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Effect of Temperature History on Mass Transfer Diffusivity in Convective Drying Process

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Abstract: Convective hot air drying of potato slabs and the effects of drying air temperature and slab thickness have been investigated using a batch tray dryer. The temperature of drying chamber varied in four levels (50, 60, 70 and 80°C) and the slab thickness changed in three levels (0.5, 1 and 1.5 m). For the prediction of effective moisture diffusivity (D_{eff}), the conventional Fick's diffusion model was modified considering the temperature variation of the sample during the drying period. Comparing the predictions of conventional Fick's model with those of modified model indicates that the model proposed in this study shows better agreement with the experimental data.

Key words: drying · Potato slab · Diffusion model · Temperature history · Moisture diffusivity

INTRODUCTION

Modeling the drying process and predicting the drying behavior under different conditions is necessary to have a better understanding of the mechanisms of drying. Fick's second law of diffusion, as shown in Eq. (1), has been used conventionally to describe the drying kinetics of fruit samples during the falling rate period during which moisture transfer is controlled by internal diffusion [1-11].

$$\frac{\partial M}{\partial t} = \nabla(D_{eff} \nabla M) \qquad (1)$$

Where D_{eff} is effective moisture diffusivity in the solid slab representing the conductive term of all moisture transfer mechanisms [12]. Most studies of dehydration of fruits have focused on validation of a particular model, under a limited range of drying conditions. As a result of these studies, different analytical and numerical models have been developed [1, 13]. Among different parameters influencing the drying kinetics, the effect of temperature was of most interest in these studies [14]. In some studies, food temperature is generally assumed to be constant. This assumption is not generally true during food drying, specially at the first stages of drying, during which the temperature of the sample rises to reach the final steady value. Recently, Srikiatden and Roberts (2006) studied temperature histories and gradients within the cylindrical potato samples of 0.7 and 1.4 cm diameter [12]. In their work, temperature profiles were obtained along the radial axis: center, half-radius and surface. At a given time, the temperatures at center and half-radius positions were similar but lower than the surface temperature. The temperature histories also show that the sample temperatures did not achieve the oven temperature until drying was almost completed. With the sample temperature varying with position and time during convective drying, it is difficult to properly determine the effective moisture diffusivity and its dependence on temperature. Accordingly, they concluded that the isothermal assumption is violated and can be the most significant cause of error in the calculation of D_{eff}. Also, they observed that in microwave drying the sample temperature reaches the desired temperature within a short time and are maintained at this temperature in the rest of drying period. Although it is proved that the constant temperature assumption in forecasting the moisture content of the sample during convective drying process produces considerable error, this assumption has been extensively used in order to obtain an analytical solution for mass transfer equation of diffusive drying of foodstuffs [15-20].

Therefore, the aim of this work is to introduce the temperature variation with time (temperature history) in the Fick's second law of diffusion and develop a more precise model for predicting moisture content of the sample during convective drying process. For this purpose, potato slabs in different thicknesses were experimentally dried over a wide range of temperatures.

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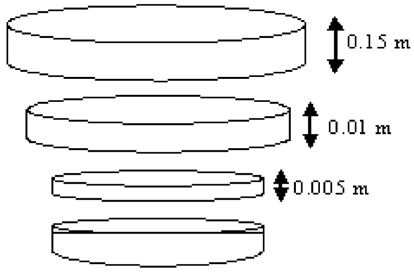

Fig. 1: Cutting method of potato slabs with different thicknesses

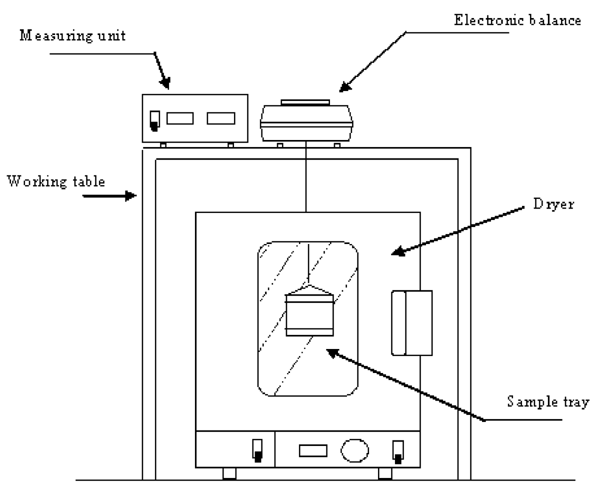

Fig. 2: Experimental apparatus used for drying of potato samples

Experimental Set up: In this investigation, forced convective drying of potato slabs has been done using a batch tray dryer equipped with forced draft fan. All samples were prepared from a single type of potato. The potatoes were cut into 0.5, 1 and 1.5 cm thicknesses with an error of ±0.5 mm. To have a one dimensional moisture transfer, potato was cut in nearly disk shaped with skin. For further explanation, method of cutting the potato slabs has been shown in Figure 1. As can be seen in Figure 1, around the cylindrical slabs has been covered with natural skin to prevent multi-dimensional mass transfer. Weighting of samples was carried out with an electronic balance every 10 min during the drying process until no further changes in their mass were observed. As will be explained later, the moisture content is calculated from the weight of the sample and expressed as kg water / kg dry solid.

Drying experiments were carried out using a laboratory scale system (ISUZU 102137). It consisted of a drying chamber, an electronic balance, wet bulb and dry bulb temperature measuring devices, a fan, electric elements and a tray in the drying chamber. In order to prevent the heat loss to the environment, the chamber is well insulated. Potato slab was placed on a stainless steel mesh tray which was suspended from an electronic balance. The balance output was recorded manually and the mass change of the sample was calculated as a function of drying time. This system is illustrated in Figure 2.

The experimental conditions were set as follow: air velocity is constant at 4 m/s in all experimental runs, air temperature is varied in the range of 50 to 80°C and various sample thicknesses of 5, 10 and 15 mm are used. The electronic balance was set to zero while the tray was suspended from it. The sample (potato slab) was then placed on the tray and weighed. The temperature was set to desired value by turning the temperature dial. Then the temperature in the chamber rose up gradually. When the temperature reached the desired value, the door was opened manually and the sample was put on the tray. Every 10 minutes, the weight of the sample was recorded. The experiment was continued until the sample became almost dry and mass change of potato slab becomes zero. Each run was repeated three times and the average of the results was used for further processing.

RESULTS AND DISCUSSION

Effect of Temperature on Drying Kinetics: Weight of sample has been recorded every 10 minutes during the drying process until the mass change of potato slab becomes zero. Experimental results show that the sample weight reduces gradually during drying time and this phenomenon is due to the loss of water from the sample. The moisture content at the end of experiment is taken as equilibrium moisture and because the air is nearly moisture free, the equilibrium moisture content is considered to be zero (M_e=0). So the initial moisture content can be calculated from following relation:

$$M_i = \frac{W_i - W_e}{W_e} \quad (2)$$

Where W is the sample weight and i and e indices represent initial and equilibrium (final) conditions.

The mean moisture content at any time ($\overline{M}$), during drying period can be calculated from Eq. (2) by replacing W_i with sample weight at each instant (W). Finally moisture ratio (MR) is defined as following relation:

$$MR = \frac{\overline{M} - M_e}{M_i - M_e} \quad (3)$$

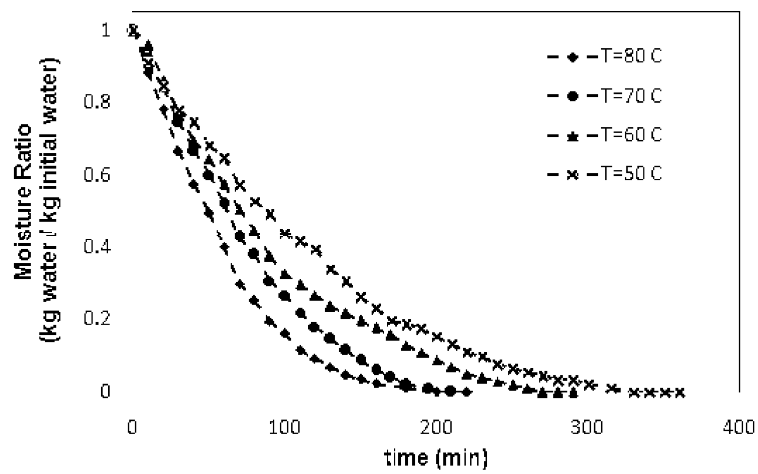

Fig. 3 : Moisture ratio vs time for 0.5 cm thickness potato samples at various chamber temperatures

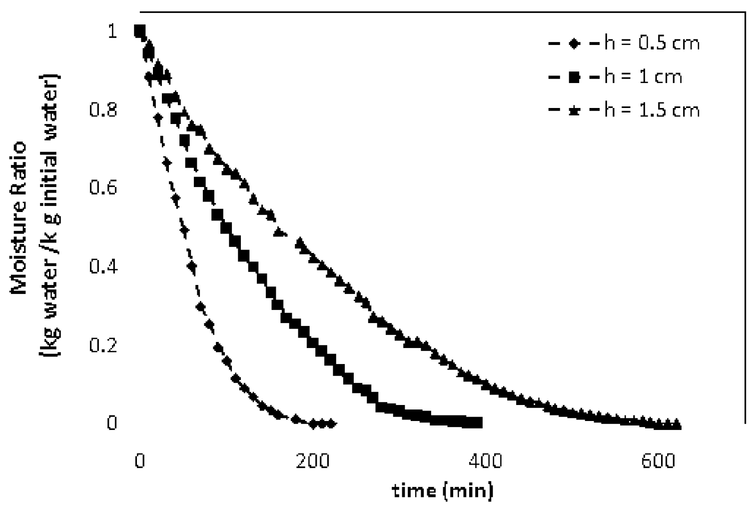

Fig. 4: Moisture ratio vs. time at chamber temperature of 80°C for different sample thicknesses

Figure 3 demonstrates the variation of moisture ratio (MR) versus drying time for potato slabs with 0.5 cm thickness at different operating temperatures. As can be anticipated this parameter is reducing during drying process at all temperatures investigated in this study but at higher temperatures (e.g. 80°C) this reduction is quicker and the sample will reach to equilibrium moisture earlier. This can be attributed to high rate of evaporation from the surface of the sample at higher temperatures which leads to higher mass transfer rate in the solid.

Effect of Slab Thickness on Drying Kinetics: In order to show the effect of sample thickness, some runs have been performed in constant temperature (80°C) and with different slab thicknesses. These results were shown in Figure 4 for three different thicknesses. As can be seen, the thinner sample (0.5 m) has been dried more rapidly. The moisture exists in the thinner sample should travel shorter distance toward the surface to evaporate. Therefore, less time is needed for it to be dried (about 200 min for 0.5 cm thickness compare to 400 min for 1 cm thickness and 600 min for 1.5 cm thickness).

Calculation of Effective Diffusivity: Drying process of food materials mostly occurs in the falling rate period and moisture transfer during drying is controlled by internal diffusion. Fick's second law of diffusion, as shown in Eq. (1), has been widely used to describe the drying process during the falling rate period for most biological materials. D_{eff} is effective moisture diffusivity and is usually determined from experimental drying curves. The major assumption in determining the effective moisture diffusivity experimentally is that the process of drying is mass transfer controlled and the temperature remains

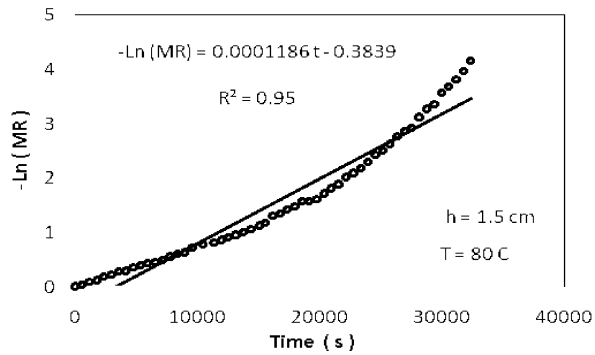

Fig. 5: Natural logarithm of moisture ratio vs time

Table 1: Effective diffusivity calculated at different temperatures and slab thicknesses using Fick's diffusion model

Temperature (°C)	Thickness (cm)	D_{eff} (m^2s^{-1})
50	0.5	5.41×10^{-10}
60	0.5	6.58×10^{-10}
70	0.5	9.60×10^{-10}
80	0.5	1.06×10^{-9}
80	1	2.36×10^{-9}
80	1.5	3.07×10^{-9}

isothermal throughout the whole sample during the entire course of drying [21]. Assuming a uniform initial moisture distribution, one dimensional diffusion, constant effective diffusivity through the thickness of slab, negligible external resistance, negligible temperature gradients and negligible shrinkage during drying results the following equation for calculating mean moisture content in the solid slab in each time instant.

$$MR = \frac{\overline{M} - M_e}{M_i - M_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-\frac{(2n+1)^2\pi^2}{h^2}D_{eff}t\right] \quad (4)$$

Where MR is the moisture ratio, dimensionless; M_i, the initial moisture content (kg water/ kg dry matter); M_e, the equilibrium moisture content (kg water/ kg dry matter); D_{eff}, the effective moisture diffusivity, (m^2s^{-1}); h is the thickness of the slab (m), n is the positive integer n = 0, 1, 2, 3, … and t, the drying time (s). The drying air is assumed to be nearly dry, so the final moisture content of the dehydrated potato which is the equilibrium moisture content (M_e) is assumed to be zero. Because of long drying period and for the sake of simplicity, only the first term of the above equation is considered and the mean moisture content can be calculated from Eq. (5).

$$MR = \frac{\overline{M} - M_e}{M_i - M_e} = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff}}{h^2}t\right) \quad (5)$$

From this simplified equation it is concluded that there is a linear relationship between the natural logarithm of moisture ratio and time. So, when the experimental values of (*-ln MR*) are plotted against time, the slope of the curves is a measure of effective diffusivity. It should be noted that in this manner effective diffusivity is reduced to an empirical parameter that fits experimental data. The calculated D_{eff} is substituted in Eq. (4) to predict moisture ratio by the diffusion model. The typical graph for 80°C temperature and 1.5 cm thickness and also the corresponding linear equation fitted to these experimental data were shown in Figure 5.

In all the conditions investigated in this study, D_{eff} were calculated and presented in Table 1. As can be anticipated, results postulated that D_{eff} increases when the temperature in the drying chamber rises. Also, it is clear that, when the sample thickness gets larger, the effective diffusivity tends to be higher. This type of variations has been confirmed earlier by several authors for potato and other fruit samples [12, 14, 22, 23]. In addition, the values of D_{eff} calculated in this study are slightly smaller than those reported by other investigators at similar conditions. This may be due to potato skin resistance to moisture transfer from the sides of the slab.

The D_{eff} value for 1.5 cm slab was nearly three times greater than that for 0.5 cm slab and two times greater than that for 1 cm slab at 80°C. This was not surprising, because the applied diffusion model assumes that diffusion takes place from only one direction; from inside to the surface of the slabs. This assumption is valid for thin slabs, in which the edge effect (side way diffusion) is negligible. In thick slabs, in spite of the presence of skin resistance, some side diffusion might occur. Taking this effect into account, the removal of moisture in thick slabs

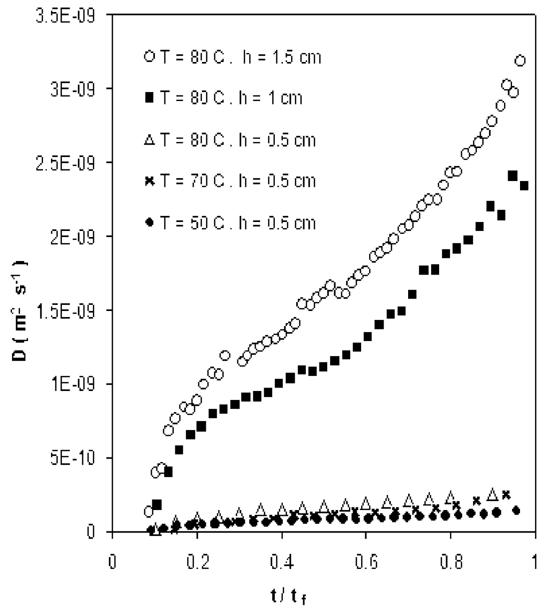

Fig. 6: Variation of D_{exp} as a function of dimensionless time (t/t_f).

might be enhanced. In addition, when the sample is dried at a high temperature, due to quicker initial rate of evaporation of moisture from the surface, the surface hardening effect occurs faster in thick slabs than thinner ones [14]. This hardening effect slows down the drying rate in the thin slabs. This effect could be helpful to explain why the diffusion coefficient in 0.5 cm slab was smaller than in 1 and 1.5 cm slabs. Therefore, edge effects might enhance the removal of moisture from thick slabs. Case hardening effect might hinder the transfer of moisture in thin slabs after drying some hours. Both these reasons would explain why the value of D_{eff} of thick slab was higher than that of thin slabs [14].

At each time instant, moisture diffusivity can be calculated by substituting experimental moisture ratio (MR) and the corresponding drying instant (t) in Eq. (5). This parameter is considered as point experimental diffusivity (D_{exp}) which indicates the diffusion rate at each time. For better comparison, Figure 6 represents the variation of the point diffusivity during drying time for all the experiments performed in this study. Due to different total drying periods for various sample thicknesses and drying temperatures, the abscissa is considered as dimensionless time (drying time instant / total drying period). As demonstrated in Figure 6, for all the samples D_{exp} is not constant and increases with time. It is also obvious that when the temperature varies for the samples of 0.5 cm thickness, no distinguishable variations occur in D_{exp}. It may be due to the weak dependency of D_{exp} on the temperature of drying chamber. On the other hand, varying the slab thickness at constant temperature (80°C) can displace the curve dramatically. It is clear that for the large sample thickness, more time is needed to rise the temperature of the sample to its final value while for the small sample thickness, less time is needed to heat up the sample and therefore, the temperature difference between the sample and dryer eliminates faster.

It can be concluded that the average temperature of the slab increases during drying time and as a result diffusivity which depends on temperature increases too. This fact leads to develop a new model for predicting diffusivity in each time instant of drying.

Development of New Model: As demonstrated in the previous section, D_{exp} is strongly related to temperature. The temperature dependency of the moisture diffusivity is described with an Arrhenius type equation:

$$D = D_o \exp\left(-\frac{E_a}{RT}\right) \quad (6)$$

Where E_a is activation energy (kJ/mol).

In the conventional models, values of $-Ln(D_{exp})$ at different temperatures are plotted versus $(1/T)$ for each slab thickness and consequently the parameters of Arrhenius type equation (D_o and E_a) are calculated with the best linear equation fitted to the experimental data. This type of modeling has been performed several times for different samples and operating conditions [8, 15, 16, 24-27]. In the above modeling T refers to the temperature of the drying chamber and not to the temperature of the sample itself. There is no reason to have the same temperatures in the sample and drying chamber in convective hot air drying at all the drying period. Specially, at the first stages of drying, the temperature of the sample rises gradually to reach its final value. This transient stage may be very short or long depending on the initial sample temperature and heating rate (°C s^{-1}) which in turn depends on the characteristics of the sample. The heating rate (a) is calculated as follow:

$$a = \frac{\textit{final temperature} - \textit{initial temperature}}{\textit{total drying time}} \quad (7)$$

Therefore, the existence of a steady temperature during whole drying period is not a valid assumption and the variation of T in Arrhenius equation should be considered. In this investigation, for the sake of

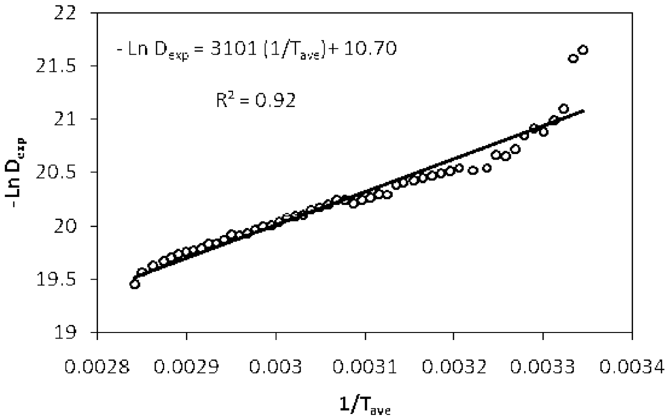

Fig. 7: Using Arrhenius equation to calculate activation energy

simplicity, a linear relationship has been assumed for temperature variation with time. As Levenspiel stated: "always start by trying the simplest model and then only add complexity to the extent needed." He renamed it the $ 10 approach which should we favor this approach rather than $ 100 complex exact approach [28]. Using appropriate initial and final conditions, the values of the constants in the linear function have been calculated and the Eq. (8) obtained:

$$T_{ave} = T_i + at \tag{8}$$

In this equation T_i represents initial temperature equals to 20°C for all the experiments. Although the temperature variation with time has been considered as explained above, temperature distribution in the solid (variation of temperature vs. position in the sample) has been ignored and the sample was assumed to be a lumped heat transfer system (small values of Biot no.) So, the temperature at a given time is considered to be uniform all over the sample thickness. Although this is not an accurate assumption, it may be true for the small thickness samples. Therefore, the average temperature of the sample in each time instant can be calculated from Eq. (8).

Now, if the values of $-ln\ (D_{exp})$ for a given thickness is plotted vs. $(1/T_{ave})$, a straight line can be fitted to the experimental data. This plot was shown in Figure 7 for the slab of 1.5 cm thickness. From the slope of this line, activation energy is derived. The values of E_a for various thicknesses and temperatures are represented in Table 2.

Having E_a and D_0 and substituting average temperature in each time instant in the Arrhenius equation, the new model for calculating moisture diffusivity as a function of drying time is developed as follow:

Table 2: The values of E_a and D_o in Arrhenius equation for all the experiments performed

Temperature (°C)	Thickness (cm)	E_a (kJ/mole)	D_o (m^2s^{-1})
50	0.5	28.9	6.81×10^{-5}
60	0.5	28.3	4.10×10^{-5}
70	0.5	31.5	7.38×10^{-5}
80	0.5	37.3	6.14×10^{-4}
80	1	33.2	1.22×10^{-4}
80	1.5	47.2	2.97×10^{-2}

$$D = D_o \exp\left(-\frac{E_a}{R\times(T_i + at)}\right) \tag{9}$$

Calculated D for corresponding drying time is substituted in Eq. (4) to predict moisture ratio. Figure 8 has compared the predictions of new model and diffusion model with experimental data of moisture ratio vs. time for the case of 1.5 cm thickness and 80°C. As shown in Figure 8, the prediction of diffusion model demonstrates large deviation from experimental results while the new model travels between data with a good accuracy. Prediction of diffusion model has been improved as the drying time approaches its final value. At this stage, the temperature reaches to a steady value, hence, the constant diffusivity assumption is valid and the prediction of diffusion model shows good agreement with the experimental data as well. It can be concluded that in convective drying, considering temperature variation of sample during the drying time has strong influences on the prediction of diffusion model.

The precision of the new model and the conventional Fick's model is quantitatively compared by calculating absolute average error according to Eq (10).

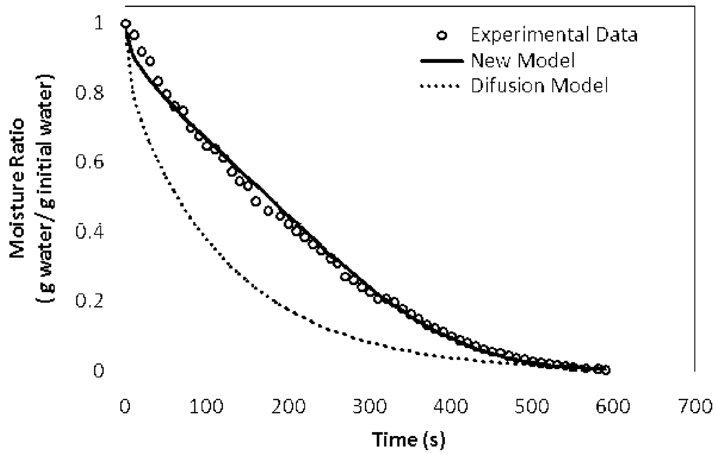

Fig. 8: Comparison of the predictions of diffusion model and new model with experimental moisture ratio data

Table 3: Absolute average errors of the models explained in this study for the calculation of moisture ratio

		% Absolute average error	
Temperature (°C)	Thickness (m)	Diffusion model	New model
50	0.5	44.15	13.16
60	0.5	45.52	13.45
70	0.5	54.59	9.97
80	0.5	45.55	20.93
80	1	54.90	8.09
80	1.5	53.89	11.02

$$\%AAE = \sum \frac{\left| MR_p - MR_{\text{exp}} \right|}{MR_{\text{exp}}} \times 100 \quad (10)$$

Where MR_p and MR_{exp} correspond to the predicted and experimental moisture ratio, respectively.

Table 3 represents quantitatively the prediction errors of the diffusion model and new model for all the experimental runs performed in this investigation. As can be seen in Table 3, diffusion model has showed larger absolute average error of about %50 for the calculation of moisture ratio in comparison to the new model which has produced the error of about %10.

CONCLUSION

Experimental drying of potato slabs in different thicknesses and various operating temperatures has been performed in this investigation in a convective air drying system under a constant air velocity. Results demonstrate that increasing slab thickness and drying temperature can enhance effective moisture diffusivity. In this article, Fick's diffusion model which considers constant diffusivity during drying period was shown to predict the moisture ratio (MR) well smaller than its experimental values with absolute average error of about %50. In convective air drying, a significant time is needed for sample to reach its final temperature. Therefore, the constant moisture diffusivity during drying time seems not to be valid. It is the main reason why the diffusion model can not predict the convective drying kinetics as well as the isothermal drying system. In this article, a simple modification has been done to consider this temperature history in the diffusion model. Experimental results are in good agreement with the prediction of new model with absolute average error of about %10.

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NOMENCLATURE

a	sample heating rate	[°C/s]
D	diffusivity	[m^2/s]
E_a	activation energy	[kJ/mole]
h	slab thickness	[m]
M	moisture content	[g water/ g dry matter]
MR	moisture ratio	[dimensionless]
n	counter (=0, 1, 2, …)	[dimensionless]
R	gas constant=8.31×10^{-3}	[kJ/mol.K]
T	temperature	[K]
t	time	[s or min]
W	weight of sample	[g]

Subscripts	
ave.	average
e	equilibrium
eff.	Effective
exp	Experimental
i	initial
p	predicted model

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