

FLUIDIZED BED DRYING OF CORN, BEAN AND CHICKPEA

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ABSTRACT

In the agricultural industry, drying is a very important process to preserve food products. Also, fluidized bed drying is the most common preferred process due to its advantages. In this paper, the effects of the fluidizing air temperature and velocity on the drying performance of corn, beans and chickpeas were investigated by carrying out a series of tests. Laboratory-scaled fluidized bed drying apparatus was used. Batch drying experiments were conducted by applying three different air temperature and two different air velocities. In addition, the Henderson and Pabis model was used to compare experimental and model results. Lastly, activation energy values were determined for the particles. Results revealed that the drying air temperature has the greatest effect on the drying kinetics of particles, whereas air velocity has a small effect. It was also observed that bean, corn and chickpea particles have different drying curves during the drying period (5,400 s). Mean absolute errors, root mean square errors and mean absolute percentage error were used as performance criterion between experimental and model results. The activation energy values of the particles showed the same pace as similar studies in the literature.

PRACTICAL APPLICATIONS

Drying is energy-intensive and has a negative environmental impact due to fact that most of the thermal energy needed is obtained by combusting fossil fuels. From 12–25% of national industrial energy consumption is attributed to thermal dehydration in industrial nations. As global economies prosper, the demand for energy for drying will increase. Thus, there is need to understand

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this operation well and to ensure that it is carried out as efficiently as possible within the economic constraints of the market. It is also important to keep abreast with the current drying technologies, as well as the emerging new ones. The drying of various feedstocks is needed for one or several of the following reasons: need for easy-to-handle free-flowing solids, preservation and storage, reduction in cost of transportation, achieving desired quality of product, etc. In many processes, improper drying may lead to irreversible damage to product quality, and hence a nonsalable product.

INTRODUCTION

Drying is the oldest and the most widely used method for preservation of foods, and it also has many practical applications in different areas, i.e., paper industry and pharmaceuticals. In the drying process, the water activity of a food is lowered – subsequently, the enzymatic activity is minimized; the weight of the product and the packaging requirements are reduced. When a wet food particle is subjected to thermal drying, the heat supplied is transported by convection from the surroundings to the particle surfaces, and from there, by conduction, further into the particle throughout the drying process. Also, moisture is removed in the opposite direction as a liquid or vapor. On the surface, it evaporates and passes on by convection to the surroundings.

Fluidized bed drying is considered as one of the most successful drying techniques. High heat and mass transfer, good temperature control, uniform temperature and high drying capacity are the main distinctive advantages of fluidized bed drying. During the fluidized bed drying process, although the drying rate is dependent on the drying temperature, it should not be increased to a very high value, as high temperature can cause the particles to spoil. Last but not least, due to the rapid drying characteristics of the technique, it has been considered as an economical drying technique compared with others.

Fluidized beds are commonly used commercially for drying such materials as granular materials, cereals, polymers, chemicals, pharmaceuticals, fertilizers, crystalline products and minerals. In the literature, there are many studies on fluidized bed drying of agricultural and other granular materials. This technique is used by many researchers with different products, such as Ozbey and Soylemez (2005) with wheat grains, Goksu *et al.* (2005) with macaroni beads, Senadeera *et al.* (2003) with green beans, potatoes and peas, Syahrul *et al.* (2003) with wheat and corn, Izadifar and Mowla (2003) with paddy rice, Prakash *et al.* (2004) with blanched carrots, Walde *et al.* (2006) with mushroom, Chen *et al.* (2001) with coal, Temple and Van Boxel (1999) with black tea, Kashaninejad *et al.* (2005) with pistachio nuts, Soponronnarit *et al.* (2001) with soybeans, Shi *et al.* (2000) with wet sand, glass beads and

sliced foods, Mizota *et al.* (2004) with anhydrous lactulose, and Topuz *et al.* (2004) with hazelnuts. However, there have been limited studies on fluidized bed drying of beans and chickpeas in the literature.

In this study, the effects of the fluidizing air temperature and velocity on the drying performance of corn, beans and chickpeas were investigated by a series of tests. A laboratory-scaled fluidized bed was constructed and used in all stages of the experiment. In the batch drying experiment, three different air temperature and two different air velocities were applied, and all of research materials were kept in the drying apparatus for 5,400 s. Also, the Henderson and Pabis model was used to compare experimental and model results. Finally, the particles' activation energy values were found.

MATERIALS AND METHODS

Experimental Materials

Corn (from Adapazari, Turkey), beans (from Konya, Turkey) and chickpeas (from Nevsehir, Turkey) were used as drying materials (approximate sizes of these are 6.5, 9 and 7 mm, respectively, and the Geldart classification of the grains is Group D; Kunii and Levenspiel 1991). In store condition, the initial moisture content of corn, beans and chickpeas are in the range of 10.91, 10.74 and 9.81% on a dry basis (d.b.), respectively. Before the experiments, all of the materials were humidified: corn: 4 h, bean: 2 h and chickpea: 3.5 h. After humidification, the moisture contents of the corn, beans and chickpeas were recorded as 23.75, 14.9 and 52.7% d.b., respectively. A moisture analyzer was used to determine the moisture level of the materials.

Fluidized Bed Drying Setup

For the experiments, a laboratory-scaled fluidized bed drying system was constructed and used (as shown in Fig. 1). The experimental setup consists of a fluidization column, perforated plate, preheater and last heater, frequency inverter, five thermocouples, two temperature and humidity measurement sticks, pitot tube, three pressure measurement sticks, electricity panel, isolation materials and fittings.

The bed column was made of iron with a 200-mm inner diameter, 1,000-mm height and 2-mm wall thickness. To obtain uniform distribution of the fluidizing air, a perforated plate was used. Preheater and last heater were used for heating the bed air, and their capacity were 5 and 6 kW, respectively. The bed air was provided by a centrifugal blower, and a frequency inverter was used for driving the blower motor. The temperature values through the bed

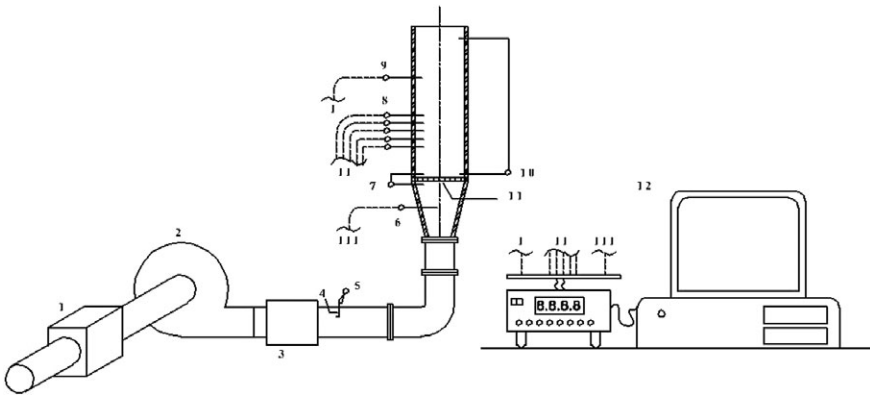


FIG. 1. SCHEMATIC DIAGRAM OF EXPERIMENTAL SETUP

- 1, preheater (for heating of inlet air); 2, fan; 3, last heater (for heating of inlet air); 4, pitot tube; 5, 7–10, pressure cell (for measurement pressure drop; 5, to observe inlet air velocity with pitot tube; 7–10, to measure distributor plate and fluidized bed pressure drop, respectively); 6–9, humidity stick (for measurement of inlet and outlet air humidity); 8, thermocouples (for measurement of fluidized bed air temperature at 8, 14, 20, 26 and 32 cm of bed); 11, perforated plate; 12, data acquisition system and PC.

in five different points were measured by type K thermocouples located at different heights (8, 14, 20, 26 and 32 cm) above the distributor plate.

The pressure difference between the two sides of the distributor plate was measured with an electronic pressure cell (Testo 506, Testo Inc., Sparta, NJ). The same equipment was also used to measure the pressure difference between the surface of the distributor plate and the highest level of the fluidized bed. Inlet and outlet humidity of the bed air were measured using a humidity measurement stick (Testo hygrotest 600 pht; it is based on two-wire technology, which is used to convert nonelectrical parameters, e.g., temperature, pressure, relative humidity, etc., to an electrical standard signal of 4 to 20 mA). All thermocouples and humidity sticks were connected with a data acquisition system, and the system was connected to a PC. By using the data acquisition system, temperature and humidity data were collected on a PC in a 5-s period. To measure and determine the air velocity, a pitot tube and electronic pressure cell were used. The moisture content of the particles was assessed by using a Precisa XM60 moisture analyzer, which works with infrared drying method.

Before beginning the experiments, the pitot tube was calibrated, and minimum fluidizing velocity of corn, beans and chickpeas were observed as 4.6, 3.68 and 4.59 m/s, respectively.

All experiments were conducted under batch fluidization. First, the blower and heater were turned on until the required temperature for the system was reached. When the required experiment temperature was reached, the blower

was turned off instantly and the particles were placed in the fluidized bed, and then the air blower was turned on again. In order not to cause temperature change, this part of the experiment was carried out in a very short time. As fluidization continued, solid samples (approximately 15 g) were removed from the column at different times and were analyzed for their moisture content. In order to detect the effectiveness of the temperature and velocity, three different temperatures and two different velocity of drying air were applied.

Errors and uncertainties are inherent in both the instrument and the process of making the measurement, and too much reliance should not be placed on any single reading from one affected by the environment. Final accuracy depends on a sound program on correct methods for taking readings on proper instruments. When readings are repeated, they tend to produce a band of results rather than a point or a line. Errors and uncertainties in the experiments can arise from instrument selection, instrument condition, instrument calibration, environment, observation, reading and test planning (Holman 1994; Akpınar *et al.* 2005). In the fluidized bed drying experiments of corn, beans and chickpeas, the temperature, velocity, pressure difference, relative humidity of drying air and weight loss of particles were measured with appropriate instruments. During the measurements of the parameters, uncertainties occurring are presented in Table 1. Considering the relative errors in the individual factors denoted by x_n , the error estimation was made using the following equation (Holman 1994):

$$W = \left[(x_1)^2 + (x_2)^2 + \dots + (x_n)^2 \right]^{1/2} \quad (1)$$

Also, some experiments were repeated to present reproducibility of the experiments. One set of drying conditions for beans were supplied again. Results of the repeated experiments and differences between them can be seen in Table 2.

TABLE 1.
UNCERTAINTIES OF THE PARAMETERS DURING
FLUIDIZED BED DRYING OF CORN, BEANS
AND CHICKPEAS

Parameter	Unit	Comment
Temperature through the bed	C	±0.1
Bed inlet and outlet temperature	C	±0.3
Relative humidity of inlet and outlet bed air	RH	±0.02
Pressure difference	hPa	±0.03
Air velocity	m/s	±0.018
Moisture quantity	g	±0.01
Measurement time of mass loss values	min	±0.1
Measurement time of temperature values	min	±0.1

TABLE 2.
COMPARISON OF THE RESULTS OF REPEATED EXPERIMENTS FOR BEANS

Specifications	M/M_0 (repeated 1)	M/M_0 (repeated 2)	Difference (%)
$T_g = 35.6C, W_0 = 700 \text{ g}, u = 5 \text{ m/s}$	1.000	1.000	0.00
	0.716	0.676	3.97
	0.500	0.531	3.05
	0.476	0.465	1.06
	0.439	0.441	0.25
	0.422	0.375	4.78
	0.418	0.349	6.90
	0.403	0.319	8.40
$T_g = 47.1C, W_0 = 700 \text{ g}, u = 5 \text{ m/s}$	1.000	1.000	0.00
	0.675	0.658	1.71
	0.510	0.501	0.90
	0.349	0.381	3.18
	0.305	0.334	2.95
	0.277	0.323	4.61
	0.255	0.304	4.87
	0.244	0.295	5.06
$T_g = 70.1C, W_0 = 700 \text{ g}, u = 5 \text{ m/s}$	1.000	1.000	0.00
	0.522	0.477	4.50
	0.350	0.363	1.23
	0.288	0.248	4.02
	0.201	0.180	2.10
	0.180	0.168	1.19
	0.157	0.142	1.52
	0.146	0.122	2.38

RESULTS AND DISCUSSION

Results Concerning the Fluidized Bed Air

As shown in Fig. 2, after 1,000 s of drying, the temperature gradient in the bed has disappeared. Before 1,000 s of the process, the inlet temperature of the drying air was higher than the outlet temperature ($T_5 \leq T_3 \leq T_1 < T_g$) because of the heat transfer from the drying air to the particles. Also, after 1,000 s of the process, there was a slow diminution of temperature due to external heat loss. On the other hand, as can be seen in Fig. 3, after 550 s of drying, the temperature gradient disappeared when the drying air temperature was lowered. After the turning point, there was no temperature gradient of the air observed in Figs. 2 and 3; these results show similarities with the previous studies in the literature.

Figure 4 shows that the moisture content of air decreased during the 1,000 s of drying as drying time increased. After this point, the decreasing pace

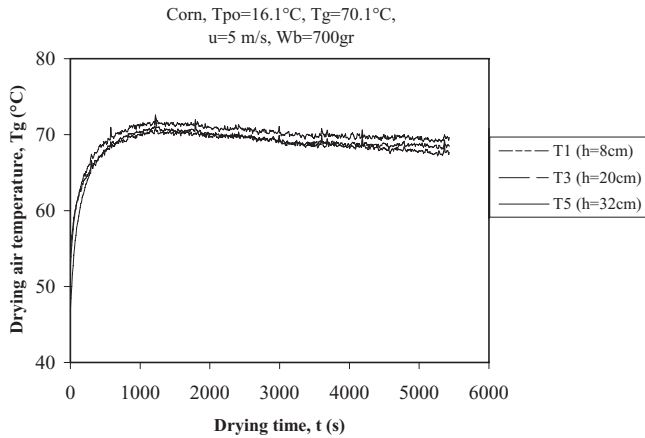


FIG. 2. TEMPERATURE DISTRIBUTION IN THE BED COLUMN (CORN, $T_g = 70.1^{\circ}\text{C}$)

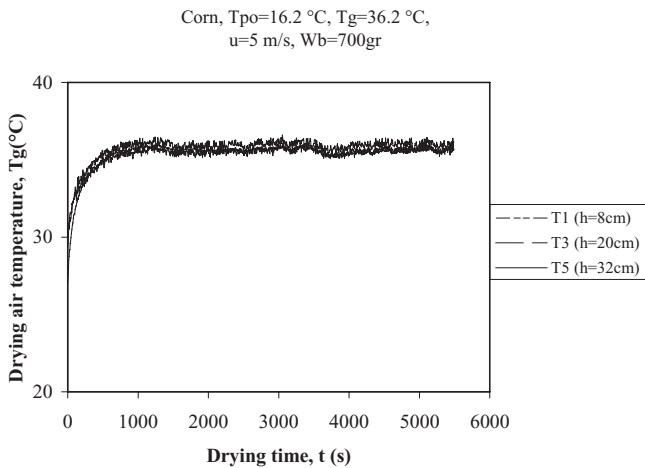


FIG. 3. TEMPERATURE DISTRIBUTION IN THE BED COLUMN (CORN, $T_g = 36.2^{\circ}\text{C}$)

of the moisture content was considerably slow. Also, because of moisture transfer from the particles to bed air, inlet and outlet humidity of the air difference was observed.

Effect of Temperature and Velocity of the Drying Air

The effect of the temperature and velocity of drying air on the fluidized bed drying of corn, beans and chickpeas were investigated. The drying curve

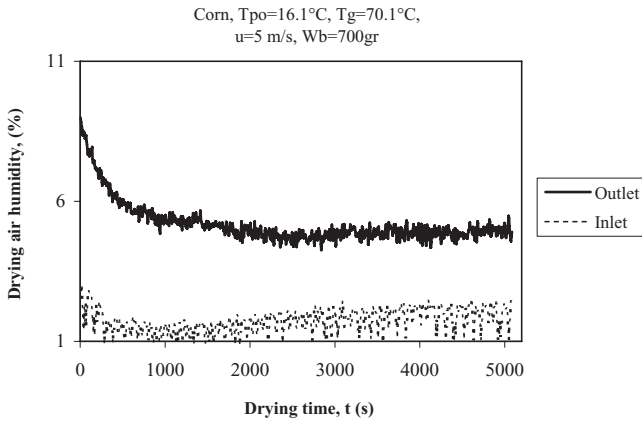


FIG. 4. DRYING AIR HUMIDITY DISTRIBUTION (CORN, $T_g = 70.1^{\circ}\text{C}$)

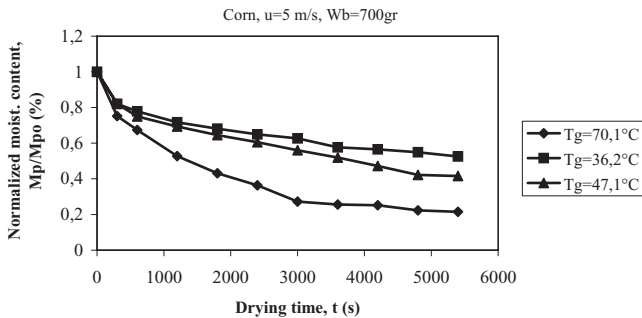


FIG. 5. DRYING CURVES OF CORN AT DIFFERENT TEMPERATURES ($u = 5\text{ m/s}$)

of the particles can be seen in Figs. 5–10. As expected, it is understood from Figs. 5, 6 and 7 that increasing the temperature allows the rate of heat transfer to the product to increase. This is reasonable because the mode of the moisture removal is by internal diffusion, and the driving force is the temperature difference between the center of the particle and fluidizing air. The greater the temperature, the greater the driving force, and hence a more expedient removal of internal moisture occurs. But in the same temperature condition, the drying velocity of the particles was different than the others. This will be discussed in the following section. Moreover, as shown in Figs. 8–10, the effect of velocity of the drying air is less than the temperature. Air velocity increment of about 16–24% will change the drying rate slightly at the same normalized moisture content. As reported by Hajidavalloo (1998), the reason

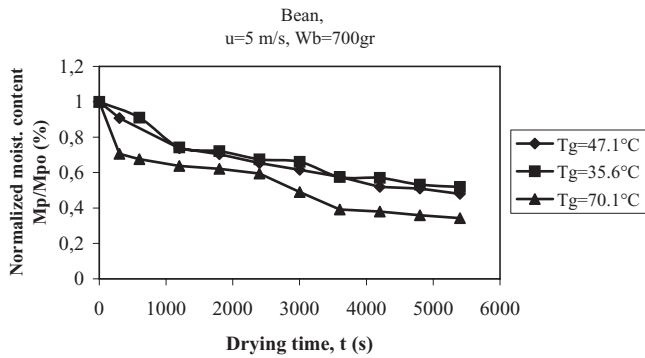


FIG. 6. DRYING CURVES OF BEANS AT DIFFERENT TEMPERATURES ($u = 5$ m/s)

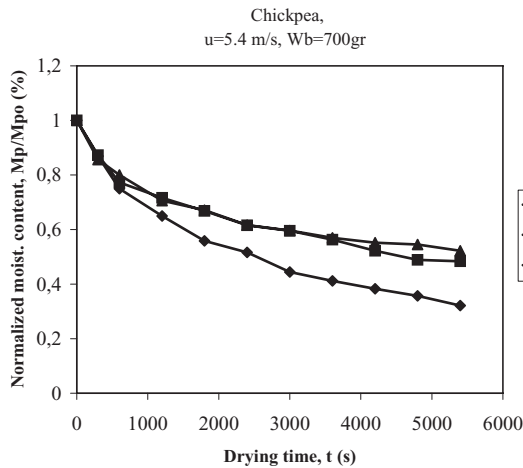


FIG. 7. DRYING CURVES OF CHICKPEAS AT DIFFERENT TEMPERATURES ($u = 5.4$ m/s)

for choosing a narrow difference in velocities between two tests conditions was the problem of fluidization of particles. Since moist particles need higher gas velocity for the onset of fluidization, it was not possible to reduce the velocity too much. Thus, it would be advantageous to use a gas velocity as low as possible. However, there is a practical restriction due to the onset of fluidization. In this work, the moisture content of particles was below the critical moisture content. Furthermore, the drying process occurs at the falling rate period. The drying rate is governed by the rate of internal moisture movement, and the influence of external variables diminishes, as indicated in Perry *et al.* (1977) (Syahrul *et al.* 2002).

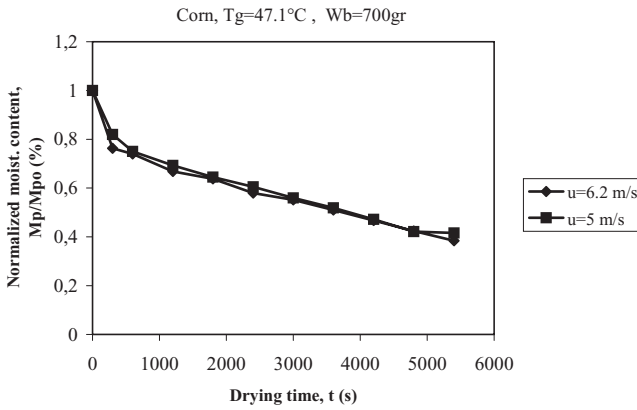


FIG. 8. DRYING CURVES OF CORN AT DIFFERENT VELOCITIES OF AIR ($T_g = 47.1\text{C}$)

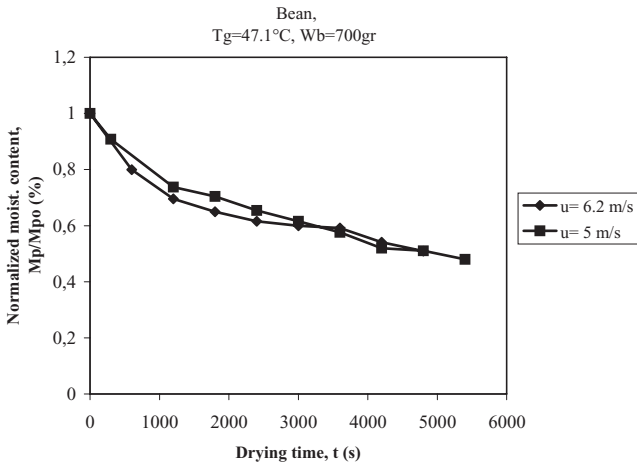


FIG. 9. DRYING CURVES OF BEANS AT DIFFERENT VELOCITIES OF AIR ($T_g = 47.1\text{C}$)

Comparing of Drying Rate of the Experimental Products

To compare the drying rate of corn, beans and chickpeas, these particles were subjected to drying at the same temperature. As seen in Fig. 11, at the first half of the drying process (0–2,400 s), three drying rates of the products were different. But, at the second half of drying process, the drying rates of chickpeas and beans are the same and less than corn. It can be clearly seen in Fig. 12 that increasing the air temperature increases the drying rate difference between corn and beans. Also, after 10 min of the drying process, the drying curve of

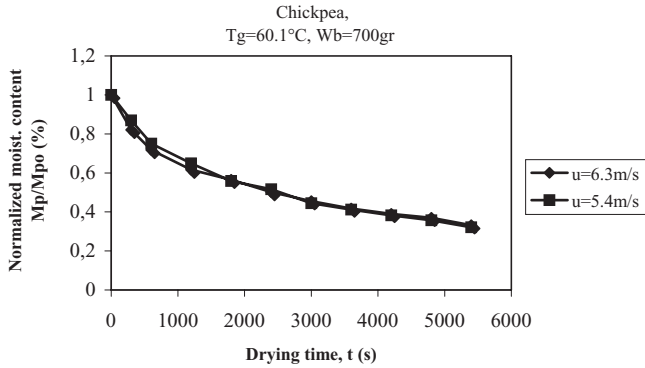


FIG. 10. DRYING CURVES OF CHICKPEAS AT DIFFERENT VELOCITIES OF AIR ($T_g = 60.1\text{C}$)

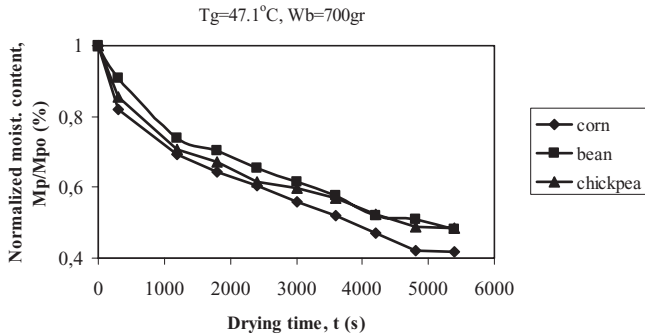


FIG. 11. COMPARISON OF DRYING RATE OF CORN, BEANS AND CHICKPEAS AT SAME TEMPERATURE AND VELOCITY

beans was different than the corn. The curve of beans has three curl points, which means that after 10 min of the bean drying, evaporation of the surface moisture was finished at the same time as that of the drying of corn. On the other hand, capillary force, which resists moisture diffusivity from the center to surface, was bigger than that of corn.

The mechanisms of moisture movements were first discussed by Sherwood (1929), who assumed that the mechanism by which the water travels from the interior to the surface is that of diffusion either of liquid water or of water vapor. Although several internal mechanisms of moisture transfer have been suggested, owing to complexity of the process, no generalized theory currently exists to explain the mechanism of internal moisture transfer, which is generally accepted to be the major rate limiting step (King and Clark 1977;

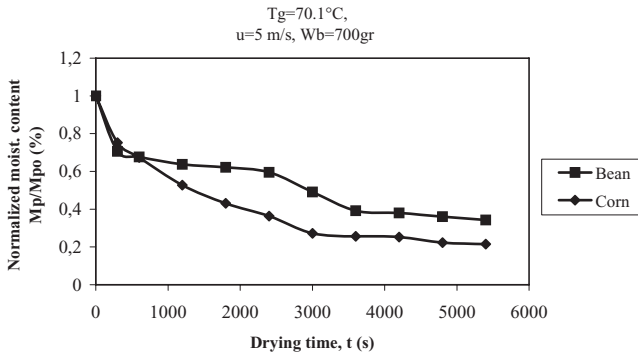


FIG. 12. COMPARISON OF DRYING RATE OF CORN AND BEANS AT SAME TEMPERATURE AND VELOCITY

Rizvi 1986). The mechanism strongly depends on the nature of the material being dried. However, liquid diffusion mechanism was suggested by many researchers to govern water movement inside hygroscopic materials of a biological nature, such as food materials (Chirife 1971; Yusheng and Poulson 1988; Datta *et al.* 1993). Diffusion phenomena are extremely complex due to the wide diversity of chemical composition and physical structure of food materials. As a consequence, traditional food processing involving diffusion has been mainly based on experimental knowledge (Khraisheh *et al.* 1997).

In this work, from the drying data analysis, it was established that the fluidized bed drying of corn, beans and chickpeas mainly consists of falling rate period. This behavior suggested strongly an internal mass transfer type drying with moisture diffusion as the controlling phenomena.

Comparison of Experimental and Model Results

In literature, there are many drying models: the Henderson and Pabis model, the two term model, the Lewis model, the Page model, the modified Page model, the Thompson model, the Wang and Singh model, and so on (Ozdemir and Devres 1999). In this study, the Henderson and Pabis model was used to compare experimental and model results. Because it has been applied in the literature and in the Henderson and Pabis model, the coefficient k is related to effective diffusivity when the drying process takes place only in the falling rate period and liquid diffusion controls the process. This model is the first term of a generalized series solution of Fick's second law and can be defined as follows:

$$MR = A \exp(-kt) \quad (2)$$

TABLE 3.
MODEL COEFFICIENTS AND PERFORMANCE CRITERION

Particle	Drying constant (adjusted)		Performance criterion		
	<i>A</i>	<i>k</i>	<i>MAE</i>	<i>RMSE</i>	<i>MAPE</i>
Corn	0.8844	0.0009	0.027	0.04	3.70
Bean	0.9213	0.0078	0.026	0.03	3.61
Chickpea	0.8762	0.0074	0.030	0.05	4.23

MAE, mean absolute errors; *RMSE*, root mean square errors; *MAPE*, mean absolute percentage error.

$$k = \frac{D\Pi^2}{R^2} \quad (3)$$

where $MR = M_p/M_{p0}$ (ratio of particle moisture to particle inlet moisture), A and k are drying constants, t is drying time, D is effective diffusivity and R is the radius of the particle.

Semitheoretical models exhibit a direct relationship between moisture content of the particle and drying time. The main drawback of these models is the negligence of the fundamentals of the drying process, as well as the lack of physical meaning of their parameters. Consequently, they cannot give a clear accurate view of the important processes that occurred during drying, but for investigating a suitable model to describe the fluidized bed drying process and for comparing the results with the experimental data, the selected model was used for all particles, and drying constants (authors' adjusted parameters) were obtained as shown in Table 3. Hence, three metrics were used as performance criterion: mean absolute errors (*MAE*), root mean square errors (*RMSE*) and mean absolute percentage error (*MAPE*). Performance criteria utilized in the study are given below:

$$MAE = \frac{1}{n} \sum_{i=1}^n |e_i| \quad (4)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n e_i^2} \quad (5)$$

$$MAPE = \frac{1}{n} \sum_{i=1}^n \left(\frac{|e_i|}{Y_i} \right) 100 \quad (6)$$

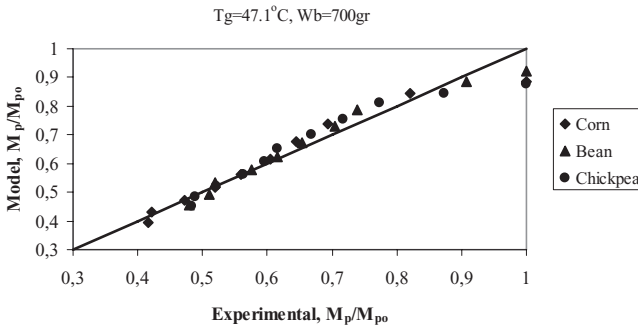


FIG. 13. COMPARISON OF MODEL PREDICTION AND EXPERIMENTAL RESULTS (CORN, BEANS AND CHICKPEAS, T_g = 47.1C, W_b = 700 g)

where e_i denotes the differences between experimental and model results, Y_i shows the experimental results and n shows number of data. Determined *MAE*, *RMSE* and *MAPE* values for corn, beans and chickpeas data can be found in Table 3. Looking at Fig. 13 and Table 3, it can be deduced that the Henderson and Pabis model based on adjusted parameters can accurately describe the experimental data for fluidized bed drying of corn, beans and chickpeas.

Determination of Activation Energy for the Particles

The effect of temperature on effective diffusivity is generally described using Arrhenius-type relationship. Diffusivity varies with temperature more than moisture content (Ozdemir and Devres 1999):

$$D = D_0 \exp\left(-\frac{Ea}{RT_a}\right) \tag{7}$$

where D_0 is a diffusivity constant equivalent to diffusivity at infinitely high temperature and Ea is the activation energy. It can be seen in Fig. 14 that, a plot of $\ln D$ versus reciprocal of the absolute temperature (T_a) gives the activation energy. (The aim of this plotting is to obtain the linear equation. Hence, three or four points for each material are enough to do so, similar to those in Khraisheh *et al.* [1997]; Ozdemir and Devres [1999].) Then, Arrhenius-type temperature dependence of effective diffusivity can be expressed as (for corn):

$$D = 0.04 \cdot 10^{-3} \exp\left(-\frac{2,255.4}{T_a}\right) \tag{8}$$

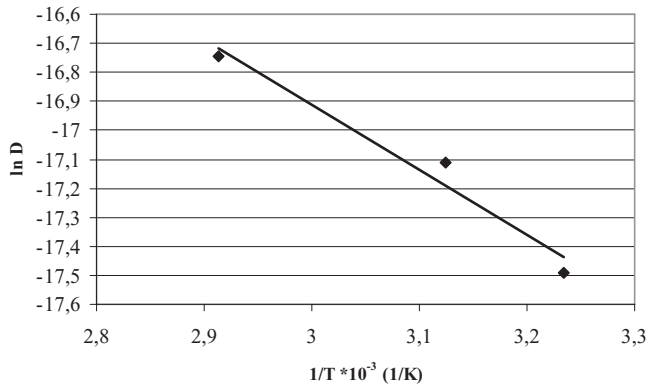


FIG. 14. ARRHENIUS TYPE RELATIONSHIP BETWEEN EFFECTIVE DIFFUSIVITY AND TEMPERATURE (FOR CORN)

from which the activation energy for water diffusion was found as 1,041.76, 572.3 and 1,238.75 kJ/kg for corn, beans and chickpeas, respectively.

CONCLUSIONS

In this study, fluidized bed drying characteristics of corn, beans and chickpeas were investigated. A laboratory-scaled fluidized bed dryer was constructed for experimental working. Three different temperatures and two different velocities of drying air were used in the experiments. As expected, temperature of drying air has an important role, while velocity of air has little effect in the process. Drying rate is enhanced with an increase in temperature for all particles. But there is a small discrepancy between corn and bean drying curves. This can be explained by the difference in capillary forces of two items, of which bean is bigger than corn. From the drying data analysis, it was concluded that the fluidized bed dryings of corn, beans and chickpeas mainly have the characteristic of falling rate period. This behavior suggested strongly an internal mass transfer type drying with moisture diffusion as the controlling phenomena.

From the literature, the Henderson and Pabis model was selected to compare with experimental results. It can be deduced that the Henderson and Pabis model can describe well the experimental data about fluidized bed drying of corn, beans and chickpeas based on adjusted parameters. Temperature dependence of the diffusivity coefficients of the particles was described by Arrhenius-type relationship. The activation energy values for moisture diffusion were determined as 1,041.76, 572.3 and 1,238.75 kJ/kg for corn, beans and chickpeas, respectively.

NOMENCLATURE

A	drying constant
D	effective diffusivity, m^2/s
D_0	diffusivity coefficient
E_a	activation energy, kJ/kg
e_i	differences between experimental and model results
h	height in the bed, cm
k	drying constant
M	moisture content, kg moisture/ kg dry solid
n	number of data
R	radius, universal gas constant
T	temperature, C
t	time, s
u	superficial gas velocity, m/s
W	total uncertainty in measurement
W_b	weight of particles in the bed, kg
x_n	relative error
Y_i	experimental results

Subscripts

a	absolute
g	gas (entering into the bed)
p	particle
0	initial

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