Effects of microwave - fluidized bed drying on quality, energy consumption and drying kinetics of soybean kernels

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Abstract Moisture content of soybean kernel at harvest time is too high for storage, and needs to be reduced. In this research, drying characteristics, quality and energy requirement for microwave-fluidized bed drying of soybean kernels were studied. The results showed that air temperature (80–140 °C), velocity (1.8–4.5 m/s) and microwave power (200–500 W) significantly influenced drying time, moisture diffusivity, rehydration capacity, cracking, and specific energy consumption ($P \leq 0.05$). Among the applied models, Page's model has the best performance to estimate the microwave-fluidized bed drying behavior of the soybean kernels. Moisture diffusivity values increased (6.25×10^{-10} to 42.14×10^{-10} m²/s) as the air velocity decreased and air temperature and microwave power increased. Activation energy was found to be between 3.33 and 17.70 kJ/mol. Minimum cracking percentage of soybean kernels (12.96 %) was obtained at 80 °C, 1.8 m/s and 200 W treatments. The increase in microwave power and decrease in air velocity level decreased the rehydration capacity. Specific energy consumption varied from 50.94 to 338.76 MJ/kg water and the lowest specific energy consumption were obtained at 80 °C, 4.5 m/s and 500 W.

Keywords Microwave-fluidized bed drying · Soybean kernel · Energy consumption · Cracking · Rehydration

Introduction

Soybean is currently one of the most important oilseeds in the world due to its high quality as a source of protein for human and animal diets (Rafiee et al. 2009). Harvesting time is one of the critical steps in soybean kernel production that can affect kernel quality. The optimum harvest moisture range of soybean is 13 % to 15 % (w.b.) for maximum weight and minimum field losses (USDA 2008; Abbasi Suoraki et al. 2010). Soybeans can generally be harvested any time after the kernels are mature and the foliage is dry (Sumner and Clark 2006). Because of unfavorable weather conditions as frequently occur in the harvest season in the main center of the soybean kernel production area of Iran, the soybean kernels will deteriorate and harvest losses will increase, so the farmers should harvest and dry kernels as soon as possible. Therefore, soybean kernels are harvested typically at moisture contents in the range 25–33 % (w.b.). But for safe storage, it is necessary to dry the kernels to lower moisture contents, e.g. less than 10 % (w.b.) depending the local climate conditions (Soponronnarit et al. 2001).

Fluidized-bed drying is one of the hot-air drying process used for raw soybean dehydration in the world during the last few years due to high heat and mass transfer rates between the hot-air and the soybean kernels. This, consequently, induces simultaneously the moisture and anti-nutritional factor faster reductions than the conventional hot air drying. However, a major disadvantage of fluidized beds is the possibility of size reduction of the particles due to attrition and collision between them (Goksu et al. 2005; Abbasi Suoraki and Mowla 2008).

In general, energy efficiency in drying is closely related to drying times. Compared fluidized bed drying, microwave drying techniques can greatly reduce the drying time of biological materials without quality degradation (Soysal et al. 2006). However, microwave processing has the disadvantage of non-homogenous distribution in a microwave cavity,

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creating problems of non-uniform heating (Goksu et al. 2005). Fluidized bed drying with microwave heating compensates for some of the drawbacks of each method. Temperature uniformity of the particles can be provided by good mixing due to fluidization and the diffusion period of drying can be reduced by the utilization of microwave energy (Abbasi Suoraki and Mowla 2008; Goksu et al. 2005).

Knowledge of the drying kinetics of the soybean is required to design, optimize, and control the drying process. Also, mathematical modeling and simulation of drying curves under different conditions is important to obtain a better control of this unit operation and an overall improvement of the quality of the final product.

The literature contains many reports about changes in soybean kernel quality during hot air drying (Rafiee et al. 2009; Abbasi Suoraki et al. 2010; Gowen et al. 2008; Sinnecker et al. 2005; Li et al. 2002; Freire et al. 2004; Overhults et al. 1973), fluidized bed drying (Soponronnarit et al. 2001; Osella et al. 1997), concurrent sliding moving bed drying (Pfeifer et al. 2010; Felipe and Barrozo 2003; Barrozo et al. 2006), spouted bed drying (Duarte et al. 2004; Wiriyumpaiwong et al. 2003), rotary dryer (Luz et al. 2010), near-infrared radiation-fluidized-bed drying (Dondee et al. 2011), microwave-hot air drying (Gowen et al. 2008). These studies focused mainly the effects of air temperature, relative humidity and initial moisture content on quality of soybean such as urease activity, cracking, breakage, fatty acids, protein and germination. However, there is no information regarding the microwave-fluidized bed drying kinetics of soybean kernels in the literature. Therefore, the main objectives of this study is to investigate the drying behavior of soybean kernels in microwave –fluidized bed dryer, to compare the experimental data found during drying with the predicted values obtained by using some drying models, to calculate the effective moisture diffusivity and activation energy, to determine the specific energy consumption, and to evaluate the qualities of soybean kernels, including rehydration capacity, percentage of cracking.

Materials and methods

Material

Fresh soybeans were obtained from a soybean farm in the Gorgan area (Iran). For preventing moisture losses samples were stored in a refrigerator at 4 ± 1 °C until the commencement of drying. Before starting the experiments, soybean samples were taken out of the cold room and left in ambient conditions until the kernel temperatures reached ambient air temperature. The average moisture content of the soybean samples was 24 ± 0.5 % (w.b.), as determined by oven drying at 103 °C for 24 h (Abbasi Suoraki et al. 2010).

Microwave - fluidized bed dryer

Pictures of the experimental apparatus are shown in Fig. 1. A domestic microwave oven with a maximum power output of 1,000 W (ME 3410 W, Samsung, Thailand) was used in this study. The circuits were modified to allow the power to be controlled using an external phase controller, which could automatically and continuously adjust the microwave power output from 0 to 1,000 W. Dimensions of the microwave cavity were $44.5 \times 42.0 \times 38.9$ cm. The fluidized bed consisted of a cylindrical chamber with an inner diameter of 9 cm (10 cm outside diameter), a height of 60 cm, and 12 kW hot-air heaters controlled by a PID controller (with accuracy of ± 1 °C). The backward curve centrifugal fan was driven by a 1.5 kW motor connected to a frequency inverter to adjust the air flow rate precisely. 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. Circular holes 10 mm in diameter were cut at the base and top of the microwave oven chamber to place the cylindrical chamber. Metallic covers were used at the inlet and outlet of the drying air stream, to prevent microwaves from leaking out of the oven. Since the ratio of cylinder diameter to height is much greater than 10, the wall effect was negligible.

Based on the mass and energy balance, the solids moisture content can be calculated from the temperature (T_{out}) and relative humidity (RH) of the outlet air, which can be measured using temperature and humidity sensors directly. The following steps can be followed for calculation (Wang et al.; 2009).

First, the saturation vapour 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 given in Table 1.

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

$$M_{w,in} = 0.62198 \frac{P_{w,in}}{P_o - P_{w,in}}, P_{w,in} = \frac{H_{r,in} P_v}{100} \quad (2)$$

and

$$M_{w,out} = 0.62198 \frac{P_{w,out}}{P_o - P_{w,out}}, P_{w,out} = \frac{H_{r,out} P_v}{100} \quad (3)$$

Fig. 1 Microwave- fluidized bed dryer setup

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

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

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

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

$$M_f = 0.0006362 \times 0.9 \rho_{air} u \quad (5)$$

where, u is the inlet air velocity (m^3/min) and the density of the air, ρ_{air} (kg/m^3) can be calculated as:

$$\rho_{air} = 1.24703 - 0.002787 T_{out} - 3.23518 \times 10^{-5} T_{out}^2 \quad (6)$$

Hence, the average solids moisture content can be calculated as:

$$X_p = \frac{W_o X_o - W}{W_o - W} \quad (7)$$

where, W_o is the initial sample weight (kg), W is the water loss of sample (kg), and X_o is the initial sample moisture content (dry basis).

Table 1 Coefficients in Eq. (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}

In each experiment, 103 g of fresh soybeans (bed depth of 5 cm) was used. Drying experiments were conducted at microwave powers of 200, 300, 400 and 500 W and air temperatures 80, 100, 120 and 140 °C and air velocities of 1.8, 3.1 and 4.5 m/s, with three replications. The experimental system was operated at ambient conditions, i.e. average room air conditions of 17 ± 1.6 °C and 34 ± 2 % relative humidity.

Moisture diffusion model

In thin layer drying of agricultural products, analysis of the dehydration process that takes place in the falling rate period is calculated using a simple diffusion model based on Fick's second law. Evaluation of the moisture diffusion mechanism in spherical bodies can be represented by the following equation (Sharma and Prasad 2004):

$$\frac{\partial X}{\partial t} = D_{eff} \left(\frac{\partial^2 X}{\partial r^2} + \frac{2}{r} \frac{\partial X}{\partial r} \right) \quad (8)$$

where, D_{eff} is the effective moisture diffusivity (m^2/s); r is the radius of soybean kernel (3.75 mm), X is the moisture content (kg water/kg dry matter), and t is the time (s).

The method of slopes was used for the estimation of effective moisture diffusivity of soybean kernels at corresponding moisture contents under different drying conditions. An analytical solution of Eq. (8) can be derived by making the following assumptions (Pathare and Sharma 2006; Caglar et al. 2009):

1. Moisture is initially uniformly distributed throughout the mass of a sample.
2. Mass transfer is symmetric with respect to the centre of the cylinder.
3. Surface moisture content and temperature of the sample instantaneously reach equilibrium with that of the surrounding air.
4. Mass transfer is by diffusion only.
5. Diffusion coefficient is constant and shrinkage is negligible.
6. Resistance to mass transfer at the surface is negligible compared to the internal resistance of the sample.

With the above assumptions, the following initial and boundary conditions are usually used in solving Eq. (8):

$$X(r, 0) = X_o; X(r_o, t) = X_e; \frac{\partial X(r = o, t)}{\partial r} = 0 \quad (9)$$

The solution of Eq. (8) with initial and boundary conditions as in Eq. (9) can be obtained for the moisture diffusion model of spherical bodies as follows (Caglar et al. 2009):

$$MR = \frac{X - X_e}{X_o - X_e} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-\frac{n^2 \pi^2}{r_o^2} D_{eff} t\right) \quad (10)$$

where, MR is the moisture ratio (dimensionless), X_t , X_o and X_e are the moisture content at any time of drying, initial moisture content and equilibrium moisture content (kg water/kg dry matter), respectively. The equilibrium moisture content was calculated using the equation given by Soponronnarit et al. (2001):

$$H_r = \exp\left[\left(\frac{-21065}{R \times T}\right) \times X_e^{-1.25}\right] \quad (11)$$

where, H_r is the air relative humidity (%), T is the air temperature (K) and R is the gas constant (8.314 J/mol.K).

For long drying periods, Eq. (10) can be further simplified to include only the first term of the series. Effective moisture diffusivity is obtained by plotting the experimental drying data in terms of $\ln(MR)$ versus time. From Eq. (12), a plot of $\ln(MR)$ versus time gives a straight line with a slope of (S) , in which:

$$\ln(MR) = \ln\left(\frac{6}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}}{r_o^2}\right) t \quad (12)$$

$$S = \frac{\pi^2 D_{eff}}{r_o^2} \quad (13)$$

Computation of activation energy

The dependence of the effective moisture diffusivity on the temperature is generally described by the Arrhenius equation:

$$D_{eff} = D_o \exp\left(\frac{-E_a}{RT_{abs}}\right) \quad (14)$$

where, D_o is the pre-exponential factor of Arrhenius equation (m^2/s), E_a is the activation energy (kJ/mol), R is the universal gas constant (kJ/mol K), and T is absolute temperature (K). The activation energy can be determined from the slope of Arrhenius plot, $\ln(D_{eff})$ versus $1/T_{abs}$.

Mathematical modeling of drying kinetics

The drying data obtained were fitted with three different moisture ratio models (Table 2). The models were evaluated and compared with experimental data using the coefficient of determination (R^2); root mean square error (RMSE) and reduced chi-square (χ^2) based on the following relationships (Wang et al. 2007):

$$R^2 = 1 - \left(\frac{\sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2}{\sum_{i=1}^N (MR_{pre,i} - \overline{MR}_{exp})^2} \right) \quad (15)$$

$$\chi^2 = \frac{\sum_{i=1}^n (MR_{exp,i} - MR_{pre,i})^2}{N} \quad (16)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (MR_{exp,i} - MR_{pre,i})^2}{N}} \quad (17)$$

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.

Specific energy consumption

The energy consumed for drying a kilogram of sample is calculated using Eq. (18) (Motevali et al. 2011).

$$E_s = \left(\frac{Au\rho_a C_a \Delta T + P}{m_w} \right) \times t \quad (18)$$

where, A is the cross sectional area of column, ρ_a is air density (kg/m^3), ΔT is temperature difference of inlet and outlet air ($^{\circ}C$), u is air velocity (m/s), C_a is air specific heat (J/kg $^{\circ}C$), P is microwave power (W); t is the time (s), m_w is the mass of evaporated water (kg), and E_s is the specific

Table 2 Mathematical models given by various authors for the drying data

Model name	Model	References
Page	$MR = \exp(-kt^n)$	Lee and Kim (2009)
Logarithmic	$MR = a \exp(-kt) + b$	Kingsly et al. (2007)
Midilli et al.	$MR = a \exp(-kt^n) + bt$	Wang et al. (2007)

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

Table 3 Effect of microwave power, air temperature and velocity on drying time (min)

P (W)	u (m/s)	Air temperature (°C)			
		80	100	120	140
200	1.8	29.0 (±1.5)	26.0 (±1.3)	22.5 (±1.5)	24.0 (±1.8)
	3.1	33.7 (±2.5)	27.0 (±1.5)	25.5 (±2.0)	21.0 (±2.3)
	4.5	38.5 (±3.0)	30.0 (±2.7)	23.3 (±1.5)	18.8 (±2.8)
300	1.8	21.0 (±1.5)	19.0 (±1.6)	19.0 (±1.1)	16.5 (±1.5)
	3.1	24.5 (±1.8)	21.0 (±1.5)	17.5 (±0.8)	14.5 (±0.8)
	4.5	28.0 (±2.1)	24.5 (±1.4)	17.0 (±1.0)	11.5 (±0.5)
400	1.8	13.0 (±0.9)	14.0 (±0.6)	12.0 (±0.6)	11.5 (±1.0)
	3.1	14.5 (±1.0)	12.5 (±0.8)	12.0 (±0.7)	9.5 (±1.0)
	4.5	17.0 (±1.2)	11.0 (±0.8)	9.3 (±1.0)	7.5 (±0.4)
500	1.8	10.5 (±1.0)	10.0 (±0.5)	9.0 (±1.0)	6.4 (±0.8)
	3.1	11.0 (±0.8)	8.7 (±0.7)	7.3 (±0.9)	5.4 (±0.8)
	4.5	13.0 (±0.6)	8.0 (±0.8)	6.8 (±1.0)	3.3 (±0.5)

energy consumption to evaporate a unit mass of water from the product in microwave-fluidized bed dryer (J/kg water).

Caking of soybean kernels

Percentage of cracking of soybean kernels was inspected visually by sorting out the cracked and broken kernel with fluorescent light using a 80 g sample. The cracking percentages (Cr) can be calculated using the following equations:

$$Cr = \frac{m_c}{m_s} \times 100 \quad (19)$$

where, m_c and m_s indicate the mass of cracked kernels and mass of the samples (kg), respectively.

Rehydration capacity

Rehydration is one of the important properties used to measure the quality of dried food materials. Five grams of the dried soybean were added to 60 ml of distilled water, in a 300 ml flask beaker at 25 °C for 2 h. Then, the samples were weighed using a digital balance (GF-600, A & D, Japan) with a precision of 0.01 g. Rehydration capacity was calculated as the

Fig. 2 Relationship between the moisture ratio and drying time during microwave-fluidized bed drying at different microwave powers

maximum amount of water absorbed (kg) per kg of dry material as determined at the end of the rehydration time for each experiment in three replications.

Results and discussion

Drying kinetics

The drying times involved in reducing the moisture content of soybean kernels from their initial level to about 10 % (w.b.), under various microwave-fluidized drying conditions, are presented in Table 3. The results indicate that by increasing the drying air temperature and using microwave energy power as an assisting heat source, the values of drying time decreased. This decrease can be due to the penetration of microwave energy into the sample and also due to the creation of a large vapor pressure difference between center and surface of kernel. At higher velocity, lower temperature of hot air reduced the temperature of the material surface in contrast to higher air temperature which increased the material surface temperature. The rationale for this effect lies in lower temperature of the hot air stream flowing across the product than the material temperature during microwave drying that induced the cooling effect as opposed to air temperature higher than the temperature of the material surface. The obtained results were similar to those reported by Sharma et al. (2004) for drying of onion slices, Das et al. (2004) for drying of parboiled rice and Motevali et al. (2011) for drying of pomegranate arils.

The shortest drying time (3.3 min) among all the drying conditions studied was obtained in the microwave—fluidized bed drying at 140 °C air temperature, 4.5 m/s air velocity and 500 W microwave power level. When the average drying times of microwave - fluidized bed and other drying method in literature were compared, the drying time was reduced approximately by 68–97 % with the addition of the microwave energy into the fluidized bed. This means that the magnitude of contribution of microwave energy on the fluidized bed drying is large. On the other hand, fluidization or air flow is essential to remove the moisture that accumulates on the surface of the particles under the created extra internal movement as well as providing uniformity of drying among the particles.

Sangkram and Noomhorm (2002) concluded that during convective drying of soybean kernels (80–140 °C); it took 105 to 450 min to dry soybean samples (25 to 10 % w.b.). The results obtained in the present work showed that as compared to convective case; the drying time can be shortened by 30–150 times by using microwave-fluidized bed drying. Beside of this, by performing microwave - fluidization drying at 500 W, 140 °C and 4.5 m/s, instead of near infrared radiation—

fluidized bed drying of soybean kernel at 4, 6 and 8 kW, 4.5 m/s, 40 °C and kernel bed depth of 6 cm, as reported by Dondee et al. (2011), the drying time can be shortened by about 40 times. In addition, drying time of soybean samples decreased about 70 times compared to hot air drying of soybean at 30–70 °C with air velocity of 1 m/s as reported by Rafiee et al. (2009).

Fitting models to the experimental data

The moisture ratio versus time curves for microwave-fluidized bed drying of soybean samples at different drying conditions are shown in Fig. 2. The drying curve became steeper with the increase in microwave power, air temperature and decrease in air velocity indicating faster drying of the product. This indicates that mass transfer within the sample was more rapid during these conditions. More heat generation within the sample created a large vapor pressure difference between the centre and the surface of the product. This results in a steep rise in the temperature of soybean kernels, sometimes approaching the boiling point of water. The hot air flowing across the soybean sample has a temperature lower than that of the sample during microwave drying which in turn picks up the heat from the soybean thus imparting a cooling effect.

Among of semi-empirical models examined, Page's model was observed the most appropriate one for all the experimental data with higher value for the coefficient of determination (R^2) and lower chi-square (χ^2) and RMSE compared with the statistical values obtained for other models. Results of the statistical analysis for Page's model are summarized in Tables 4, 5, 6. In all cases, the R^2 values for the models were

Table 4 Estimated values of coefficients and statistical analysis for the Page's model at 1.8 m/s air velocity

P (W)	T (°C)	Constants	R^2	χ^2	RMSE
200	80	$k=0.0107$; $n=1.398$	0.997	0.00014	0.00918
	100	$k=0.0119$; $n=1.430$	0.999	0.00007	0.00767
	120	$k=0.0142$; $n=1.423$	0.999	0.00018	0.00980
	140	$k=0.0136$; $n=1.431$	0.999	0.00010	0.00916
300	80	$k=0.0113$; $n=1.523$	0.997	0.00131	0.03366
	100	$k=0.0123$; $n=1.556$	0.998	0.00011	0.00939
	120	$k=0.0115$; $n=1.581$	0.996	0.02532	0.14233
	140	$k=0.0138$; $n=1.598$	0.999	0.00819	0.07010
400	80	$k=0.0093$; $n=1.893$	0.997	0.00045	0.01898
	100	$k=0.0081$; $n=1.891$	0.999	0.00002	0.00135
	120	$k=0.0107$; $n=1.915$	0.998	0.00017	0.00116
	140	$k=0.0108$; $n=1.926$	0.999	0.00019	0.00118
500	80	$k=0.0099$; $n=2.022$	0.999	0.00013	0.01001
	100	$k=0.0114$; $n=2.009$	0.998	0.00002	0.00394
	120	$k=0.0129$; $n=2.091$	0.999	0.00004	0.00532
	140	$k=0.0210$; $n=2.200$	0.999	0.00002	0.00418

Table 5 Estimated values of coefficients and statistical analysis for Page's model at 3.1 m/s air velocity

P (W)	T (°C)	Constants	R ²	χ^2	RMSE
200	80	k=0.0091; n=1.391	0.996	0.00085	0.02081
	100	k=0.0109; n=1.412	0.998	0.00001	0.00355
	120	k=0.0121; n=1.420	0.997	0.00032	0.01694
	140	k=0.0139; n=1.467	0.996	0.00551	0.00691
300	80	k=0.0096; n=1.510	0.998	0.00076	0.02603
	100	k=0.0115; n=1.536	0.998	0.00012	0.01002
	120	k=0.0133; n=1.581	0.996	0.00876	0.08612
	140	k=0.0134; n=1.669	0.999	0.00409	0.05788
400	80	k=0.0090; n=1.830	0.999	0.00070	0.02637
	100	k=0.0096; n=1.905	0.999	0.00135	0.03244
	120	k=0.0108; n=1.908	0.998	0.00122	0.03080
	140	k=0.0124; n=2.032	0.992	0.00094	0.02709
500	80	k=0.0118; n=1.921	0.999	0.00020	0.01350
	100	k=0.0245; n=1.826	0.998	0.00013	0.01071
	120	k=0.0390; n=2.030	0.997	0.00150	0.03669
	140	k=0.0308; n=2.102	0.999	0.00001	0.00361

greater than 0.989, indicating good fit. The R² values varied between 0.989 and 0.999, χ^2 values between 0.0001 and 0.02532, and RMSE values between 0.00116 and 0.14233. Microwave-fluidized drying method had a significant effect on the drying rate constant (k) of the samples. It was determined that the value of the drying rate constant increased with microwave power and air temperature and decreased with air velocity. At low air temperature, heat removal from the product and cooling effect accelerated with an increase in air

Table 6 Estimated values of coefficients and statistical analysis for Page's model at 4.5 m/s air velocity

P (W)	T (°C)	Constants	R ²	χ^2	RMSE
200	80	k=0.0078; n=1.387	0.999	0.00002	0.00441
	100	k=0.0099; n=1.412	0.999	0.00001	0.00322
	120	k=0.0132; n=1.448	0.997	0.00010	0.00750
	140	k=0.0149; n=1.491	0.999	0.00002	0.00415
300	80	k=0.0079; n=1.501	0.995	0.01755	0.12683
	100	k=0.0098; n=1.510	0.997	0.00112	0.03179
	120	k=0.0133; n=1.586	0.999	0.00020	0.01325
	140	k=0.0138; n=1.830	0.997	0.00420	0.05717
400	80	k=0.0090; n=1.740	0.999	0.00001	0.00252
	100	k=0.0121; n=1.870	0.998	0.00003	0.00528
	120	k=0.0191; n=1.888	0.989	0.00005	0.00561
	140	k=0.0195; n=1.985	0.994	0.00055	0.01911
500	80	k=0.0115; n=1.810	0.999	0.00007	0.00860
	100	k=0.0197; n=1.951	0.999	0.00016	0.00120
	120	k=0.0220; n=2.103	0.989	0.00090	0.00897
	140	k=0.0658; n=2.312	0.999	0.00019	0.00137

velocity, which more reduced the temperature of the product and water vapour pressure. This resulted in decreased drying rate of product when air velocity was increased. In other words, the values of *k* and *n* decreased that the drying process become slower with increase in air velocity during microwave- fluidized bed drying. Such phenomenon has been observed by other researchers during hot air-microwave drying of food materials (Sharma et al. 2004; Abbasi Suoraki et al. 2009).

A comparison of the experimental and predicted moisture ratio values using the Page model is illustrated in Fig. 3. As can be observed in these figures, consistency of fitting the drying data in to this model is very good for all of the experimental drying conditions. Thus, this model may be assumed to represent the drying behavior of soybean kernels for microwave-fluidized bed drying.

Effective moisture diffusivity

Table 7 shows the changes of effective diffusion coefficients with microwave powers, air velocities and temperatures. The D_{eff} values of dried samples were varied in the range of 6.25×10^{-10} to 42.14×10^{-10} m²/s. These values are within the general range of 10^{-6} – 10^{-11} m²/s for drying of food materials (Arumuganathan et al. 2009). It can be seen that D_{eff} values increase substantially with microwave power and air temperature. When microwave treatment was added to fluidized bed drying, the mass transfer drying mechanism was complemented by a hydrodynamic phenomenon creating a pressure increase due to the evaporation of water inside the solid under the action of the microwaves. Increased velocity of airflow has an inverse relationship with moisture diffusivity or drying rate, and low rhythm of soybean kernels drying at high air velocities is due to higher cooling of soybean kernels. Therefore, the higher drying temperature and microwave power and lower air velocity can accelerate the water molecules present in the soybean kernels to evaporate faster, thus providing a faster decrease of the soybean samples moisture content and the corresponding higher value of effective moisture diffusivity. The values of D_{eff} are comparable with the reported values of 0.95 – 7.94×10^{-10} m²/s mentioned for hot air drying of banana slices (Thuwapanichayanan et al. 2011); 5.39 – 20.9×10^{-10} m²/s for infrared drying of seedless grape (Caglar et al. 2009); 12.9 – 316.8×10^{-10} m²/s for microwave-convective drying of garlic cloves (Sharma and Prasad 2004); and 3.2 – 11.2×10^{-9} m²/s for hot air drying of red bell pepper (Vega et al. 2007).

Activation energy

The $\ln(D_{\text{eff}})$ was plotted versus $1/T_{\text{abs}}$ and the energy of activation (E_a) was calculated using Eq. (14). The E_a was calculated for each value of air velocity and microwave power

Fig. 3 Comparison of experimental moisture ratio with predicted moisture ratio using the Page's model

(Table 8). The E_a is the energy barrier that must be overcome in order to activate moisture diffusion. Results indicated that the E_a values for soybean kernels varied between 5.15 and 17.70 kJ/mol for microwave-fluidized bed conditions. The values of energy of activation lie in the range of 12.7–110 kJ/mol for most food materials. The obtained values of energy

activation of soybean kernels at microwave-fluidized bed dryer are lower than the general range for various food materials. This reduction in activation energy was because of the volumetric heating effect by microwaves, which increased the drying rate and moisture diffusivity. It was also observed that as air velocity was increased at a given microwave power,

Table 7 Moisture diffusivity coefficient ($\times 10^{-10}$ m²/s) values for microwave-fluidized bed drying of soybean kernels

P (W)	u (m/s)	Air temperature (°C)			
		80	100	120	140
200	1.8	8.18 (± 0.11)	9.34 (± 0.13)	10.32 (± 0.28)	10.46 (± 0.30)
	3.1	7.16 (± 0.53)	8.27 (± 0.85)	8.97 (± 0.52)	12.26 (± 0.61)
	4.5	6.25 (± 0.74)	7.87 (± 0.90)	10.44 (± 1.03)	11.91 (± 0.83)
300	1.8	10.83 (± 0.46)	12.54 (± 0.69)	12.64 (± 1.45)	14.47 (± 1.09)
	3.1	9.91 (± 0.71)	11.47 (± 1.12)	13.76 (± 2.41)	15.53 (± 1.39)
	4.5	8.48 (± 0.49)	9.93 (± 0.67)	13.76 (± 1.69)	20.41 (± 2.14)
400	1.8	17.42 (± 1.79)	16.79 (± 1.04)	20.53 (± 2.11)	19.56 (± 1.45)
	3.1	16.22 (± 1.48)	18.20 (± 1.24)	20.07 (± 2.06)	23.86 (± 1.63)
	4.5	13.36 (± 1.37)	20.24 (± 1.03)	25.90 (± 2.10)	29.24 (± 2.87)
500	1.8	20.76 (± 1.09)	22.55 (± 1.83)	26.72 (± 0.78)	38.56 (± 1.97)
	3.1	20.70 (± 1.30)	27.03 (± 2.05)	42.14 (± 1.42)	38.98 (± 2.18)
	4.5	17.73 (± 1.17)	27.28 (± 1.94)	34.82 (± 2.53)	27.28 (± 2.37)

Table 8 Activation energy (kJ/mol) for soybean kernel at microwave-fluidized bed dryer

P (W)	Air velocity (m/s)		
	1.8	3.1	4.5
200	5.15 (± 0.24)	8.68 (± 0.61)	13.53 (± 0.61)
300	5.27 (± 1.01)	9.20 (± 0.89)	17.70 (± 1.22)
400	3.33 (± 0.29)	7.57 (± 0.20)	15.89 (± 0.10)
500	12.03 (± 0.33)	14.34 (± 1.23)	9.71 (± 0.39)

activation energy increased. This was because the increase in air velocity resulted in cooling of drying product, i.e. reducing its temperature and thus decreasing the moisture diffusivity.

Specific energy consumption

The specific energy consumption under various conditions of microwave-convective drying process is presented in Table 9. Results of analyses showed that the minimum energy required for drying soybean kernels was 50.94 (MJ/kg water), which occurred at 500 W microwave power, 80 °C and 1.8 m/s air velocity while the maximum energy requirement was 338.76 (MJ/kg water) observed at 200 W microwave power, 4.5 m/s air velocity and 100 °C. In other words, the maximum energy consumption was 6.65 times higher than the minimum energy required. Increased energy consumption with increasing air velocity can be attributed to sample surface cooling due to faster air which decreases moisture evaporation rate and increases drying time. It was seen that at 3.1 and 4.5 m/s air velocity, specific energy consumption decreases with increasing air temperature. By increasing the temperature, drying time has been reduced and this was more influential than on the energy consumption than on the specific heat of air. Effect of decreasing drying time at higher temperatures is more

pronounced than the effects of increased temperature and specific heat of air (Alibas 2007; Aghbashlo et al. 2008; Caglar et al. 2009). In addition, energy consumption decreases with increasing drying microwave power. This reduction in energy consumption was due to the volumetric heating effect of microwaves, which reduced the drying time considerably (Table 3). Specific energy consumption at 500 W microwave power decreased 1.53–3.16 times compared to the 200 W at various air temperatures and velocity. At 500 W and 1.8 m/s treatment, there was no significant difference between specific energy consumption at 80 and 140 °C air temperature. Nonetheless, drying time at 140 °C air temperature is 39 % less than that in the 80 °C air temperature (Table 3). Also, at 140 °C and 500 W microwave treatment, by performing drying at 4.5 m/s air velocity, instead of 1.8 m/s drying of soybean samples, the drying time can be shortened about 50 %, however, specific energy consumption increased 8.81 %.

Cracking of soybean kernels

According to the results shown in Table 10, percentage of cracking of soybean kernels increased with drying air temperature, velocity and microwave power as heat and mass transfer rates increased ($P < 0.05$). The cracking of soybean kernels was varied from a minimum of 12.96 % to maximum of 39.67 % for the experimental range of the variables. Since water movement is limited by water diffusion in the soybean kernel, the temperature of the kernel surface increases to more than the air wet bulb temperature as drying proceeds, so that the soybeans become brittle at the surface and prone to cracking. Also, a higher amount of the percentage of cracking kernels at higher air velocity is due to the combined effects of the strong impact of soybean kernel with other kernels, wall chamber and drying rate (Wiriyaumpaiwong et al. 2003; Dondee et al. 2011). The cracking of soybean kernels occurred

Table 9 Effect of drying conditions on specific energy consumption (MJ/kg water) during microwave-fluidized bed drying of soybean kernels

P (W)	u (m/s)	Air temperature (°C)			
		80	100	120	140
200	1.8	114.01 (± 5.90)	127.98 (± 6.41)	135.72 (± 9.07)	161.50 (± 12.06)
	3.1	208.69 (± 1.54)	215.86 (± 11.92)	251.32 (± 19.73)	243.03 (± 25.92)
	4.5	331.34 (± 25.81)	338.76 (± 30.49)	313.88 (± 2.19)	312.66 (± 45.86)
300	1.8	89.68 (± 6.19)	100.52 (± 8.46)	119.92 (± 6.95)	120.96 (± 11.02)
	3.1	160.59 (± 11.81)	174.56 (± 12.46)	176.225 (± 7.52)	171.50 (± 8.86)
	4.5	252.43 (± 18.83)	283.79 (± 16.20)	240.05 (± 14.11)	191.74 (± 8.35)
400	1.8	60.16 (± 4.18)	79.06 (± 3.92)	80.00 (± 3.99)	88.34 (2.70)
	3.1	100.15 (± 6.91)	108.29 (± 6.95)	124.96 (± 7.81)	115.60 (± 7.31)
	4.5	159.55 (± 11.23)	131.01 (± 8.99)	133.71 (± 14.58)	127.51 (± 6.80)
500	1.8	50.94 (± 5.44)	59.87 (± 2.99)	63.05 (± 7.02)	51.30 (± 6.01)
	3.1	79.70 (± 5.44)	78.66 (± 7.16)	77.29 (± 8.39)	67.43 (± 9.36)
	4.5	125.96 (± 5.76)	97.81 (± 9.18)	100.37 (± 14.76)	56.20 (± 8.64)

Table 10 Changes of soybean kernels cracking percentage at different drying conditions

P (W)	u (m/s)	Air temperature (°C)			
		80	100	120	140
200	1.8	12.96 (± 2.09)	14.66 (± 1.99)	18.27 (± 1.74)	21.50 (± 2.81)
	3.1	13.97 (± 3.16)	17.36 (± 2.41)	23.85 (± 2.52)	25.41 (± 2.76)
	4.5	18.89 (± 1.82)	23.08 (± 3.40)	26.16 (± 1.21)	27.09 (± 3.08)
300	1.80	14.22 (± 2.56)	16.78 (± 2.95)	21.19 (± 2.97)	23.29 (± 1.72)
	3.10	16.40 (± 1.83)	21.50 (± 2.17)	25.12 (± 1.64)	27.92 (± 2.49)
	4.50	22.48 (± 3.47)	25.37 (± 3.29)	28.07 (± 2.71)	31.47 (± 2.86)
400	1.80	17.18 (± 2.88)	19.24 (± 2.00)	25.49 (± 1.89)	27.20 (± 2.31)
	3.10	18.24 (± 2.29)	24.38 (± 3.95)	30.48 (± 3.10)	32.12 (± 3.17)
	4.50	23.94 (± 1.53)	30.81 (± 3.17)	34.96 (± 3.73)	33.00 (± 3.48)
500	1.80	22.53 (± 2.96)	25.15 (± 2.43)	27.91 (± 2.83)	31.39 (± 2.51)
	3.10	25.93 (± 3.17)	25.65 (± 3.95)	33.44 (± 3.34)	37.64 (± 3.04)
	4.50	29.75 (± 4.43)	33.13 (± 5.03)	37.75 (± 4.18)	39.67 (± 3.60)

in the V-shaped fissures, as observed from the experiments. This result is similar to those reported by several workers (Soponronnarit et al. 2001; Dondee et al. 2011). The cracking of soybean kernels under microwave-fluidized bed drying in the present study were lower when compared with individual hot-air fluidized bed drying at the same level of moisture content, reported by previous studies: 40–60 % by Soponronnarit et al. (2001) and 53.5–79 % by Wiriyumpaiwong et al. (2003). Also, Dondee et al. (2011) reported that percentage of damage of soybean kernels was

negligible under combined near-infrared radiation and fluidized bed drying, which was lower than 9.7 %.

Rehydration capacity

The microwave-fluidized drying method had a significant effect on rehydration capacities of soybeans (Fig. 4), because the heat applied during drying increased both hydration of the starch and elasticity of the cell walls, thereby increasing the water-holding capacity. A maximum rehydration capacity

Fig. 4 Rehydration capacities of soybeans at different drying conditions

(0.819 ± 0.013) was obtained for the experiment performed at 100 °C, 4.5 m/s and 400 W. Rehydration ratio at high microwave power and low air velocity improves rehydration due to the effect of temperature on cell wall and tissue (Singh et al. 2006; Doymaz and Ismail 2011). This can be explained by the high internal pressure produced by microwave heating which can cause structure of soybean kernels to expand.

Conclusion

Drying kinetics, rehydration, percentage of cracking, specific energy consumption of soybean kernels during microwave- fluidized bed drying were investigated and the process was modeled. The Page model was selected as the best, based on R^2 , χ^2 and RMSE values. The effective moisture diffusivity (D_{eff}) increased with increasing air temperature and microwave power and decreased with air velocity and it varied from 6.25×10^{-10} to 42.14×10^{-10} m²/s. The highest rehydration capacity (0.813) was recorded for the samples dried at 80 °C, 1.8 m/s and 500 W and the lowest (0.683) at 140 °C, 4.5 m/s and 200 W. The activation energy for moisture diffusion was found as 3.33 and 17.70 kJ/mol. Percentage of cracking varied from 12.96 to 39.67 % over the drying conditions range. Specific energy consumption obtained for microwave-fluidized bed drying of soybeans kernels showed a range between 50.94 and 338.76 (MJ/kg water). The minimum specific energy consumption was found at 80 °C, 4.5 m/s and 500 W with the drying time period (10.5 min). It is expected that this research will help growers reduce the cost of drying and obtain more quality dried soybeans. They are also usable in dryer design for scale up work.

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