Modeling some drying characteristics of garlic sheets under semi fluidized and fluidized bed conditions

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Abstract

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Thin layer drying properties of high moisture garlic sheets under semi fluidized and fluidized bed conditions with high initial moisture content (about 154.26% d.b.) were studied. Air temperatures of 50, 60, 70 and 80°C were applied to garlic samples. Among the applied models, Page model was the best to predict the thin layer drying behavior of garlic sheets. Using this model, correlation coefficient (R^2) was high for all drying cases. The computed values of D_{eff} were between 3.38×10^{-10} and 2.54×10^{-9} m^2/s during the falling rate drying. Values of D_{eff} for garlic sheets were also increased with increasing in input air temperature. Activation energy values were varied between 51.32 and 60.58 kJ/mol for 50 to 80°C, respectively. The specific energy consumption (*SEC*) for garlic specimens was placed in the range of 0.316×10^6 and 0.979×10^6 kJ/kg from 50 to 80°C, respectively. An increase in air temperature caused decrease in *SEC* value. Application of semi fluidized bed convective drying with temperature between 50 and 60°C was suitable to produce dried garlic.

Keywords: energy; diffusivity; garlic; moisture ratio; Page model

Garlic (*Allium sativum* L.) is an important crop in the world. Due to its therapeutic properties it has been cultivated in many countries. Garlic is also usually used as a flavoring agent; it may be used in the shape of powder or granule as a valuable condiment for foods.

When the garlic bulb is cut or split, pungency of flavor is diffused, while fresh garlic bulb has no distinct pungency. Process of drying garlic is usually evaluated based on many indices such as: drying time, effective moisture diffusivity, activation energy, specific consumption of energy and color. Applying of proper drying method is a key to producing high quality dried garlic with a higher diffusivity, lower drying time and energy and better appearance as similar to fresh garlic as possible.

If the environmental conditions are suitable and the rest period passed about 60–80 days, the sprout of the garlic will quickly appeared after dormancy. When sprouting is started, the nutritional storage in the garlic will be decreased and due to withering the stem and trunk, garlic quality is obviously reduced. Drying is one of the best methods for preserving the garlic quality.

It is proved that the quality of dried food products are strongly affected by applied drying methods and various physical, chemical and biological changes may be created in the food material (Krokida et al. 2000). In other words, some properties of foodstuffs such as color, structure, aroma compounds and nutritional substance were changed or deteriorated. These changes may tend to reduce the product quality (Pezzutti, Crapiste 1997).

Hot-air drying of garlic slices in a common fixed bed method is unfortunately not suitable due to a significant decrease in the quality of dried product related to the fresh one. Applying high temperature (about 60°C) in a fixed bed drying causes an increase in drying period, energy consumption, color degradation and mass transfer.

In recent years, fluidized bed drying was investigated and utilized as a new method for obtaining dried foodstuffs with high quality (Poomsa-Ad et al. 2002; Cubillos, Reyes 2003; Amiri Chayjan et al. 2009; Gazor 2009). Fluidized bed drying is rapid and more uniform compared with fixed bed drying (Soponronnarit et al. 1997). Fluidized bed drying was employed for drying of some agricultural grain products such as: broad beans (Hashemi et al. 2009), milky mushroom (Arumuganathan et al. 2009), rough rice (Amiri Chayjan et al. 2009), green beans (Souraki, Mowla 2007) and corn (Soponronnarit et al. 1997).

Suspending of grain particles in air flow is known as fluidization. At the beginning of air passing through grain bed, a fixed bed will be created. With gradually increasing in air flow rate, a bed of fluffy material is obtained, namely minimum fluidized bed (semi fluidized bed); afterward with another increase in air flow rate, bubbling fluidized bed and transportation phenomenon would be observed. At the semi fluidized bed, maximum value of pressure drop is obtained and particles weight is equal to frictional force between bed particles (Kunii, Levenspiel 1991; Soponronnarit et al. 1997).

Mathematical modeling of garlic drying using defined models can precisely predict the drying kinetics in a drying system (Kaleta, Górnicki 2010). Effective moisture diffusivity is affected by air temperature and velocity (Senadeera et al. 2000, 2003). All effective parameters on the mass transfer phenomenon in drying process are represented by effective moisture diffusivity (Hashemi et al. 2009). Activation energy is important for estimation of minimum energy requirement for carrying out the drying process of garlic (Aghbashlo et al. 2008). All consumed energy for transferring of 1 kg water from fresh garlic id defined as specific energy consumption (*SEC*) (Koyuncu et al. 2007).

Although many investigations were carried out on drying indices for various crops and agricultural products, no study reported about drying of fresh garlic sheets in semi fluidized and fluidized bed dryer. Also drying properties of garlic sheets in fluidized bed drying are not available.

The main goals of this study were to find a mathematical model for predicting the drying behavior of high moisture garlic sheets and to compute the effective moisture diffusivity, activation energy and specific energy consumption of high moisture garlic sheets during falling rate of semi fluidized and fluidized bed thin layer drying method and their relation to input parameters such as air temperature and velocity.

MATERIAL AND METHODS

Fluidized bed drying condition

In order to apply fluidized bed condition in drying of garlic sheets, maximum pressure drop against air flow velocity in fluidization curve was determined (Kunii, Levenspiel 1991). A digital apparatus (Standard ST-8897, Standard Instruments Co., Ltd., Hong Kong, China) utilized for recording both static pressure drop (kPa) and outlet air velocity (m/s). About 25 g garlic sample was used in fluidization experiments. First experimental point was determined at air velocity about 2.8 m/s as a semi fluidized bed condition. Two other points were in fluidized bed condition with air velocities of 4.26 and 5.4 m/s, respectively. These points and related fluidization curve were shown in Fig. 1. The net static pressure of garlic bed for points of A, B and C were obtained 0.048, 0.037 and 0.026 kPa. As can be observed, net static pressure for point A (Fig. 1) is maximized and is defined as semi fluidized condition.

Experimental setup

Fresh garlic was purchased from a local farm in September 2010. Garlic samples were kept in a

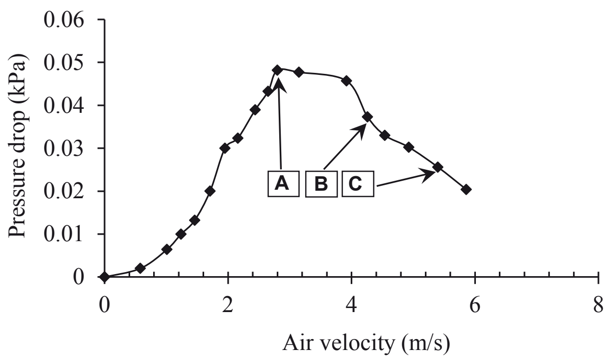

Fig. 1. Fluidization curve of garlic slices and selected points as experimental cases: (A) semi fluidized bed (2.8 m/s), (B) fluidized bed (4.26 m/s), (C) fluidized bed (5.4 m/s)

refrigerator at 3 ± 1°C. Ambient air temperature and relative air humidity changed from 26 to 32°C and from 22 to 31%, respectively. During the drying experiments, inlet and outlet temperatures of the drying chamber and the ambient air relative humidity and temperature were measured. An experimental fluidized bed dryer utilized to perform the experiments. Applied air temperatures in the experiments were 50, 60, 70, and 80°C. In total, 12 experiments were conducted. Initial and final moisture contents determination of garlic samples was conducted using gravimetric method at 103°C (Vázquez et al. 1999). Drying process was started at initial moisture content of about 154.26% (d.b.) and finished at final moisture content of about 5% (d.b.).

Modeling

Fick's second law for moisture diffusion in infinite slab was employed for modeling. Due to minor diameter of garlic sheets, that were much smaller than their major diameter, we therefore assumed that the garlic sheets are similar to infinite slab. After solution of Fickian equation for an infinite slab, the following equation was obtained and can describe effective moisture diffusivity changes in garlic sheets:

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\exp\left(\frac{-D_{\text{eff}}(2n-1)^2\pi^2 t}{4L^2}\right) \quad (1)$$

where:
MR – moisture ratio (decimal)
M – moisture content at any time ($kg_{water}/kg_{dry\ mater}$)
M_0 – initial moisture content ($kg_{water}/kg_{dry\ mater}$)
n = 1, 2, 3, ... – number of terms taken into consideration
t – time of drying (s)
D_{eff} – effective moisture diffusivity (m^2/s)
L – thickness of garlic sheet (m)

For a long drying period, only the first term of Eq. (1) can be considered. This simplification has no negative effect on the final answer (Ramesh et al. 2001):

$$\ln(MR) = \ln\left(\frac{M - M_e}{M_0 - M_e}\right) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{D_{\text{eff}}\pi^2 t}{4L^2}\right) \quad (2)$$

The simplified form of MR is as follows:

$$MR = \left(\frac{8}{\pi^2}\right)\exp\left(\frac{\pi^2 D_{\text{eff}} t}{4L^2}\right) \quad (3)$$

The slope (B) is determined by plotting time against ln(MR) as follows:

$$B = \frac{\pi^2 D_{\text{eff}}}{4L^2} \quad (4)$$

Activation energy was obtained using an Arrhenius type equation (Babalis, Belessiotis 2004):

$$D_{\text{eff}} = D_0 \exp\left(-\frac{E_a}{RT}\right) \quad (5)$$

For calculating E_a, Eq. (5) can be linearized as follows:

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

where:
E_a – activation energy (kJ/mol)
R – universal gas constant (8.3143 kJ/mol.K)
T – absolute air temperature (K)
D_0 – pre-exponential factor of the equation (m^2/s)

After plotting of 1/T against ln(D_{eff}) using Eq. (6), six fitted models were obtained as straight lines with the slope of B_1.

$$B_1 = \frac{E_a}{R} \quad (7)$$

Simplified form of Eq. (3) for all models can be written as exponential equations as follows:

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

They are mathematical models for prediction of garlic drying kinetics in thin layer mode. Some of these models were employed in this study (Table 1).

The value of equilibrium moisture content (M_e) is very small compared to M and M_0 (Hassan-Beygi et al. 2009). Thus $(M - M_e)/(M_0 - M_e)$ was changed to M/M_0. Therefore all models in Table 1 and the basic Eq. (2) can be written as follows:

$$MR = \frac{M}{M_0} \quad (9)$$

Specific energy consumption (SEC) was calculated using the following model (Zhang et al. 2002):

$$SEC = \frac{(C_{Pa} + C_{Pv}h_a)Qt(T_{in} - T_{am})}{m_v V_h} \quad (10)$$

where:
SEC – specific energy consumption (kJ/kg)
C_{Pv},C_{Pa} – specific heat capacity of vapor and air, respectively, (1,004.16 and 1,828.8 J/kg°C)

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

Model	Equation[1]	References
Demir et al.	$MR = a\exp(-kt)^n + b$	Demir et al. (2007)
Page model	$MR = \exp(-kt^n)$	Arumuganathan et al.(2009)
Two-term exponential	$MR = a\exp(-kt) + (1 - b)\exp(-kct)$	Sharaf-Elden et al. (1980)
Henderson and Pabis	$MR = a\exp(-kt)$	Yaldiz et al. (2001)
Logarithmic	$MR = a\exp(-kt) + c$	Yaldiz et al. (2001)
Lewis	$MR = \exp(-kt)$	Aghbashlo et al. (2009)
Wang and Singh	$MR = 1 + at + bt^2$	Wang, Singh (1978)

[1]a, b, c, k, k_0, k_1, n – drying constants

Q – inlet air to drying chamber (m^3/s)
t – total drying time (1/min)
h_a – absolute air humidity (kg$_{vapor}$/kg$_{dry\ air}$)
T_{in}, T_{am} – inlet air to drying chamber and ambient air temperatures, respectively (°C)
m_v – mass of removal water (kg)
V_h – specific air volume (m^3/kg)

Curve Expert (version 1.4) software (Microsoft Corporation, Mississippi, USA) was used to fit the mathematical models to experimental data. Three comparative indices were used as the goodness of fit and to select the best model such as: (1) correlation coefficient (R^2), (2) chi-square (χ^2) and (3) root mean square error (*RMSE*). The best model should have the highest R^2 value and the lowest χ^2 and *RMSE* values (Demir et al. 2004; Erenturk et al. 2004). These indices are as follow:

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

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

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

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 modeling

The drying kinetic of garlic sheets in semi fluidized and fluidized bed conditions obtained at different temperatures. Results proved that drying air temperature is the most important parameter in drying kinetic. With an increase in air temperature, drying time was reduced.

Modeling of drying experiments was performed using non-linear regression analyses of Curve Expert (version 1.4). Comparative indices for all drying cases are represented in Table 2. Demir et al., Page model, Two term exponential, Logarithmic and Wang and Singh models have the R^2 value greater than 0.99. Finally, Page model was selected as the best model for prediction the drying kinetic of high moisture garlic. Coefficients of Page model for all drying curves are presented in Table 3. The average R^2 value of Page model (0.9986) showed that the selected model is suitable for prediction of garlic drying process.

Effective moisture diffusivity

Variations of the ln(*MR*) against drying time (hour) in all bed conditions and temperature levels for thin layer drying of garlic sheets were depicted in Fig. 2. With regard to low thickness of specimens (about 1 mm), one falling rate was obtained in drying of garlic sheets. Trend of drying curves proved that the slope of lines in all bed conditions increased with an increase in temperature values. Effect of air velocity on the slope of D_{eff} for different bed conditions was negligible; hence changes in air velocity in domain of fluidized bed had no effective change in D_{eff} value, especially for low temperatures. Eqs 2 and 4 were used

Table 2. Comparative indices of statistical model parameters for thin layer drying of high moisture garlic sheets

Model	Air temperature (°C)	R^2			χ^2			*RMSE*		
		2.8 m/s	4.26 m/s	5.4 m/s	2.8 m/s	4.26 m/s	5.4 m/s	2.8 m/s	4.26 m/s	5.4 m/s
Demir et al.	50	0.9990	0.9992	0.9964	0.0017	0.0011	0.0054	0.0372	0.0301	0.0648
	60	0.9992	0.9996	0.9990	0.0010	0.0004	0.0012	0.0278	0.0174	0.0300
	70	0.9966	0.9950	0.9948	0.0032	0.0055	0.0046	0.0451	0.0605	0.0525
	80	0.9994	0.9986	0.9982	0.0004	0.0008	0.0013	0.0130	0.0185	0.0254
Page	50	0.9994	0.9980	0.9992	0.0010	0.0033	0.0010	0.0301	0.0548	0.0298
	60	0.9992	0.9994	0.9992	0.0009	0.0005	0.0007	0.0282	0.0210	0.0247
	70	0.9994	0.9992	0.9974	0.0005	0.0007	0.0014	0.0202	0.0241	0.0334
	80	0.9952	0.9938	0.9962	0.0035	0.0043	0.0007	0.0500	0.0554	0.0229
Two-term exponential	50	0.9988	0.9992	0.9950	0.0019	0.0012	0.0078	0.0415	0.0323	0.0832
	60	0.9990	0.9994	0.9986	0.0011	0.0005	0.0017	0.0312	0.0210	0.0385
	70	0.9958	0.9936	0.9936	0.0041	0.0071	0.0058	0.0579	0.0769	0.0681
	80	0.9992	0.9986	0.9980	0.0004	0.0009	0.0014	0.0169	0.0253	0.0324
Henderson and Pabis	50	0.9972	0.9964	0.9868	0.0046	0.0058	0.0206	0.0646	0.0727	0.1353
	60	0.9982	0.9976	0.9986	0.0016	0.0028	0.0017	0.0377	0.0497	0.0385
	70	0.9906	0.9894	0.9912	0.0039	0.0119	0.0080	0.0872	0.0995	0.0800
	80	0.9641	0.9629	0.9946	0.0265	0.0258	0.0039	0.1375	0.1357	0.0540
Logarithmic	50	0.9990	0.9992	0.9964	0.0017	0.0011	0.0054	0.0383	0.0309	0.0670
	60	0.9992	0.9996	0.9990	0.0010	0.0004	0.0012	0.0288	0.0181	0.0312
	70	0.9966	0.9950	0.9948	0.0032	0.0055	0.0046	0.0482	0.0642	0.0567
	80	0.9994	0.9986	0.9982	0.0004	0.0009	0.0013	0.0151	0.0226	0.0285
Lewis	50	0.9960	0.9960	0.9789	0.0065	0.0068	0.0332	0.0787	0.0806	0.1770
	60	0.9984	0.9964	0.9978	0.0021	0.0041	0.0027	0.0445	0.0621	0.0503
	70	0.9864	0.9846	0.9872	0.0134	0.0173	0.0117	0.1103	0.1259	0.1026
	80	0.9582	0.9562	0.9934	0.0308	0.0305	0.0047	0.1624	0.1616	0.0641
Wang and Singh	50	0.9976	0.9950	0.9976	0.0039	0.0084	0.0012	0.0595	0.0875	0.0573
	60	0.9942	0.9986	0.9960	0.0079	0.0014	0.0014	0.0837	0.0351	0.0661
	70	0.9980	0.9976	0.9964	0.0018	0.0027	0.0084	0.0383	0.0474	0.0513
	80	0.9994	0.9986	0.9968	0.0003	0.0008	0.0115	0.0146	0.0239	0.0406

Table 3. Coefficients of Page model for prediction of kinetic drying of high moisture garlic sheets

Bed condition	Temperature (°C)	k	n
Semi fluidized bed (2.8 m/s)	50	3.8534	1.1019
	60	4.6402	1.0508
	70	9.7840	1.2351
	80	28.748	1.4898
Fluidized bed (4.26 m/s)	50	3.2959	1.0781
	60	4.6924	1.0972
	70	9.7901	1.2573
	80	24.009	1.4791
Fluidized bed (5.4 m/s)	50	5.3186	1.2938
	60	5.5939	1.0706
	70	10.997	1.2182
	80	11.681	1.1118

for calculation of D_{eff} values. These values for all bed conditions and temperatures are presented in Table 4. Maximum value of D_{eff} (2.54×10^{-9} m^2/s) among all drying cases was obtained for semi fluidized condition with air velocity of 2.8 m/s and air temperature of 80°C. This is due to the most effective contact between garlic sheets and air flow. Also minimum value of D_{eff} (3.38×10^{-10} m^2/s) belonged to fluidized condition with air velocity of 5.4 m/s and air temperature of 50°C. This is due to the low energy rate transferred to the garlic sheet and also low effective contact in turbulent flow of fluidized bed.

Values of D_{eff} for high moisture garlic sheets are greatly affected by drying air temperature. As can be seen in Table 4, an increase of 10°C in input drying temperature, cause about twice increase in D_{eff} values. This pattern was observed in previous studies, such as: peaches (Kingsly et al. 2007) and plums (Goyal et al. 2007).

Effect of bed condition on D_{eff}

Variations of D_{eff} against air temperature at different bed conditions are plotted in Fig. 3. Three exponential models were fitted to the obtained values of D_{eff}. These models as well as related R^2 values are represented in Tables 5 and 6. Results showed that the maximum value of D_{eff} was obtained at the highest air temperature level; they also indicated that applying fluidized bed condition caused a decrease in D_{eff} at upper air temperatures. Drying air contact with garlic sheets at semi fluidized bed was the most effective due to its highest values of D_{eff}. Also at lower air temperatures, no significant difference was observed between D_{eff} values of bed conditions (air velocity levels), as applying minimum fluidized bed condition with lower air velocity was even more suitable. Four quadratic models were applied to fit on the obtained moisture diffusivity. Applied models and related R^2 values for four air temperatures are presented in Table 6.

Computation of activation energy

Fig. 4 shows the curve of ln(D_{eff}) against $1/T$ for drying of garlic sheets in falling rate period. Activation energy (E_a) was calculated using Eq. (6). The obtained values of E_a for all bed conditions as well as R^2 values are represented in Table 7. Values of E_a for food and agricultural crops generally varied between 12.7 and 130 kJ/mol (Aghbashlo et al. 2008). Minimum and maximum values of E_a for high moisture garlic sheets varied between 51.32 and 60.58 kJ/mol for all bed conditions. Two modes of moisture in agricultural materials are surface and chemical. Because most of the water in high moisture garlic in falling rate period is in the

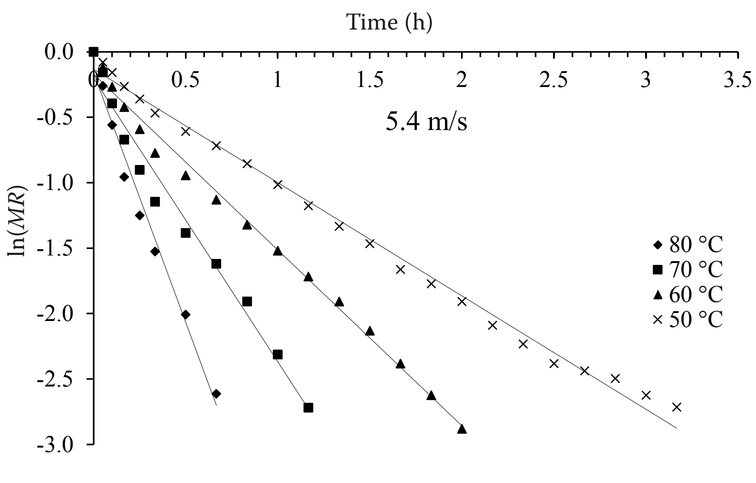

Fig. 2. ln(MR) against time (s) for thin-layer drying of high moisture corn and all bed conditions

Table 4. Effective moisture diffusivity and correlation coefficient for three bed conditions at different temperatures

T (°C)	Semi fluidized bed (V = 2.8 m/s)		Fluidized bed (V = 4.26 m/s)		Fluidized bed (V = 5.4 m/s)	
	D_{eff} (m²/s)	R^2	D_{eff} (m²/s)	R^2	D_{eff} (m²/s)	R^2
50	3.72×10^{-10}	0.9934	3.63×10^{-10}	0.9856	3.38×10^{-10}	0.9935
60	6.12×10^{-10}	0.9914	5.97×10^{-10}	0.9864	5.64×10^{-10}	0.9921
70	1.17×10^{-09}	0.9933	1.07×10^{-09}	0.9908	9.75×10^{-10}	0.9877
80	2.54×10^{-09}	0.9832	2.19×10^{-09}	0.9850	1.71×10^{-09}	0.9821

form of chemical absorption, relatively more energy is consumed to exhaust water and undesirable change in chemical properties is noticeable in this period (Amiri Chayjan et al. 2009).

Maximum value of E_a belonged to the minimum fluidized bed condition with air velocity 2.8 m/s. With increasing air velocity, the activation energy was decreased. A linear equation is fitted to the calculated data of E_a against air velocity as follows:

$$E_a = -3.5451v - 70.673 \quad R^2 = 0.9950 \tag{14}$$

Specific energy consumption

Computed *SEC* values for drying of samples are presented in Fig. 5. It can be observed that the *SEC* was increased as air temperature was decreased. Air velocity has a direct relation with *SEC*, as an increase in air velocity caused an intensive increase in *SEC*. The minimum value of *SEC* (0.316×10^6 kJ/kg) was obtained for minimum fluidized bed condition and drying air temperatures 90°C. The maximum value of *SEC* (0.979×10^6 kJ/kg) was obtained for fluidized bed condition with air velocity of 5.4 m/s and drying air temperature 50°C. Results indicated that an increase in drying temperature affect *SEC* inversely. With increasing air velocity, effective contact between air and garlic sheets was contrarily increased but an output energy loss was increased and *SEC* was therefore increased. Three linear models were applied to fit the *SEC* data in semi fluidized bed and fluidized bed conditions as follows:

$$SEC = 5{,}298.1T + 106 \quad R^2 = 0.9941 \text{ (2.8 m/s)} \tag{15}$$

Table 5. Fitted exponential models to D_{eff} values for different bed conditions

Air velocity (m/s)	Model	R^2
Semi fluidized bed (2.8 m/s)	$D_{eff} = 2 \times 10^{-10} \times \exp(0.641T)$	0.9904
Fluidized bed (4.26 m/s)	$D_{eff} = 2 \times 10^{-10} \times \exp(0.5976T)$	0.9937
Fluidized bed (5.4 m/s)	$D_{eff} = 2 \times 10^{-10} \times \exp(0.5419T)$	0.9995

Table 6. Fitted power models to D_{eff} value for different air temperatures

Air temperature (°C)	Model	R^2
50	$D_{eff} = -6 \times 10^{-12} \times T^2 + 3 \times 10^{-11} \times T + 3 \times 10^{-10}$	1
60	$D_{eff} = -7 \times 10^{-12} \times T^2 + 4 \times 10^{-11} \times T + 6 \times 10^{-10}$	1
70	$D_{eff} = -9 \times 10^{-12} \times T^2 - 3 \times 10^{-12} \times T + 1 \times 10^{-09}$	1
80	$D_{eff} = -6 \times 10^{-11} \times T^2 + 2 \times 10^{-10} \times T + 2 \times 10^{-09}$	1

Table 7. Activation energy and related correlation coefficient for different bed conditions

Bed condition	Semi fluidized bed (V = 2.8 m/s)	Fluidized bed (V = 4.26 m/s)	Fluidized bed (V = 5.4 m/s)
Equation	$\ln(D_{eff}) = 0.76 - \frac{7{,}286.3}{T}$	$\ln(D_{eff}) = 0.766 - \frac{6{,}795.4}{T}$	$\ln(D_{eff}) = -2.7285 - \frac{6{,}172.1}{T}$
E_a (kJ/mol)	60.58	56.50	51.32
R^2	0.9846	0.9888	0.9976

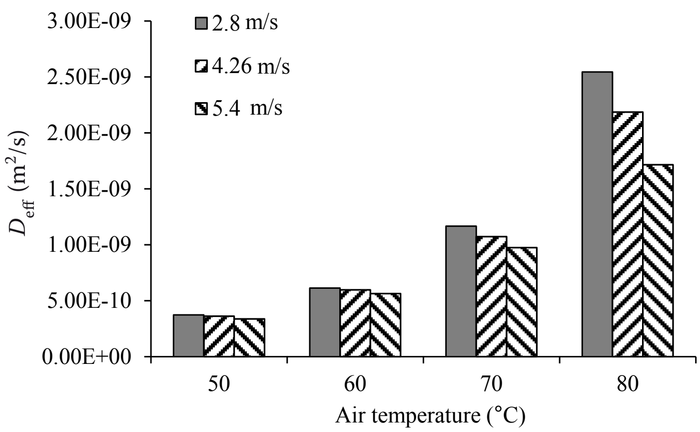

Fig. 3. Influence of air temperature on effective moisture diffusivity (D_{eff}) in thin-layer drying of high moisture garlic in different bed conditions

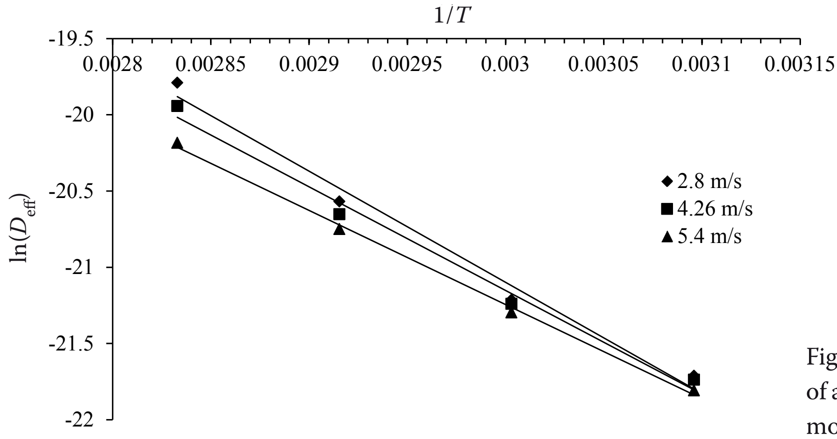

Fig. 4. ln(D_{eff}) versus 1/T at different levels of air velocities for thin-layer drying of high moisture garlic

$$SEC = -6,085.7T + 106\ R^2 = 0.9850\ (4.26\ \text{m/s}) \quad (16)$$

$$SEC = -6,596.6T + 10^6\ R^2 = 0.9899\ (5.4\ \text{m/s}) \quad (17)$$

Comparison between dried garlic sheets

With regard to calculated indices such as D_{eff}, E_a and SEC, semi fluidized bed condition was selected as the best method applied in this study. Colour analysis was accomplished on dried garlic samples from semi fluidized method. Results showed that the garlic sheets dried at 50 and 60°C have acceptable colour. But its color at 70 and 80°C changed to brown or black and transformation also occurred. If a fluidized bed industrial dryer is designed for garlic drying, then quality of final dry product should be considered.

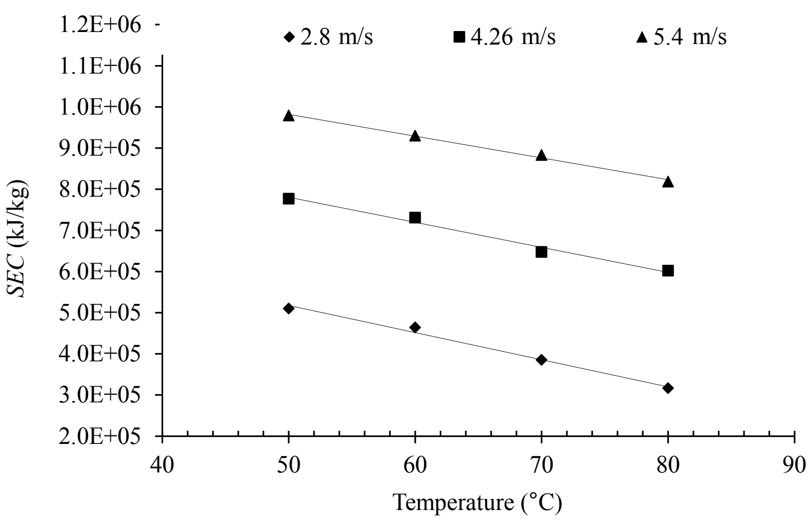

Fig. 5. Specific energy consumption for thin layer drying of high moisture garlic sheets at different air temperatures of semi fluidized and fluidized bed drying

CONCLUSIONS

(1) The Page model was the best for prediction of high moisture garlic sheets drying kinetics in the semi fluidized and fluidized bed conditions.
(2) Effective moisture diffu-sivity of garlic sheets varied between 3.38×10^{-10} and 2.54×10^{-9} m^2/s in this study. Increase in air temperature in each bed condition caused increase in D_{eff} value whereas increase in air velocity in an air temperature level decreased the D_{eff} value.
(3) The activation energy E_a for garlic sheets in the drying experiments varied between 51.32 and 60.58 kJ/mol and these values correspond with the activation energy of other agricultural and food products in a general range reported by many researchers.
(4) Specific energy consumption calculated for garlic sheets thin layer drying experiments varied between 0.316×10^6 and 0.979×10^6 kJ/kg.
(5) A comparison between garlic slices that are dried at different air temperature levels using semi fluidized bed condition indicates that the usage of convective dryer with temperature between 50 and 60°C is suitable to preserve natural color and shape of dried garlic sheets.

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