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Modeling of moisture diffusivity, activation energy and specific energy consumption of high moisture corn in a fixed and fluidized bed convective dryer

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Abstract

Thin layer drying characteristics of high moisture corn under fixed, semi fluidized and fluidized bed conditions with high initial moisture content (66.82% wb) in a laboratory fluidized bed convective dryer was studied at air temperatures of 50, 65, 80 and 95°C. In order to find a suitable drying curve, seven thin layer-drying models were fitted to the experimental data of moisture ratio. Among the applied mathematical models, Midilli *et al.* model was the best for drying behavior prediction in corn thin layer drying. This model presented high values for correlation coefficient (R^2). Fick´s second law was used to compute moisture diffusivity with some simplifications. Computed values of moisture diffusivity varied at the boundary of $4.87 \times 10^{-11} - 2.90 \times 10^{-10}$ m^2 s^{-1} and $1.02 \times 10^{-10} - 1.29 \times 10^{-9}$ m^2 s^{-1} during the first and second drying falling-rate, respectively. Values of effective moisture diffusivity for corn were also increased as input air temperature was increased. Value of activation energy varied from a minimum of 18.57 to a maximum of 50.74 kJ mol^{-1} from 50 to 95°C with drying conditions of fixed to fluidized bed. Specific energy consumption (SEC) for thin-drying of high moisture corn was found to be in the range of $0.33 \times 10^6 - 1.52 \times 10^6$ kJ kg^{-1} from 50 to 95°C with drying condition of fluidized and fixed bed, respectively. Increase in air temperature in each air velocity caused decrease in SEC value. These corn properties would be necessary to design the best dryer system and to determine the best point of drying process.

Additional key words: drying; maize; Midilli *et al*. model; semi fluidized.

Resumen

Modelización de la difusividad de la humedad, la energía de activación y el consumo específico de energía para el grano de maíz húmedo en un secador convectivo de lecho fijo y fluidizado

Se estudiaron las características del secado en capa delgada del grano de maíz húmedo en condiciones de lecho fijo, semi-fluidizado y fluidizado con alto contenido de humedad inicial (66,82%), en un secador de convección de lecho fluidizado de laboratorio a las temperaturas del aire de 50, 65, 80 y 95°C. Con el fin de encontrar una curva de secado apropiada, se ajustaron siete modelos matemáticos de secado en capa delgada a los datos experimentales de la ratio de humedad. Entre los modelos aplicados, el de Midilli *et al.*, con un alto coeficiente de correlación (R^2), fue el mejor para predecir el secado del maíz en capa delgada. Se utilizó la segunda ley de Fick para calcular, con algunas simplificaciones, la difusividad de la humedad, que dio unos valores entre $4{,}87 \times 10^{-11} - 2.90$ y $1{,}02 \times 10^{-11} - 1.29$ m^2 s^{-1} durante la primera y segunda fase de secado de rapidez decreciente, respectivamente. Los valores de la difusividad efectiva de la humedad para el maíz también aumentaron al aumentar la temperatura de entrada del aire. El valor de la energía de activación varió desde un mínimo de 18,57 a un máximo de 50,74 kJ mol^{-1} entre 50 y 95°C, con condiciones de secado del lecho fijo a fluidizado. El consumo específico de energía (SEC) para secado en capa delgada del grano de maíz húmedo fue entre $0{,}33 \times 10^6$ y $1{,}52 \times 10^6$ kJ kg^{-1} entre 50 y 95°C, en lecho fluidizado y fijo, respectivamente. Un aumento de la temperatura en la velocidad del aire disminuye el valor de SEC. Es necesario conocer estas propiedades del maíz para diseñar el mejor sistema de secado y para determinar el mejor punto del proceso de secado.

Additional key words: lecho semi-fluidizado; modelo de Midilli *et al*.; secado de maíz.

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Introduction

The main goal in agricultural and food products drying is the reduction of their moisture content to a specific level, allowing safe storage over an extended period of time. Due to a longer storage life, product diversity, and a substantial volume reduction, fruits and vegetables drying is popular. Thin layer drying models are used to predict drying time for food and agricultural products and also to generalize the kinetics of drying process. Drying kinetics of products is greatly affected by air temperature, air velocity and material characteristics (Erenturk and Erenturk, 2007).

Corn (*Zea mays* L.) is one of the most important agricultural crops in Iran with 1,600,000 tons production in 2008 (FAOSTAT, 2008). Because of high moisture content, harvested corn is contaminated with molds after several days, which are harmful to human health. Drying corn in natural sun drying method takes time and corn could be contaminated by insects, dust, sand particles and molds. Drying this crop is therefore necessary to reduce the moisture fast and uniform. Thus, it is safe method for the production of food and agricultural crops. Also, precise prediction of drying time is crucial important to increase the dryer capacity and to reduce the energy consumption (Doymaz and Pala, 2002).

In Iran, milky corn is harvested for human consumption, but its high moisture content levels (about 70% d.b.) causes fast spoilage and growing molds. Reducing corn moisture content is a proper way to prevent these losses.

One of the most popular methods of drying materials with high moisture content is fluidized bed. Fluidization defined as suspending the grain particles in a fluid. When air flow is passed upward through grain bed at a low flow rate, a fixed bed will be obtained. With an increase in air flow rate, the grain bed is expanded to provide minimum fluidized bed (semi fluidized bed), bubbling fluidized bed and transportation, respectively. At the minimum fluidized bed, pressure drop is maximized and weight of the particles counterbalances the frictional force between particles. In a bubbling fluidized bed, gas bubbles disturb movement of the grain particles. In a transportation stage, pneumatic conveying of grain particles is occurred. Bubbling fluidized bed and transportation stage defined as fluidization state (Kunii and Levenspiel, 1991; Brooker *et al*., 1992).

Foster *et al*. (1980) dried corn samples in two stages using a solar dryer, being samples successfully dried at the second stage.

Li and Morey (1984) studied the thin layer convective drying method in yellow dent corn. Results showed that drying process is affected by drying air flow rate, air temperature, air relative humidity and initial moisture content.

Soponronnarit *et al*. (1997) studied the drying characteristics of corn in a laboratory fluidized bed dryer at 150, 170 and 200°C air temperatures. They reported that corn drying with high initial moisture content with air temperature at 170°C could be done without quality loss.

Suárez *et al*. (1984) dried sweet corn samples with 3.2 to 4.4 $kg_{water}\ kg_{dry\ solid}^{-1}$ initial moisture content. Results showed that the drying time of treated samples with ethyl oleate was about 2.1 to 2.8 times faster than those untreated.

Some physical and thermal properties of food and agricultural products, such as moisture diffusion, heat and mass transfer, specific energy and activation energy consumption are important for a proper dryer design (Aghbashlo *et al*., 2008). Some researchers have studied activation energy and moisture diffusion in a thin layer drying of various agricultural and food products. These include hazelnuts (Ozdemir and Devres, 1999), grapes (Pahlavanzadeh *et al*., 2001), seedless grapes (Doymaz and Pala, 2002), potato slices (Akpinar *et al*., 2003), candle nuts (Tarigan *et al*., 2006), onion slices (Pathare and Sharma, 2006), plums (Goyal *et al*., 2007), beriberi fruit (Aghbashlo *et al*., 2008), and milky mushroom (Arumuganathan *et al*., 2009). Although many information has been gathered about the activation energy and effective moisture diffusivity for various agricultural and food products, small number of reports are available on the activation energy and effective

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Abbreviations used: C_{Pa} (specific heat capacity of air, 1,828.8 J kg^{-1}°C^{-1}), C_{Pv} (specific heat capacity of vapor, 1004.16 J kg^{-1}°C^{-1}), D_{eff} (effective moisture diffusivity, $m^2\ s^{-1}$), D_0 (pre-exponential factor of the Arrhenius equation, $m^2\ s^{-1}$), E_a (activation energy, kJ mol^{-1}), h_a (absolute air humidity, $kg_{vapor}\ kg^{-1}{}_{dry\ air}$), M (moisture content, $kg_{water}kg^{-1}{}_{dry\ mater}$), M_0 (initial moisture content, $kg_{water}kg^{-1}{}_{dry\ mater}$), MR (moisture ratio, decimal), $MR_{\exp,i}$ (experimental moisture ratio of ith data, decimal), $MR_{pre,i}$ (predicted moisture ratio of i^{th} data, decimal), m_v (mass of removal water, kg), n (1, 2, 3, ... the number of terms taken into consideration), N (number of observations), Q (inlet air to drying chamber, $m^3\ s^{-1}$), ^{r} (radius of kernel, m), R (universal gas constant, 8.3143 kJ $mol^{-1}\ K^{-1}$), SEC (specific energy consumption, kJ kg^{-1}), t (drying time, s), T_a (absolute air temperature, K), T_{am} (ambient air temperatures,°C), T_{in} (inlet air temperature to drying chamber,°C), V_h (specific air volume, $m^3\ kg^{-1}$), z (number of drying constants).

moisture diffusivity for milky or high moisture content corn during fixed, semi fluidized and fluidized convective drying (Soponronnarit *et al.*, 1997). Indices of effective moisture diffusivity and activation energy are necessary for designing, modeling and optimizing the mass transfer processes such as moisture adsorption or dehydration during storage.

The main objectives of this research were to determine the activation energy, effective moisture diffusivity and specific energy consumption of high moisture content corn during first and second falling-rate of fixed, semi fluidized and fluidized bed thin layer drying process and their dependence on factors such as input air temperature and air velocity.

Material and methods

Determination of drying conditions

In order to determine corn pressure drops and air flow velocities at the outlet, simultaneously, the fan speed was increased gradually using the inverter (Vincker VSD2) and the parameters were recorded. A differential digital manometer (Testo 505-P1) and a vane type digital anemometer were used for measuring static pressure loss and outlet air velocity, respectively. To obtain air pressure drop across the corn bed, at first, the total static pressure drop due to corn column and bed plate was measured. Then air pressure drop due to empty chamber was measured. In each experiment, the difference between total and bed plate static pressure drop gave the net static pressure drop of the bed material.

Maximum value of static pressure drop *versus* a specific air velocity in fluidization systems is defined as the minimum fluidization point or semi fluidized bed (Kunii and Levenspiel, 1991). Fluidization experiments were carried out in four replications with 50 g corn samples load. After determining the semi fluidized bed with air velocity about 1 m s^{-1}, one point before it (in fixed bed domain) was selected as a fixed bed condition with air velocity of 0.5 m s^{-1} and one point after it (in fixed bed domain) was selected as a fluidized bed condition with air velocity of 1.5 m s^{-1} and the drying experiments were conducted.

Experiments

Fresh milky corn was supplied from a local market in July 2009. The samples were stored in a refrigerator at 4 ± 1°C. Average environmental conditions of ambient air temperature and air relative humidity ranged between 30 to 36°C and 20 to 30%, respectively. Accuracy of thermometer Lutron TM-903 with sensor type k was ±(0.5% reading + 1°C) and accuracy for humidity meter Lutron TM-903 for relative humidity lower than 70% was ±3% RH and for upper than 70% was ± (3% reading + 1% RH). During the experiments, the ambient air temperature, air relative humidity and inlet and outlet temperatures of the dryer chamber were recorded. A fluidized bed dryer was used to carry out the drying experiments (Fig. 1). After 30 min: when the dryer conditions reached the steady state, about 50 ± 1 g corn were located on the tray of the dryer and drying process was started. Experiments were conducted at the drying air temperatures of 50, 65, 80 and 95°C, the drying conditions of fixed bed (0.5 m s^{-1}), semi fluidized bed (1 m s^{-1}) and fluidized bed (1.5 m s^{-1}). Samples were weighed during the drying process using a digital balance with 0.01 g accuracy. The gravimetric method was used to determine the initial and final moisture contents of corn samples at 70°C during 24 h (ASAE, 2007). Drying process was carried out using samples with initial moisture content of about 66.8% (wb) and terminated when the moisture content decreased to about 5% (wb). In this study, the influence of the drying conditions on the effective moisture diffusivity, activation energy and specific energy consumption in thin-layer drying of high moisture corn are explained.

Experimental and mathematical modeling

Fick's second law of diffusion with spherical coordinates was applied in this study. The assumptions in Fick's equation solution were: moisture migration in diffusion, negligible volume shrinkage, constant temperature and diffusion coefficients (Crank, 1975; Di Matteo *et al.*, 2000):

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(\frac{-D_{eff} n^2 \pi^2 t}{r^2} \right) \quad [1]$$

where MR = moisture ratio, decimal; M = moisture content at any time, $kg_{water} kg^{-1}_{dry\ matter}$; M_e = equilibrium moisture content, M_0 = initial moisture content, $kg_{water} kg^{-1}_{dry\ matter}$; n = 1, 2, 3, ... the number of terms taken into consideration; t = drying time, s; D_{eff} = effective moisture diffusivity, m^2 s^{-1}; r = radius of kernel, m.

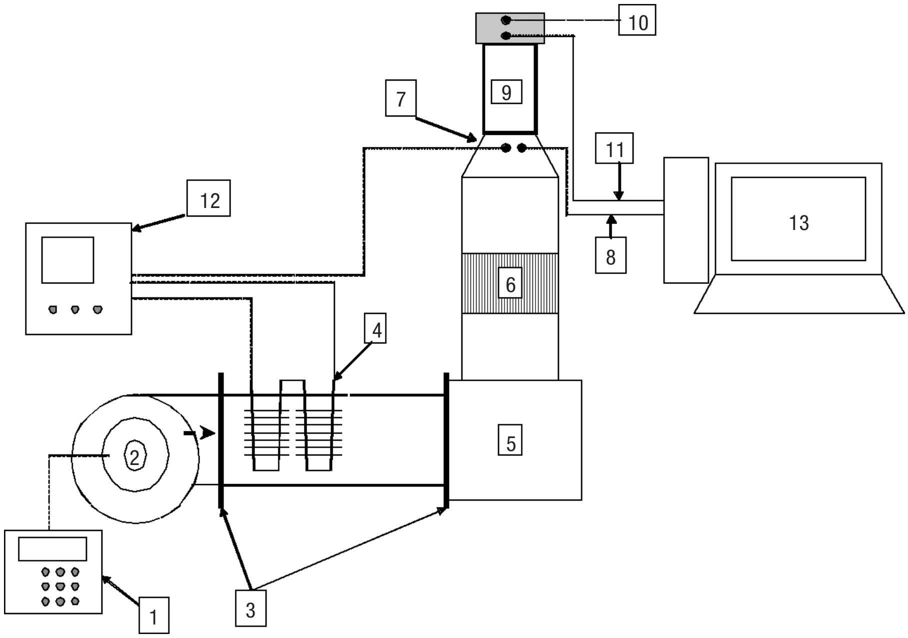

Figure 1. Schematic diagram of a laboratory scale fluidized bed dryer: (1) inverter, (2) fan and electrical motor, (3) flange, (4) electrical heater, (5) mixing chamber, (6) pipe network, (7) diffuser, (8) input air temperature recorder, (9) drying chamber, (10) air velocity sensor, (11) output air temperature recorder, (12) temperature controller, (13) computer.

For longer drying periods, Eq. [1] can be simplified to first term of series only, without much affecting the accuracy of the prediction (Ramesh *et al*., 2001):

$$\ln(MR) = \ln\left(\frac{M - M_e}{M_0 - M_e}\right) = \ln\left(\frac{6}{\pi^2}\right) - \left(\frac{D_{eff}\pi^2 t}{r^2}\right) \quad [2]$$

then:

$$MR = \left(\frac{6}{\pi^2}\right)\exp\left(\frac{D_{eff}\pi^2 t}{r^2}\right) \quad [3]$$

The slope (k_0) is calculated by plotting ln(MR) *versus* time according to Eq. [4]:

$$k_0 = \frac{D_{eff}\pi^2}{r^2} \quad [4]$$

The activation energy was calculated using an Arrhenius-type equation (López *et al*., 2000; Akpinar *et al*., 2003):

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT_a}\right) \quad [5]$$

$$\ln(D_{eff}) = \ln(D_0) - \left(\frac{E_a}{R}\right)\left(\frac{1}{T_a}\right) \quad [6]$$

where E_a = activation energy, kJ mol^{-1}; R = universal gas constant, 8.3143 kJ mol^{-1} K^{-1}; T_a = absolute air temperature, K; D_0 = pre-exponential factor of the Arrhenius equation, m^2 s^{-1}.

From Eq. [6], the plot of ln(D_{eff}) *versus* 1/T_a gives a straight slope of K_1:

$$K_1 = \frac{E_a}{R} \quad [7]$$

Linear regression analysis method was used to fit the equation to the experimental data to obtain the coefficient of determination (R^2).

Eq. [2] can also be written in a more simplified form as:

$$MR = \frac{M - M_e}{M_0 - M_e} = a\exp(-kt) \quad [8]$$

Eq. [8] is known as single exponential equation. The empirical models were used as alternative approach to analyze thin layer drying. Some commonly used equations in thin layer drying studies are shown in Table 1. In order to select a suitable model describing the drying process of corn with high moisture content, drying curves were fitted with thin layer drying equations.

The values of M_e are relatively small compared to M or M_0 (Aghbashlo *et al*., 2008; Arumuganathan *et*

Table 1. Thin layer drying models used in modeling of high moisture corn

Model	Equation[1]	References
Newton	MR = exp(-kt)	Liu and Bakker-Arkema (1997)
Page	MR = a exp (-kt^n)	Zhang and Litchfield (1991)
Midilli	MR = a exp(-kt^n) + bt	Midilli *et al.* (2002)
Henderson and Pabis	MR = a exp(-kt)	Chhinnman (1984)
Logarithmic	MR = a exp(-kt) + c	Yaldiz *et al.* (2001)
Two-term	MR = a exp(k$_0$t) + b exp(-k$_1$t)	Henderson (1974)
Wang and Singh	MR = 1 +at +bt^2	Wang and Singh (1978)

[1] a, b, c, k, k$_0$, k$_1$ and n are drying constants.

al., 2009). Thus $(M-M_e)/(M_0-M_e)$ is simplified to M/M_0. Therefore the basic Eq. [7] and all models in Table 1 can be reduced to:

$$MR = \frac{M}{M_0} \quad [9]$$

Specific energy consumption (SEC, kJ kg^{-1}) was calculated using the following equation (Zhang *et al.*, 2002):

$$SEC = \left[\frac{Q(C_{Pa}+C_{Pv}h_a)(T_{in}-T_{am})}{V_h}\right]\left(\frac{t}{m_v}\right) \quad [10]$$

where C_{Pv} and C_{Pa} = the specific heat capacity of vapor and air, respectively, 1004.16 and 1828.8 J kg^{-1}°C^{-1}; Q = inlet air to drying chamber, m^3 s^{-1}; h_a = absolute air humidity, kg$_{vapor}$ kg$^{-1}_{dry\ air}$; T_{in} and T_{am} = inlet air to drying chamber and ambient air temperatures, respectively, °C; V_h = specific air volume, m^3 kg^{-1}; t = total drying time, min^{-1} and m_v = mass of removal water, kg.

To determine the drying kinetics, corn samples were dried in a laboratory thin layer dryer at 50, 65, 80 and 95°C. About 50 g corn sample was uniformly spread in a thin layer on perforated stainless steel tray for drying. Moisture loss was recorded by a digital balance (AND GF-6000, Japan). Drying process was continued untill there was no large difference between the subsequent moisture losses. The input air velocity passing through the corn sample was regulated at fixed, semi fluidized and fluidized bed conditions with air velocities of 0.5, 1 and 1.5 m s^{-1}, respectively. Experiments were conducted in three replications.

Non-linear regression analysis was done using MATLAB (version 7) software package. Correlation coefficient R^2 was one of the main criteria for selecting the best model. The goodness of fit was also determined using various statistical parameters such as reduced chi-square (χ^2) and root mean square error ($RMSE$) values. For quality fit, R^2 value should be higher and χ^2 and $RMSE$ values should be lower (Togrul and Pehlivan, 2002; Demir *et al.*, 2004; Erenturk *et al.*, 2004). The parameters were calculated using the following expressions:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}[MR_{\exp,i} - MR_{pre,i}]}{\sum_{k=1}^{N}\left[MR_{pre,i} - \frac{\sum_{k=1}^{n} MR_{pre,i}}{n}\right]} \quad [11]$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pre,i}\right)^2}{N-z} \quad [12]$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pre,i})^2\right]^{\frac{1}{2}} \quad [13]$$

where $MR_{\exp,i}$ = experimental moisture ratio of i^{th} data; $MR_{pre,i}$ = predicted moisture ratio of i^{th} data; N = number of observations; z = number of drying constants.

Results and discussion

Mathematical models

The drying time of corn samples at different temperatures derived for all bed conditions are presented in Figure 2. The average final moisture content of corn samples was about 5% (wb). According to the results drying air temperature played has an important role in drying. When the air temperature was increased, the drying time was reduced. This phenomenon is because of applying more energy rate to the bed material and increasing in draying rate. The results are similar to the earlier studies of drying garlic slices (Madamba *et al.*, 1996), onion slices (Sarsavadia *et al.*, 1999),

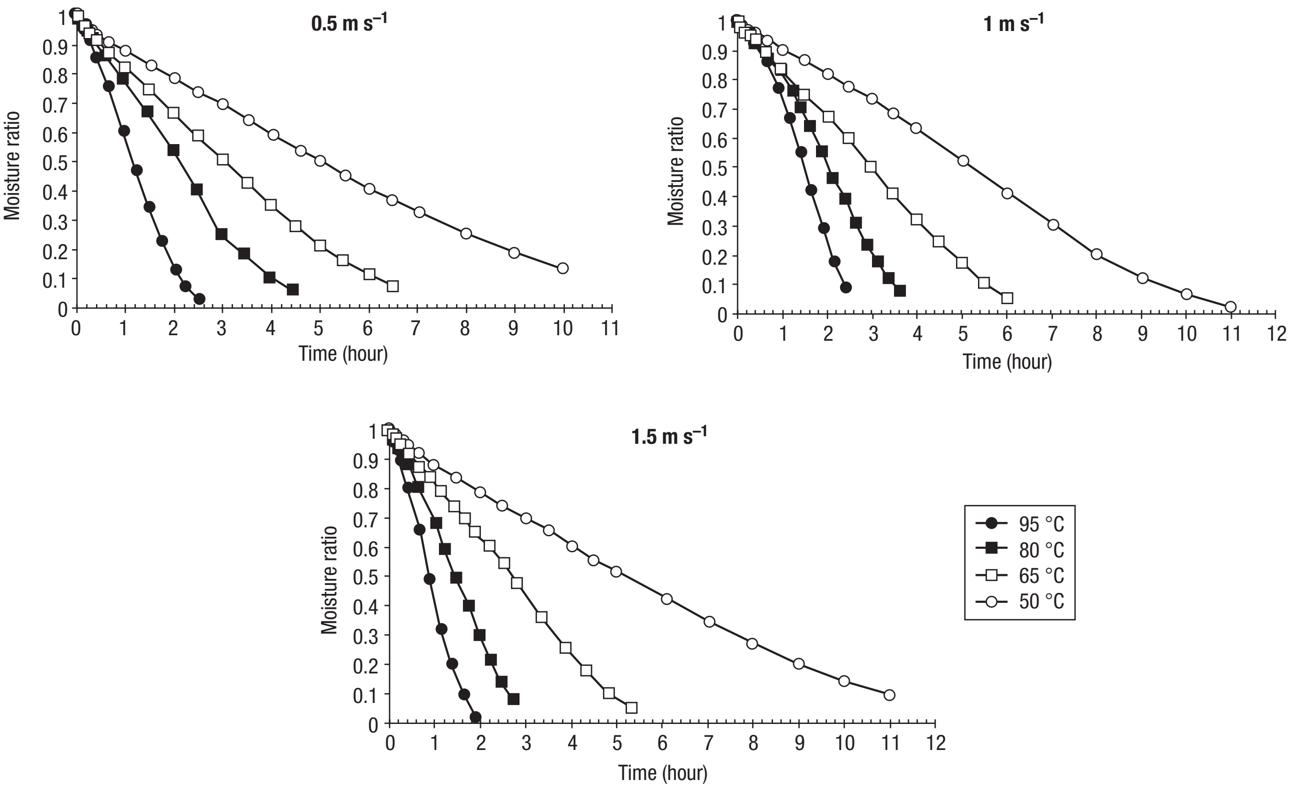

Figure 2. Moisture ratio of dried high moisture corn at three drying air velocities of fixed and fluidized beds.

egg plants (Akpinar and Bicer, 2005), peach slices (Kingsly *et al*., 2007), plum slices (Goyal *et al*., 2007), berberis fruit (Aghbashlo *et al*., 2008), mushroom (Arumuganathan *et al*., 2009) and carrot slices (Aghbashlo *et al*., 2009).

With regard to the drying curves (Fig. 2), it is obvious that all drying process of high moisture corn took place in the first and second falling-rate period for the entire duration. In other words, each drying curve constructed from two lines, a straight line at first drying period and a decreasing line at the end of process. This claim was strongly approved in Figure 3. In this figure, each drying curve was clearly included two lines. The first and the second lines were shown the first drying and the second falling periods, respectively. Similar results have been observed in drying some agricultural products such as: onion (Rapusas and Driscoll, 1995), lettuce and cauliflower leaves (López *et al*., 2000), apricots (Doymaz, 2004), figs (Piga *et al*., 2004), peaches (Kingsly *et al*., 2007), plums (Goyal *et al*., 2007), berberis fruit (Aghbashlo *et al*., 2008), mushroom (Arumuganathan *et al*., 2009) and carrot slices (Aghbashlo *et al*., 2009). In other word, moisture content of all these products has been high, but drying behavior of some was similar to a straight line. Corn drying in falling-rate period proved that the internal mass transfer occurred by diffusion.

The average moisture ratio of dried corn at different temperatures was verified using seven different empirical models to find out their suitability to describe the drying behavior. Non-linear regression analyses using MATLAB 7 (R 14) was employed for statistical modeling of drying curves through selecting the General Equations option from Curve Fitting toolbox 1.1. Correlation coefficient and other indices are summarized in Table 2. To select the best model for describing the drying curves, criterion of R^2 should have higher value and the others (and) lower values. All values of Page, Midilli *et al*., two term and Wang and Singh models were greater than 0.99. Table 2 shows the goodness of fit of all applied models in this study. Results indicated that the Midilli *et al.* model in average gave comparatively the higher R^2 values for all the drying temperatures, where the χ^2 and *RMSE* values were also found to be the lowest. Thus, the Midilli *et al.* model suggested a representation of thin layer drying behavior of high moisture corn in a convective dryer. Coefficients of Midilli *et al.* model for all temperatures and bed condi-

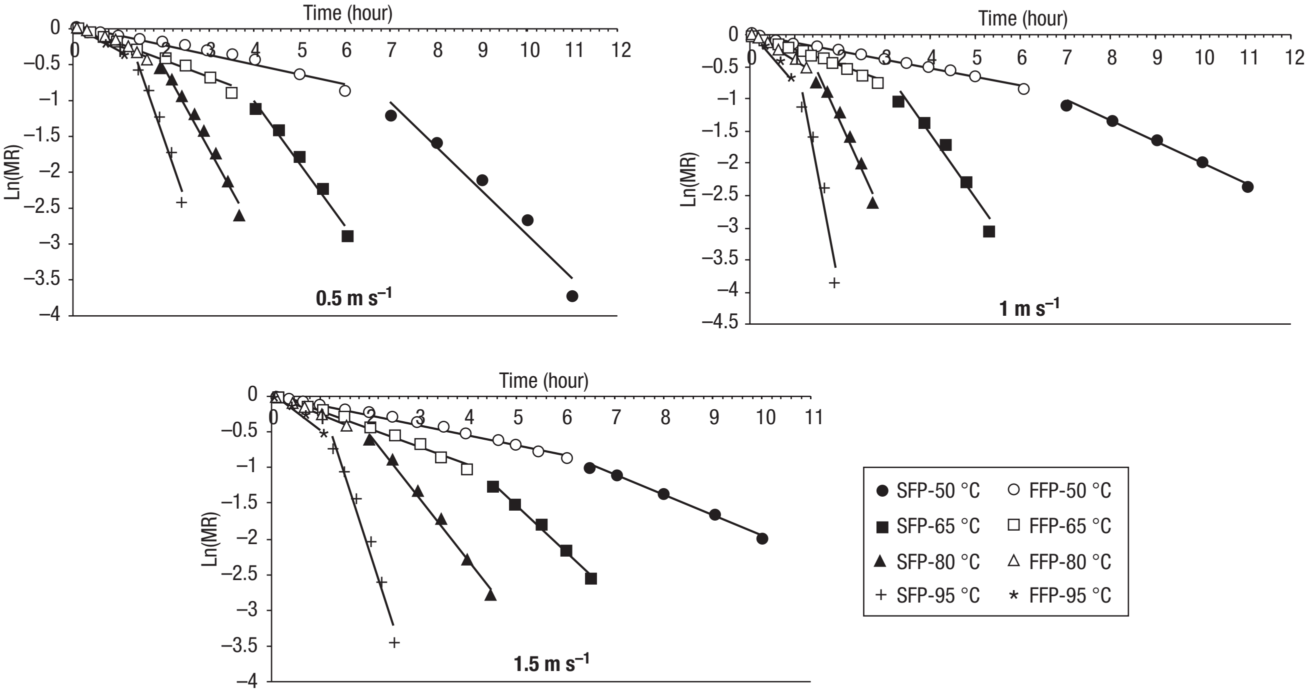

Figure 3. Ln(MR) *versus* time (s) when air velocities are 0.5, 1 and 1.5 m s^{-1} for thin-layer drying of high moisture corn.

tions are presented in Table 3. All predicted values of moisture ratio were plotted against experimental data for all temperatures and bed conditions as shown in Figure 4. The R^2 value of this curve proved that the prediction process has been carried out with high precision.

Computation of effective moisture diffusivity

Experiments of drying process were continued until the differential mass between the two weighing became less than 0.05 g. Figure 3 shows the variations of the

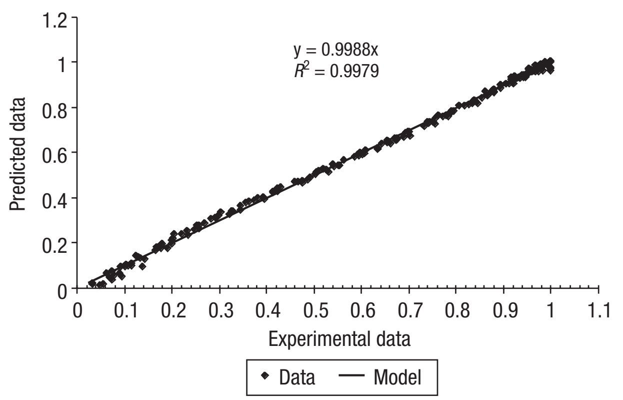

Figure 4. Experimental values of moisture ratio *versus* predicted values using Midilli *et al.* (2002) model for corn drying (all temperatures and bed conditions).

Ln(MR) *versus* drying time (s) in different air velocity and temperature levels. These drying curves show that drying high moisture content corn was occurred in falling-rate period. In other words, drying force controlled the liquid diffusion in first and second falling-rate drying process, and drying curves are similar to two straight lines as the first and second falling-rate periods. Trend of plotted curves show that with increase in the temperature values, the slope of straight line was increased. Air velocity also affected the slope of D_{eff} adversely; hence decrease in air velocity caused increase in D_{eff}. Slope of D_{eff} in second falling-rate was further. Values of D_{eff} were determined using Eq. [4]. These values are shown in Table 4 for all levels of air velocities and temperatures. The maximum values of D_{eff} during the first and second falling-rate of drying belonged to semi fluidized condition with air velocity of 1 m s^{-1}. Because of this condition the most effective contact between grain and air velocity was accrued. The maximum value of D_{eff} for first and second falling-rate of drying was obtained as 2.90×10^{-10} m^2 s^{-1} and 1.29×10^{-9} m^2 s^{-1}, respectively, both were calculated at the air temperature of 95°C. The minimum values of D_{eff} during the first falling-rate of drying (4.87×10^{-11} m^2 s^{-1}) belonged to fixed bed with air velocity of 0.5 m s^{-1}, and for second one (1.02×10^{-10} m^2 s^{-1}) belonged to fluidized bed, both at air temperature of 50°C.

Table 2. Values of statistical model parameters for high moisture corn

Model	Air temperature (°C)	R^2			χ^2			*RMSE*		
		0.5 m s^{-1}	1 m s^{-1}	1.5 m s^{-1}	0.5 m s^{-1}	1 m s^{-1}	1.5 m s^{-1}	0.5 m s^{-1}	1 m s^{-1}	1.5 m s^{-1}
Newton	50	0.9395	0.9330	0.9807	0.1326	0.0922	0.0317	0.3499	0.2895	0.1710
	65	0.9536	0.9387	0.9708	0.0844	0.0891	0.0540	0.2823	0.2876	0.2233
	80	0.9045	0.9394	0.9500	0.1755	0.1075	0.0731	0.4064	0.3191	0.2627
	95	0.8785	0.9757	0.9324	0.1559	0.0438	0.1104	0.3848	0.2042	0.3246
Page	50	0.9920	0.9959	0.9944	0.0163	0.0558	0.0084	0.1174	0.2137	0.0843
	65	0.9931	0.9931	0.9942	0.0125	0.0099	0.0107	0.1054	0.0921	0.0951
	80	0.9947	0.9908	0.9949	0.0097	0.0163	0.0082	0.0925	0.1208	0.0854
	95	0.9943	0.9938	0.9952	0.0074	0.0104	0.0078	0.0816	0.0970	0.0842
Midilli	50	0.9955	0.9996	0.9974	0.0092	0.0006	0.0039	0.0798	0.0195	0.0520
	65	0.9987	0.9984	0.9968	0.0024	0.0021	0.0053	0.0432	0.0387	0.0606
	80	0.9960	0.9982	0.9986	0.0074	0.0028	0.0023	0.0752	0.0470	0.0423
	95	0.9977	0.9972	0.9990	0.0027	0.0046	0.0015	0.0465	0.0610	0.0305
Henderson and Pabis	50	0.9475	0.9511	0.9824	0.1082	0.0673	0.0288	0.3026	0.2347	0.1561
	65	0.9616	0.9505	0.9748	0.0698	0.0633	0.0465	0.2491	0.2329	0.1984
	80	0.9238	0.9493	0.9637	0.1400	0.0827	0.0589	0.3515	0.2720	0.2288
	95	0.9059	0.9773	0.9485	0.1094	0.0379	0.0840	0.3138	0.1852	0.2763
Logarithmic	50	0.9960	0.9954	0.9994	0.0084	0.0063	0.0009	0.0804	0.0677	0.0263
	65	0.9989	0.9975	0.9991	0.0019	0.0033	0.0016	0.0398	0.0509	0.0351
	80	0.9886	0.9983	0.9895	0.0209	0.0060	0.0170	0.1312	0.0711	0.1190
	95	0.9785	0.9994	0.9944	0.0249	0.0009	0.0092	0.1455	0.0278	0.0891
Two- term	50	0.9909	0.9973	0.9991	0.0193	0.0065	0.0015	0.1156	0.0643	0.0322
	65	0.9985	0.9975	0.9989	0.0026	0.0032	0.0170	0.0450	0.0478	0.1085
	80	0.9938	0.9978	0.9948	0.0172	0.0036	0.0087	0.1147	0.0533	0.0823
	95	0.9944	0.9990	0.9941	0.0393	0.0017	0.0098	0.1773	0.0371	0.0895
Wang and Singh	50	0.9958	0.9935	0.9992	0.0085	0.0088	0.0012	0.0848	0.0848	0.0319
	65	0.9989	0.9977	0.9992	0.0019	0.0030	0.0014	0.0411	0.0507	0.0344
	80	0.9940	0.9983	0.9948	0.0110	0.0028	0.0084	0.0985	0.0500	0.0864
	95	0.9955	0.9994	0.9930	0.0053	0.0010	0.0115	0.0691	0.0301	0.1022

Table 3. Coefficients of Midilli *et al.* (2002) model for prediction of kinetic drying of corn

Temperature	Coefficients	95°C	80°C	65°C	50°C
Fixed bed	a	0.8336	0.9774	1.0021	1.0022
	k	–0.5746	–0.2701	0.0124	0.0005
	n	0.4039	0.6323	0.7318	1.0536
	b	–0.7553	–0.4821	–0.1562	–0.0946
Semi fluidized bed	a	0.9745	0.6573	0.9762	0.5938
	k	0.7110	–0.4568	–0.0251	–0.4694
	n	1.7062	0.0283	–0.0082	–0.0488
	b	–0.0495	–0.3671	–0.1852	–0.0772
Fluidized bed	a	0.9651	1.0076	0.6125	0.6238
	k	0.4326	0.6067	–0.4364	–0.4219
	n	1.8277	6.7203	–0.0498	–0.0458
	b	–0.0296	–0.2453	–0.1353	–0.0815

Table 4. Effective moisture diffusivity and correlation coefficient for three experimental air velocities at different temperatures. FFP and SFP are first and second falling periods, respectively

T	V = 0.5 m s^{-1}				V = 1 m s^{-1}				V = 1.5 m s^{-1}			
	FFP	R^2	SFP	R^2	FFP	R^2	SFP	R^2	FFP	R^2	SFP	R^2
50°C	4.87×10^{-11}	0.9657	2.21×10^{-10}	0.9614	4.76×10^{-11}	0.9909	1.15×10^{-10}	0.9916	4.99×10^{-11}	0.9902	1.02×10^{-10}	0.9959
65°C	8.60×10^{-11}	0.9808	3.11×10^{-10}	0.9670	9.01×10^{-11}	0.9871	3.55×10^{-10}	0.9663	8.76×10^{-11}	0.9841	2.32×10^{-10}	0.9915
80°C	9.32×10^{-11}	0.9694	4.07×10^{-10}	0.9728	1.52×10^{-10}	0.9896	5.42×10^{-10}	0.9695	9.65×10^{-11}	0.9912	3.12×10^{-10}	0.9913
95°C	1.20×10^{-10}	0.9597	4.68×10^{-10}	0.9686	2.90×10^{-10}	0.9757	1.29×10^{-9}	0.9539	1.83×10^{-10}	0.9813	7.61×10^{-10}	0.9713

Drying air temperature greatly affected the D_{eff} values of high moisture corn. As it is observed in the Table 4, D_{eff} value was increased as drying air temperature increased. A similar result regarding the effect of air drying temperature on moisture diffusivity during convective air drying has been found in apricots (Pala *et al.*, 1996; Doymaz, 2004), peaches (Kingsly *et al.*, 2007), plums (Goyal *et al.*, 2007), berberis fruit (Aghbashlo *et al.*, 2008), mushroom (Arumuganathan *et al.*, 2009) and carrot slices (Aghbashlo *et al.*, 2009).

Effect of air condition on effective moisture diffusivity

Values of D_{eff} were plotted against air temperature at different levels of air velocities as shown in Figure 5. Six power models were applied to fit the computed values of D_{eff} in first and second falling period. Fitted models and related R^2 values are presented in Tables 5 and 6. Values of D_{eff} at different levels of air temperature are depicted in Figure 5. Results proved that the minimum value of D_{eff} belonged to minimum value of air temperature. These findings also indicated that the influence of air velocity on increasing D_{eff} at upper air temperatures was high. Drying air contact with corn kernels at semi fluidized conditions was most effective because of its highest values of D_{eff}. Results also showed that at lower air temperatures, bed condition (air velocity levels) were not significantly different, as applying lower air velocities were even more effective. Because the drying process of corn was in the falling-rate period, mass transfer was therefore occurred by the use of diffusion phenomenon. In the diffusion mode, the effect of outer factors such as air temperature and air velocity on the mass transfer was not significant and only needed more time for transfer of moisture from the inner layer of grain to the surface.

Quadratic model type was fitted to calculated moisture diffusivity values. Applied quadratic models and related R^2 values for different air temperatures are presented in Table 6. The values of D_{eff} were plotted against air temperature and air velocity as shown in Figure 5.

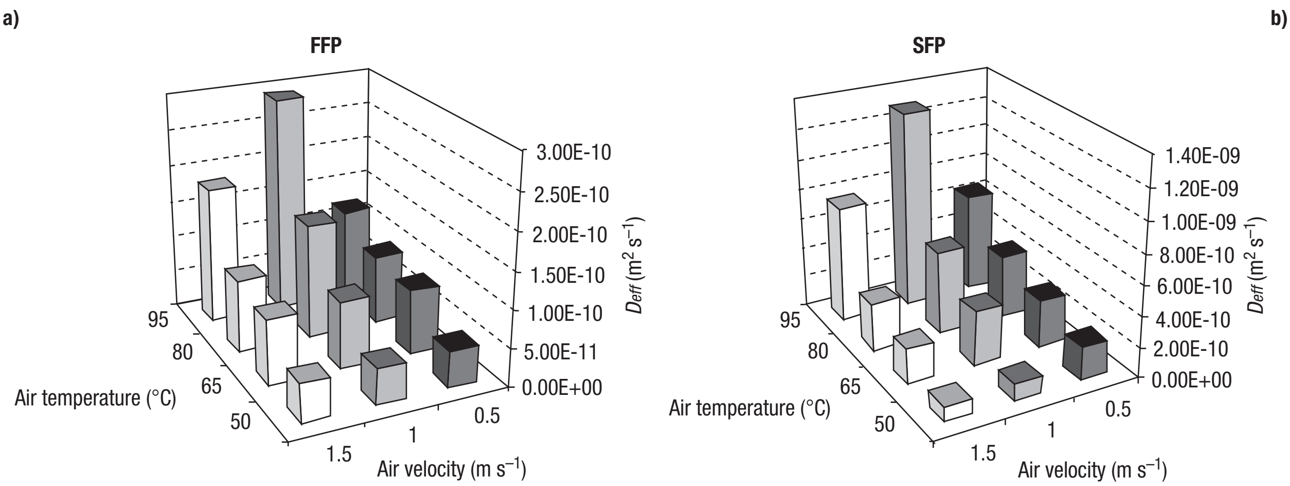

Figure 5. Effect of air temperature and velocity on effective moisture diffusivity (D_{eff}) for a) first (FFP) and b) second falling period (SFP) of thin-layer drying of high moisture corn.

Table 5. Fitted power models to effective moisture diffusivity (D_{eff}) values of dried corn for different air velocities

Air velocity ($m\ s^{-1}$)	Drying period	Model	R^2
0.5	FFP	$D_{eff} = 10^{-9} \times T^{1.3317}$	0.9621
	SFP	$D_{eff} = 10^{-9} \times T^{1.6149}$	0.9791
1	FFP	$D_{eff} = 3 \times 10^{-12} \times T^{2.7638}$	0.9931
	SFP	$D_{eff} = 3 \times 10^{-13} \times T^{3.6011}$	0.9906
1.5	FFP	$D_{eff} = 10^{-10} \times T^{1.8482}$	0.9568
	SFP	$D_{eff} = 4 \times 10^{-12} \times T^{2.9435}$	0.9811

Minimum value of D_{eff} was occurred at semi fluidized point with air velocity of 1 m s^{-1}.

Computation of activation energy

Values of Ln(D_{eff}) were plotted against 1/T as shown in Figure 6 for first and second falling period. Activation energy (E_a) was obtained using Eq. [6]. Computed values of E_a for different levels of air velocities and related R^2 values are presented in Table 7. In general, E_a for food and agricultural crops lies in domain of 12.7-110 kJ mol^{-1} (Aghbashlo *et al.*, 2008). Minimum and maximum values of E_a for figs have been reported 30.8 and 48.47, respectively (Babalis and Belessiotis, 2004). Minimum and maximum values of E_a for high moisture corn varied from 18.57 to 26.19 kJ mol^{-1} in first falling period and from 22.96 to 41.69 kJ mol^{-1} in second falling period for all air velocity levels. Two forms of water existence in fruits include surface and chemical absorptions. As most of the water in high moisture corn in first falling-rate period is in the form of surface absorption, little energy is required to exhaust water and undesirable change in chemical properties is negligible in this period (Aghbashlo *et al.*, 2008). If proper dryer with suitable air velocity and temperature is selected for corn drying, damages should be decreased. Activation energy of high moisture corn is

Table 6. Fitted power models to D_{eff} values of dried corn for different air temperatures

Air temperature (°C)	Drying period	Model	R^2
50	FFP	$D_{eff} = 2 \times 10^{-8} \times v^2 - 5 \times 10^{-8} \times v + 2 \times 10^{-7}$	1
	SFP	$D_{eff} = 7 \times 10^{-7} \times v^2 - 2 \times 10^{-6} \times v + 2 \times 10^{-6}$	1
65	FFP	$D_{eff} = -5 \times 10^{-8} \times v^2 + 10^{-7} \times \varpi + 3 \times 10^{-7}$	1
	SFP	$D_{eff} = -10^{-6} \times v^2 + 10^{-8} \times v + 2 \times 10^{-7}$	1
80	FFP	$D_{eff} = -8 \times 10^{-7} \times v^2 + 2 \times 10^{-6} \times v - 3 \times 10^{-7}$	1
	SFP	$D_{eff} = -3 \times 10^{-6} \times v^2 + 5 \times 10^{-6} \times v - 3 \times 10^{-7}$	1
95	FFP	$D_{eff} = -2 \times 10^{-6} \times v^2 + 4 \times 10^{-6} \times v - 10^{-6}$	1
	SFP	$D_{eff} = -6 \times 10^{-5} \times v^2 + 10^{-5} \times v - 5 \times 10^{-5}$	1

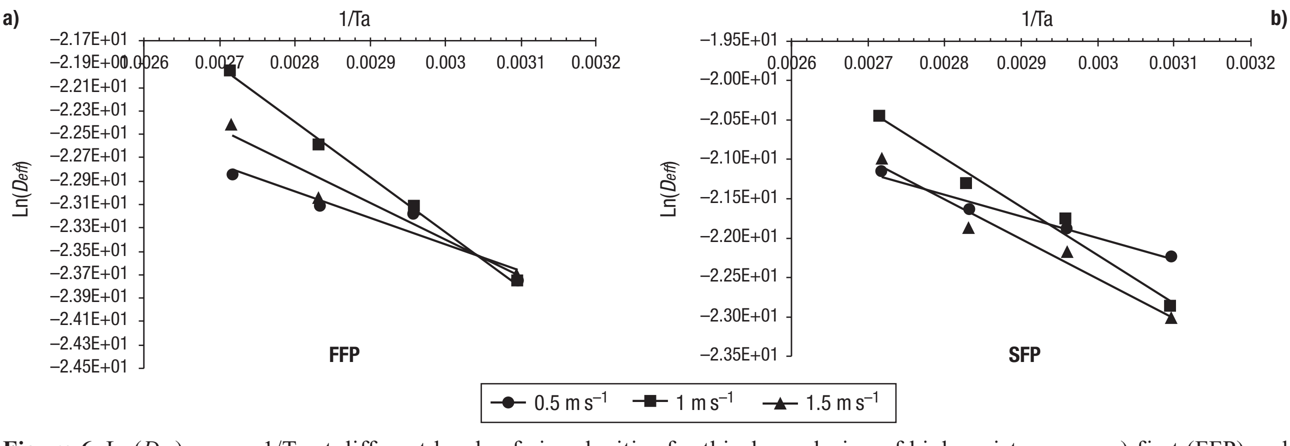

Figure 6. Ln(D_{eff}) *versus* 1/Ta at different levels of air velocities for thin-layer drying of high moisture corn a) first (FFP) and b) second falling period (SFP) of drying process.

Table 7. Activation energy and related correlation coefficient for different levels of air velocities in two drying periods of corn. FFP and SFP: first and second falling periods

	V = 0.5 m s^{-1}		V = 1 m s^{-1}		V = 1.5 m s^{-1}	
	FFP	SFP	FFP	SFP	FFP	SFP
E_a (kJ mol^{-1})	18.57	22.96	39.14	50.74	26.19	41.69
R^2	0.9504	0.9855	0.9969	0.9811	0.9646	0.9763

higher, compared to other food products, Because of: 1) high initial moisture content (66.82% wb), 2) form of water in high moisture corn, 3) tissue of corn or starchy structure of high moisture corn and 4) rigorous changes of D_{eff} value for air temperature levels at constant air velocity.

Values of E_a were plotted against air velocity as shown in Figure 7. Quadratic models were fitted to data set and values of R^2 were presented. Maximum value of E_a was occurred when air velocity laid in the range of 1-1.5 m s^{-1} (Fig. 7). Activation energy was increased when air velocities were above 1 m s^{-1}. Similar result has been obtained by Demirel and Turhan (2003) about lesser activation energy requirement for banana slices during high air temperature drying. Two order equations are fitted to the calculated data of E_a *versus* air velocity as follows:

$$E_a = -111.12v^2 + 222.24v - 60.38 \quad \text{(FFP)} \quad [14]$$

$$E_a = -67.04v^2 + 141.74v - 35.52 \quad \text{(SFP)} \quad [15]$$

Computation of specific energy consumption

During the experiments, the specific energy consumption (*SEC*) for removing 1 kg moisture content from material by the use of an electrical heater and energy requirements for drying 1 kg of fresh high moisture corn were calculated for each experiment using Eq. [10]. Computed values of *SEC* is shown in Figure 8. It was observed that the *SEC* increased as drying air temperature was decreased. Increasing air velocity affected intensively causing an increase in *SEC*. Maximum value of *SEC* 1.52×10^6 (kJ kg^{-1}) obtained at air velocity of 1.5 m s^{-1} with drying air temperature of 50°C. The minimum value of *SEC* needed 0.33×10^6 (kJ kg^{-1}) while air velocity and drying air temperatures were 0.5 m s^{-1} and 90°C, respectively. Results proved that increasing in drying time affect *SEC* inversely. In other words, each factor caused an increase in drying time, also caused an increase in energy consumption. With increasing in air velocity, effective contact between air and corn kernels was reduced and *SEC* was therefore increased. Similar results have been obtained for paddy (Khoshtaghaza *et al.*, 2007) and berberis fruit (Aghbashlo *et al.*, 2008).

Conclusions

Results showed that the Midilli *et al.* model was the best for prediction of high moisture corn drying ki-

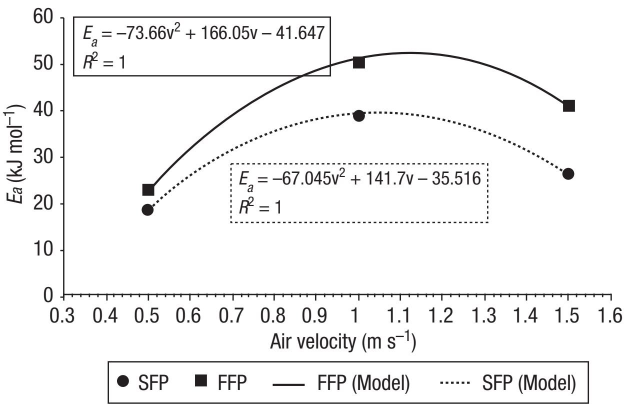

Figure 7. The effect of air velocity on activation energy value for thin-layer drying of high moisture corn.

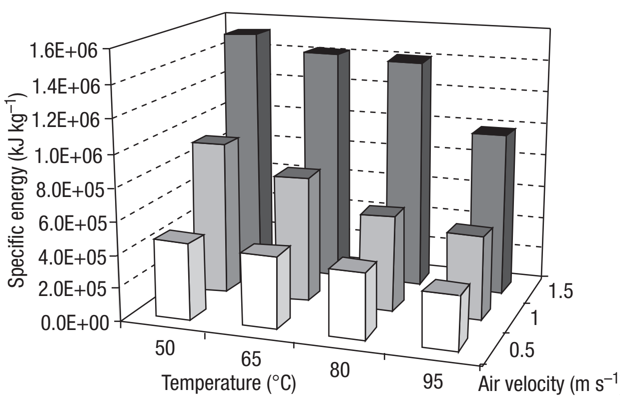

Figure 8. Specific energy consumption for thin layer drying of high moisture corn at different levels of air temperatures and velocities.

netics. Maximum value of D_{eff} during corn drying was obtained in semi fluidized bed condition (air velocity of 1 m s^{-1}) and the air temperature of 95°C. Minimum value of D_{eff} was obtained in fixed bed condition (air velocity of 0.5 m s^{-1}) and the air temperature of 50°C. values of D_{eff} for corn were also increased as input air temperature increased. Minimum and maximum values of E_a for dried corn were 18.57 and 41.69 kJ mol^{-1}, respectively. In fixed bed condition, activation energy had the minimum value. Maximum value of E_a was calculated in semi fluidized bed condition. Maximum value of *SEC* for corn drying obtained in fluidized bed condition with drying air temperature of 50°C. Minimum value of *SEC* was also obtained in fixed bed condition with drying air temperature of 95°C. Increase in air temperature in each air velocity caused a decrease in *SEC* value.

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