161–165.
9. Doymaz, I. and Ismail, O. 2011. Drying Characteristics of Sweet Cherry. *Food Bioproducts Proc.,* **89:** 31–38.
10. Duarte, C. R., Murata, V. V. and Barrozo, M. A. S. 2004. The Use of a Population Balance Model in the Study of Inoculation of Soybean Seeds in a Spouted Bed. *Cana. J. Chem. Eng.,* **82**: 116–121.
11. Duc, L. A., Han, J. W. and Keum, D. H. 2011. Thin Layer Drying Characteristics of Rapeseed (*Brassica napus* L.). *J. Stored Prod. Res.,* **47**: 32-38.
12. Evin, A. 2011. Thin Layer Drying Kinetics of *Gundelia tournefortii* L. *Food Bioproducts Proc.,* **25**: 2711-2718.
13. Felipe, C. A. S. and Barrozo, M. A. S. 2003. Drying of Soybean Seeds in a Concurrent Moving Bed: Heat and Mass Transfer and Quality Analysis. *Drying Tech.,* **21(3):** 439-456.

14. Figiel, A. 2010. Drying Kinetics and Quality of Beetroots Dehydrated by Combination of Convective and Vacuum-microwave Methods. *J. Food Eng.,* **98:** 461–470.
15. Freire, F. B., Marcos, A. S. B., Dermeval, J. M. S. and Freire, T. 2004. Study of the Drying Kinetics in Thin Layer Fixed and Moving Bed. *Proceedings of the 14th International Drying Symposium (IDS 2004)*, August 22-25, 2004, São Paulo, Brazil, **C:** 1684-1691.
16. Gowen, A. A., Abu-Ghannam, A., Frias, J. and Oliveira, J. 2008. Modeling Dehydration and Rehydration of Cooked Soybeans Subjected to Combined Microwave–hot-air Drying. *Innovative Food Sci. Emerg. Technol.*, **9**: 129–137
17. Jangam, S. V., Joshi, V. S., Mujumdar, A. S. and Thorat, B. N. 2008. Studies of Dehydration of Sapota (*Achras zapota*). *Drying Tech.,* **26:** 369–377.
18. Kaymak, F. 2002. Drying and Rehydration Kinetics of Green and Red Pepper. *J. Food Sci.,* **67:** 168–175.
19. Khazaei, J. and Daneshmandi, S. 2007. Modeling of Thin-layer Drying Kinetics of Sesame Seeds: Mathematical and Neural Networks Modeling. *Int. Agrophysics,* **21**: 335-348.
20. Kingsly, R. P., Goyal, R. K., Manikantan, M. R. and Ilyas, S. M. 2007, Effects of Pretreatments and Drying Air Temperature on Drying Behavior of Peach Slice. *Int. J. Food. Sci. Tech.,* **42:** 65–69.
21. Kundu, K. M., Datta, A. B. and Chatterjee, P. K. 2001. Drying of Oil Seeds. *Drying Tech.,* **19(2):** 343–358.
22. Kunii, D. and Levenspiel, O. 1991. *Fluidization Engineering*. Butterworth-Heinemann, Boston, 69 PP.
23. Li, Z., Kobayashi, N., Nishimura, A. and Hasatani, M. 2002. Sorption Drying of Soybean Seeds with Silica Gel. I. Hydrodinamics of a Fluidization Bed Dryer. *Drying Tech.,* **20(6):** 1193–1213.
24. McMinn, W. A. M. 2006. Thin-layer Modelling of the Convective, Microwave, Microwave-convective and Microwave-vacuum Drying of Lactose Powder. *J. Food Eng.,* **72:** 113–123.
25. Midilli, A., Kucuk, H. and Yapar, Z. 2002. A New Model for Single Layer Drying. *Drying Tech.,* **20(7):** 1503–1513.
26. Mohapatra, D. and Rao, S. P. 2005. A Thin Layer Drying Model of Parboiled Wheat. *J Food Eng.,* 66 (4): 513-518.
27. Motevali, A., Minaei, S. and Khoshtagaza, M. H. 2011. Evaluation of Energy Consumption in Different Drying Methods. *Energy Con. Manag.,* **52:** 1192–1199.
28. Palacios, T. R., Potes, L. B., Montenegro, R. A. and Giner, S. A. 2004. Peanut Drying Kinetics: Determination of the Effective Diffusivity for In-shell and Shelled Peanuts by Applying a Short-time Analytical Model to Measured Data. *Proceedings of the 14th International Drying Symposium (IDS 2004),* (Eds.): Silva, M. A. and Mujumdar, A. S. August 22-25, 2004, Brazil, PP. 1448-1455.
29. Pfeifer, A. A., Murata, V. V. and Barrozo, M. A. S. 2010. Modelling of Soybean Seed Drying in Concurrent Sliding Bed Dryers: Effect of the Number of Stages on the Seed Quality and Drying Performance. *Biosys. Eng.,* **107:** 341-348.
30. Rafiee, S., Keyhani, A., Sharifi, M., Jafari, A., Mobli, H. and Tabatabaeefar, A. 2009. Thin Layer Drying Properties of Soybean (Viliamz Cultivar). *J. Agri. Sci. Tech.,* **11:** 289-300.
31. Reyes, A., Ceron, S., Zuniga, R. and Moyano, P. 2007. A Comparative Study of Microwave-assisted Air Drying of Potato Slices. *Biosys, Eng.,* **98:** 310-318
32. Rizvi, S. S. H. 1986. Thermodynamic Properties of Foods in Dehydration. In: "*Engineering Properties of Foods*", (Eds.): Rao, M. A. and Rizvi, S. S. H. Marcel Dekker, New York, PP. 190–193.
33. Rojanasaroj, C., White, G.M., Loewer, O.J. and Engli, D.B. 1976. Influence of Heated Air Drying on Soybean Impact Damage. *Trans. ASAE,* **19:** 372–377.
34. Sangkram, U. and Noomhorm, A. 2002. The Effect of Drying and Storage of Soybean on the Quality of Bean, Oil, and Lecithin Production. *Drying Tech*., **20(10):** 2041–2054
35. Sharma, G. P. and Prasad, S. 2004. Effective Moisture Diffusivity of Garlic Cloves Undergoing Microwave-convective Drying. *J. Food Eng.,* **65:** 609-617.
36. Sharma, G. P., Verma, R. C. and Pathare, P.B. 2005. Thin-layer Infrared Radiation Drying of Onion Slices. *J. Food Eng.,* **67:** 361-366.

37. Shittu, T. A. and Raji, A. O. 2011. Thin Layer Drying of African Breadfruit (*Treculia africana*) Seeds: Modeling and Rehydration Capacity, *Food Bioprocess. Tech.,* **4:** 2246–231.
38. Sinnecker, P., Braga, N.,Macchione, E. L. A. and Lanfer-Marquez, U. M. 2005. Mechanism of Soybean (*Glycinemax L.* Merrill) Degreening Related to Maturity Stage and Postharvest Drying Temperature. *Postharvest Biol. Tech.,* **38:** 269-279.
39. Soponronnarit, S., Swasdisevi, T., Wetchacama, S. and Wutiwiwatchai, W. 2001. Fluidised Bed Drying of Soybeans. *J. Stored Prod. Res.*, **37:** 133-151
40. Stewart, O. J., Raghavan, G. S. V., Orsat, V. and Golden, K. D. 2003. The Effect of Drying on Unsaturated Fatty Acids and Trypsin Inhibitor Activity in Soybean. *Process Biochem.,* **39:** 483-489.
41. Wang, H. G., Senior, P. R., Mann, R. and Yang, W. Q. 2009. Online Measurement and Control of Solids Moisture in Fluidized Bed Dryers. *Chem. Eng. Sci.,* **64:** 2893-2902.
42. Wang, Z., Sun, J., Chen, F., Liao, X. and Hu, X. 2007 Mathematical Modelling on Thin Layer Microwave Drying of Apple Pomace with and without Hot Air Pre-drying. *J. Food Eng.,* **80:** 536-544.
43. Wiriyaumpaiwong, S., Soponronnarit, S. and Prachayawarakorn, S. 2003. Soybean Drying by Two-dimensional Spouted Drying. *Drying Tech.,* **21(9):** 1735–1757.

ویژگی‌های خشک کردن بستر سیال سویا

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چکیده

در تحقیق حاضر به مطالعه تاثیر دما و سرعت هوا بر روی سینیتیک خشک شدن و انرژی مصرفی ویژه خشک‌کردن بستر سیال سویا در دمای ۸۰، ۱۰۰، ۱۲۰ و ۱۴۰°C و نرخ سرعت هوای ۱/۸، ۳/۱ و m/s ۴/۵ پرداخته شده است. شش مدل ریاضی برای تفسیر رفتار خشک‌شدن بستر سیال سویا مورد بررسی قرار گرفته شد. ثابت نرخ خشک شدن (k) با افزایش دما و سرعت هوا افزایش یافته، که منجر به کاهش زمان خشک شدن شد. اگر چه مدل میدیلی بهترین تطابق داشت، مدل پیج به دلیل ساده تر بودن، داشتن ۲ ثابت در مقایسه با چهار ، انتخاب شد. خشک شدن سویا در نرخ نزولی رخ داده که توسط نفوذ رطوبتی کنترل می شود. یک رابطه چند جمله‌ای درجه سوم میان نفوذ موثر رطوبتی و میزان رطوبت پیدا شد. نفوذ موثر با کاهش میزان رطوبت و افزایش دما و سرعت هوا، افزایش یافت. نفوذ موثر برای محدوده دمایی و سرعتی ذکر شده از $۴/۵۹۵ \times ۱۰^{-۱۱}$ تا $۳/۳۲۵ \times ۱۰^{-۱۰}$ m²/s متغیر بود. مقادیر انرژی فعال‌سازی برای نفوذ رطوبتی برای سرعت هوای ۱/۸، ۳/۱ و m/s ۴/۵ به ترتیب ۳۵/۳۳، ۳۲/۸۵ و ۳۰/۷۳kJ/mol به دست آمد. مشاهده شد که کاهش انرژی فعال‌سازی سبب افزایش نرخ خشک‌شدن می‌گردد. حداقل و حداکثر انرژی مورد نیاز خشک کردن سویا به ترتیب ۲۶/۹۰ و kWh/kg ۱۱۱/۰۵ در ۱۴۰°C، ۱/۸ m/s و ۸۰°C، ۴/۵ m/s تعیین شد.