Drying Characteristics of Dried Banana (M*usa sapientum*)

E. A. Amankwah, K. A. Dzisi, E. Agyabeng Fofie, P. Marmah, A. J. B. van Boxtel

***Abstract*—Drying characteristics of banana slices were determined for 4, 6 and 8mm thickness in a conventional oven dryer at temperatures between 50-70 °C. Six empirical models were used for fitting the experimental drying curve. The influence of banana thickness and temperature on the moisture diffusivity and drying rate were investigated. Temperature strongly affected moisture diffusivity and drying rate. Drying rate increased with decreased thickness while moisture diffusivity dropped at higher banana slice thickness. The Lewis model fitted well the experimental data.**

***Index Terms*—Banana drying, moisture content, effective diffusivity, activation energy**

I. INTRODUCTION

Banana is mostly eaten fresh but drying of banana has not been fully exploited. Drying occurs by surface liquid evaporation and internal liquid vapor diffusion [1]. Drying prevents bacteria and molds growth, and by so doing, extending the shelf-life of a food product. Fresh banana fruits are highly perishable and bulky. According to [2] a ripe banana contains moisture of 74.8% (wb) and is therefore very susceptible to post-harvest losses [3]. In Ghana post-harvest losses are a major challenge to tropical fruits. It is therefore important to find innovative ways to preserve them, and in particular banana. The dimension of food in terms of thickness is an important factor since during drying moisture moves outwardly from the center. The smaller the thickness the higher the drying rate, however, the greater the effect of heat on the heat sensitive components of the food. Meanwhile, [4] has reported that slab thickness has little influence on diffusivity. Due to the high content of sugars in banana, the pore spaces on the surfaces are often blocked making it difficult to dry and thus reducing the drying rate. Some workers have reported of reduction in drying rate with decreased moisture content [4]-[5].

Two periods of falling rate have been reported [6]. A third period was found by [7] when sample moisture was dried below 0.2 kg/kg db. The first falling rate period deals with moisture near the banana surface. Continuous drying leads to case hardening of the surface while the internal area is still wet. Moisture then takes a longer time to reach the surface and thus reducing the drying rate rapidly. It was reported by [5] that effective moisture diffusivity of banana ranged between $8.5x10^{-11}$-$2.29x10^{-10}$ at 70-100 ºC. It showed clearly that temperature has a strong influence on the effective diffusivity however, he worked on banana thickness of 3mm with two diameters, 25 and 35mm. Taiwo [3] reported of effective diffusivity between $1.17x10^{-9}$ – $4.67x10^{-9}$ for 10, 20 and 30mm thickness of blanched field pumpkin slices at 60 and 70 ºC, while [8] also mentioned values of $1.7x10^{-10}$ - $1.15x10^{-9}$ for apricots at 40-70 ºC. It is therefore imperative to study the effect of banana thickness and temperature diffusivity and drying rate on the drying behavior during drying. Drying kinetics is used in explaining the drying behavior of products. This is done mostly by fitting curves of moisture ratio to experimental data as a function of time [9]-[13]. This work seeks to investigate how varying the thickness between 3 and 10mm and temperature of banana during drying affects the drying characteristics, and determine the model equation that best describes the experimental drying data.

II. MATERIALS AND METHODS

A. Source and preparation of sample

Fresh mature bananas (*Musa sapientum*) were obtained from a local market at Ejisu in the Ashanti region of Ghana and kept at favorable conditions until they were ripened. Prior to drying, the bananas (*Musa sapientum*) were first cleaned (washed with clean water) peeled and cut into thickness of 4, 6 and 8mm with stainless steel knife and dimension

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measured with digital caliper (01407A, Neiko, USA). An average diameter of 2.4cm was used for the experiment.

B. Experimental and drying procedure

The initial moisture content of the fresh ripe banana was found to be in the range of 2.41 and 2.49 kg/kg db. Approximately 100g each of banana samples for each selected thickness was weighed using a Pioneer OHAUS weighing balance (model: PA 2102, China, ±0.02g). The banana slices were placed on perforated (1x1mm) sieve trays and dried at 50 °C, 60 °C and 70 °C in Beveiliging conventional oven dryer (model: DMV 1250, Holland). The weights of the drying bananas were determined every 30 minutes for the first two hours after which further weights were taken after one hour interval till the end of drying. The initial moisture content (kg/kg db) was determined by increasing the temperature to 105 °C after drying was completed for 12 hours.

C. Process and Parameter Modeling

Drying is often driven by diffusion. In general Fickian diffusion equation is given by (1):

$$\frac{dM}{dt} = D_e \frac{d^2M}{dx^2} \tag{1}$$

$$M(t=0) = M_0;\ M(t \geq 0), \frac{dM(x=0)}{dx}$$

$$= 0;\ x = L, M\ (t \geq 0) = M_e$$

The solution results in a series of terms which can be reduced to (2) according to [14]:

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2}{L^2} D_e t\right) \tag{2}$$

A commonly applied model for the drying kinetics [15] is:

$$\frac{dM}{dt} = -k(M - M_e);\quad M(t=0) = M_0 \tag{3}$$

The solution yields:

$$\frac{M - M_e}{M_0 - M_e} = \exp(-kt) \tag{4}$$

Equating (2) and (4) the following is obtained:

$$k = \frac{\pi^2}{L^2} D_e - \ln\left(\frac{8}{\pi^2}\right) \tag{5}$$

Where *M*, M_e, *k* are the moisture content, EMC and drying rate constant respectively. D_e and *L* are the effective diffusivity and characteristic length of banana slices.

Equation (5) indicates the relationship between the drying rate constant and effective diffusion coefficient and the characteristic length. Meanwhile, $8/\pi^2$ can be equated to 1 with no significant effect on the value of rate constant. Moisture removal from food product depends on the nature of bonds between water molecules as well as structure and composition of the food [16]. Jin et al. [17] stated that the effective diffusivity in food products depends on how moisture is distributed in the food matrix and how moisture interacts with that matrix. As a consequence, the effective diffusion coefficient varies with moisture content and thus, the drying rate constant varies over time.

By ignoring shrinkage, a general equation mostly used by researchers for calculating effective diffusivity can be derived from linearizing the exponential function (2) and (4):

$$[1]\quad \ln MR = \ln\frac{8}{\pi^2} - \frac{\pi^2}{L^2} Dt \qquad [2] \tag{6}$$

The slope is directly equated to k while D_e can be calculated from eq. (6).

D. Selection of model

To determine the mathematical models that indicate the goodness of fit, two indices were considered, which include correlation coefficient (R^2) and mean square error (*MSE*). The *MSE* values should assume the lowest while R^2 is the highest [18]. These parameters are estimated as follows:

$$R^2 = 1 - \frac{SS_{res}}{SS_{tot}} \tag{7}$$

Where SS_{res}, the sum of squares of residuals is:

$$SS_{res} = \sum_{i=1}^{N}\left(M_{exp,i} - M_{pre,i}\right)^2 \tag{8}$$

And SS_{tot}, the total sum of squares is:

$$SS_{tot} = \sum_{i=1}^{N}\left(M_{exp,i} - \bar{M}_{exp,i}\right)^2 \tag{9}$$

The MSE is given as:

$$MSE = \frac{1}{N} SS_{res} \tag{10}$$

Where, M_{exp} is the experimental data set (moisture content), M_{pre} is the predicted data set, N is the number of observations and $\bar{M}$ is the mean of experimental data set.

$$\bar{M} = \frac{1}{N}\sum_{i=1}^{N} M$$

E. Activation Energy

The dependency of the rate constant on the drying temperature employing the Arrhenius equation is given as:

$$k = k_o\, exp\left[-\frac{Ea}{R(T+273)}\right] \tag{11}$$

Where k, k_o are the rate constant and the preexponential factor respectively. Ea (kJ/mol K) is the activation energy which is considered constant, R the universal gas constant and T is the temperature (K). The effective diffusivity can be expressed as shown in (12). From the slope of (12), Ea is calculated.

$$lnD = lnD_o - \left[\frac{Ea}{R(T+273)}\right] \tag{12}$$

III. RESULTS AND DISCUSSIONS

A. Moisture loss curves

Water loss was rapid between 5-7 hours after which a slower rate was observed. It could be noticed that the smaller the thickness the earlier equilibrium was reached. This is as a result of the distance water had to travel before reaching the surface. This observation is contrary to the report of [4] who mentioned that thickness has little effect on diffusivity. Thuwapanichayanam [5] also found out that change in diameter of banana slices did not affect the rate of moisture loss. However they emphasized that moisture takes place in the direction of the thickness. Temperature had a strong influence on the time of drying. Figs. 1 and 2 show the drying curves and drying rates in time at varying thickness for different temperatures.

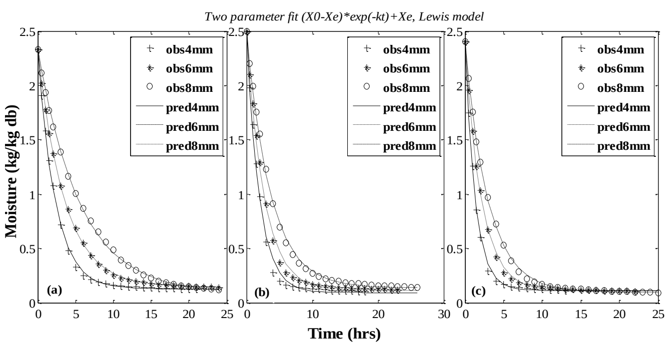

Fig. 1: Fitted curve with the Lewis model for Moisture (kg/kg db.) against time (hours) at 50ºC (a); 60ºC (b); and 70ºC (c)

In Fig. 2 it is observed that the rate of drying in time is higher at lower thicknesses than larger ones. The general observation is that, drying took place in the falling rate region and by diffusion as cited by [6]. Meanwhile, temperature had a strong effect on the rate of drying as shown in Fig. 2 (a), (b) and (c). These results agreed with drying of banana by [20] and apple pomace by [21] . The rate of drying was higher at the beginning of drying [19] due to higher amount of free water. As the drying proceeds, the free water present decreased rapidly slowing down the rate.

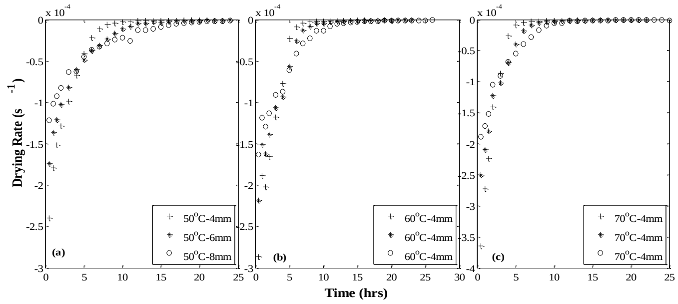

Fig. 2 Drying rate against time at 50ºC (a); 60ºC (b); and 70ºC (c)

In selecting the model that gave the goodness of fit, the consistency of *k* and its relationship with other parameters as well as the lowest MSE and highest R^2 were taken into consideration. The drying parameters, *MSE* and R^2 for various thicknesses at varying temperatures for various models are presented in Table I (a-b). However, Lewis model was selected over the Henderson and Pabis model as the best of good fit since it had the least number of parameters and the fact that, it had coefficient; a=1.01. Thus the Henderson and Pabis model collapsed into the Lewis model.

Table Ia Parameters at different temperatures and thicknesses, mean square error (MSE) and coefficient of determination (R^2) for various models

		k	k1	k2	a	b	n	Me	MSe	R^2
Lewis										
50 °C	4mm	$1.21*10^{-4}$						0.1266	$3.40*10^{-4}$	0.9991
	6mm	$7.94*10^{-5}$						0.1439	$9.04*10^{-5}$	0.9998
	8mm	$4.99*10^{-5}$						0.0858	$3.38*10^{-4}$	0.9993
60 °C	4mm	$1.42*10^{-4}$						0.0934	$2.30*10^{-3}$	0.9954
	6mm	$1.05*10^{-4}$						0.1136	$1.70*10^{-3}$	0.9964
	8mm	$7.60*10^{-5}$						0.1369	$7.29*10^{-4}$	0.9985
70 °C	4mm	$2.06*10^{-4}$						0.1126	$1.24*10^{-4}$	0.9997
	6mm	$1.31*10^{-4}$						0.1112	$8.22*10^{-5}$	0.9998
	8mm	$9.28*10^{-5}$						0.0956	$2.34*10^{-5}$	0.9999
Henderson and Pabis										
50 °C	4mm	$1.23*10^{-4}$			1.0096			0.1277	$3.10*10^{-4}$	0.9992
	6mm	$7.87*10^{-5}$			0.9938			0.1426	$7.64*10^{-5}$	0.9998
	8mm	$4.85*10^{-5}$			0.9844			0.0772	$2.17*10^{-4}$	0.9995
60 °C	4mm	$1.46*10^{-4}$			1.0250			0.0960	$2.00*10^{-3}$	0.9959
	6mm	$1.09*10^{-4}$			1.0262			0.1169	$1.50*10^{-3}$	0.9969
	8mm	$7.80*10^{-5}$			1.0200			0.1407	$5.67*10^{-4}$	0.9988
70 °C	4mm	$2.10*10^{-4}$			1.0155			0.1140	$7.24*10^{-4}$	0.9984
	6mm	$1.33*10^{-4}$			1.0129			0.1133	$3.24*10^{-4}$	0.9992
	8mm	$9.36*10^{-5}$			1.0060			0.0965	$2.03*10^{-4}$	0.9995
Two term exponential										
50 °C	4mm	0.0206			0.0058			0.1279	$4.08*10^{-4}$	0.9990
	6mm	0.0059			0.0131			0.1423	$6.40*10^{-5}$	0.9998
	8mm	0.0018			0.0265			0.0710	$1.40*10^{-4}$	0.9997
60 °C	4mm	0.0329			0.0042			0.0959	$2.40*10^{-3}$	0.9951
	6mm	0.0332			0.0030			0.1159	$2.10*10^{-3}$	0.9957
	8mm	0.0197			0.0038			0.136	$7.95*10^{-4}$	0.9984
70 °C	4mm	0.0003			1.6295			0.1260	$1.21*10^{-4}$	0.9997
	6mm	0.0288			0.0045			0.1135	$4.47*10^{-4}$	0.9989
	8mm	0.0142			0.0065			0.0957	$2.52*10^{-4}$	0.9994

Table Ib Parameters at different temperatures and thicknesses, mean square error (MSE) and coefficient of determination (R^2) for various models

		k	k^1	k^2	a	b	n	Me	MSe	R^2
Verma (Diffusion)										
50 °C	4mm		$1.21*10^{-4}$	$1.21*10^{-4}$	0.3847			0.1266	$3.40*10^{-4}$	0.9991
	6mm		$7.92*10^{-5}$	$1.03*10^{-5}$	1.0043			0.1486	$9.02*10^{-5}$	0.9998
	8mm		$4.67*10^{-4}$	$3.98*10^{-4}$	0.9519			0.0659	$1.15*10^{-4}$	0.9998
60 °C	4mm		$1.42*10^{-4}$	$1.42*10^{-4}$	0.1759			0.0934	$2.30*10^{-3}$	0.9954
	6mm		$7.14*10^{-5}$	$7.14*10^{-5}$	1.0262			0.1550	$1.10*10^{-3}$	0.9977
	8mm		$7.60*10^{-5}$	$7.60*10^{-5}$	0.4353			0.1367	$7.00*10^{-4}$	0.9985
70 °C	4mm		$2.06*10^{-4}$	$2.06*10^{-4}$	0.0919			0.1126	$8.23*10^{-4}$	0.9982
	6mm		$1.31*10^{-4}$	$1.31*10^{-4}$	0.3616			0.1120	$3.77*10^{-4}$	0.9991
	8mm		$9.29*10^{-5}$	$9.28*10^{-5}$	0.0378			0.0965	$2.16*10^{-4}$	0.9995
Two Term										
50 °C	4mm		$1.23*10^{-4}$	$1.23*10^{-4}$	0.5048	0.5048		0.1277	$3.10*10^{-4}$	0.9992
	6mm		$7.87*10^{-5}$	$7.87*10^{-5}$	0.4969	0.4969		0.1426	$7.64*10^{-5}$	0.9998
	8mm		$4.67*10^{-5}$	$4.03*10^{-4}$	0.9600	0.0406		0.0659	$1.15*10^{-4}$	0.9998
60 °C	4mm		$1.46*10^{-4}$	$1.46*10^{-4}$	0.5125	0.5125		0.0960	$2.00*10^{-3}$	0.9959
	6mm		$1.09*10^{-4}$	$1.09*10^{-4}$	0.5131	0.5131		0.1169	$1.50*10^{-3}$	0.9969
	8mm		$7.80*10^{-4}$	$7.80*10^{-4}$	0.5100	0.5100		0.1407	$6.00*10^{-4}$	0.9988
70 °C	4mm		$2.10*10^{-4}$	$2.10*10^{-4}$	0.5078	0.5078		0.1140	$7.25*10^{-4}$	0.9984
	6mm		$1.33*10^{-4}$	$1.33*10^{-4}$	0.5065	0.5065		0.1133	$3.24*10^{-4}$	0.9992
	8mm		$9.36*10^{-5}$	$9.36*10^{-5}$	0.5030	0.5030		0.0965	$2.03*10^{-4}$	0.9995
Page										
50 °C	4mm	$6.98*10^{-5}$					1.0621	0.1342	$1.51*10^{-4}$	0.9996
	6mm	$8.94*10^{-5}$					0.9871	0.1400	$8.00*10^{-5}$	0.9998
	8mm	$8.21*10^{-5}$					0.9469	0.0500	$1.54*10^{-4}$	0.9997
60 °C	4mm	$2.87*10^{-5}$					1.1822	0.1134	$6.38*10^{-4}$	0.9987
	6mm	$2.64*10^{-5}$					1.1524	0.1331	$4.93*10^{-4}$	0.9990
	8mm	$3.17*10^{-5}$					1.0935	0.1551	$1.85*10^{-4}$	0.9996
70 °C	4mm	$7.01*10^{-5}$					1.1278	0.1262	$1.41*10^{-4}$	0.9997
	6mm	$7.04*10^{-5}$					1.0697	0.1198	$1.44*10^{-4}$	0.9996
	8mm	$7.05*10^{-5}$					1.0301	0.1000	$1.60*10^{-4}$	0.9996

The effective diffusivity (D_e) increased with increased temperature and thickness except at 50°C, where the internal resistance of the banana slices could not be overcome for the 8 mm thickness (Table 2). Hassini [4] reported of an almost linear relationship between effective diffusivity and initial slab thickness. However, from Fig. 4 it could be observed that near linearity is only obvious at higher temperatures. This is because at lower temperature the balance between internal forces and the driving force must be taken into account. Hence at low temperatures, thickness of sample to be dried must advisedly be chosen. On the other hand increase in thickness caused a reduction in k. Meanwhile, though generally increase in temperature led to higher driving force for heat transfer [22]-[23], for thickness beyond 6mm, temperature could not positively affect the drying rate (Fig. 3). From Table II it could be observed that effect on D_e by temperature was relatively higher as reported by [4]. Saeed [24] mentioned that drying air temperature was found to be the main factor influenced by drying kinetics. Similar behavior was reported by several authors [25]-[28]. Activation energy ranged between 23.31-28.67 kJ/mol K with 6mm thick recording the least activation energy (see Table III). This fell within the range of 11-110 kJ/mol K for food products.

Table II Effective diffusivity at various temperatures and thicknesses

Thick	50 °C	60 °C De (m2/s)	70 °C
4mm	$2.76*10^{-11}$	$3.24*10^{-11}$	$4.70*10^{-11}$
6mm	$3.20*10^{-11}$	$4.25*10^{-11}$	$5.31*10^{-11}$
8mm	$2.91*10^{-11}$	$4.43*10^{-11}$	$5.41*10^{-11}$

Table III Ea and D_eo at various thicknesses

Thick	Ea (kJ/mol)
4mm	24.39
6mm	23.31
8mm	28.67

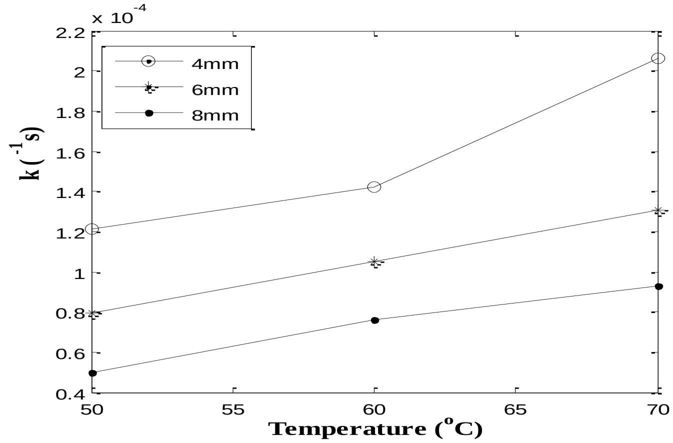

Fig. 3 Rate constant at different temperatures and thicknesses

B. Drying rate against moisture

In Fig. 5, it is apparent that drying rate decreases continuously with decreased moisture content. Below moisture content of 0.2 kg/kg db, though [4] reported of <0.5 kg/kg db, drying rate was the same for all slices. This behavior shows that the drying generally took place in the falling rate region and with three periods as reported by [7]. The rate of drying was higher at higher temperatures and lower banana slice thicknesses.

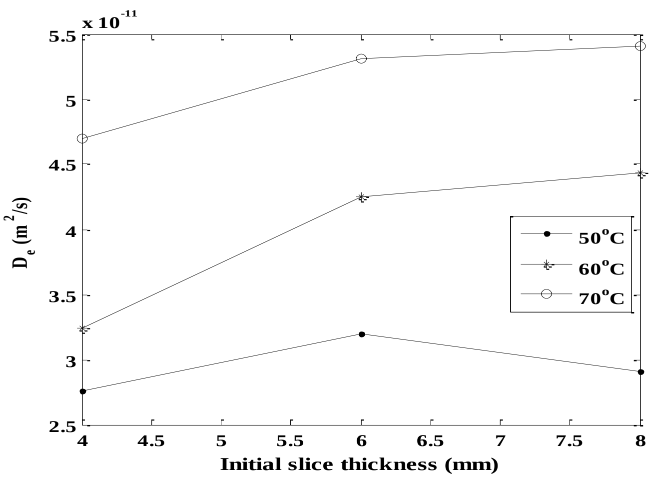

Fig. 4 Effective diffusivity as a function of initial slice thickness

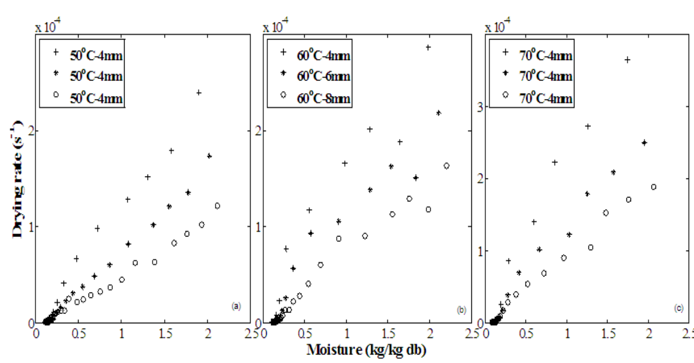

Figure 5: Drying rate against moisture at 50ºC (a); 60ºC (b); and 70ºC (c)

For banana slice drying, the critical moisture content found in this study was close to that reported by several workers who studied the drying of osmotic or non-osmotic bananas [6], [29], although the operating conditions in their studies were different from the present investigation. Abano [30] reported a strong influence of thickness on the drying rate. Meanwhile further investigation should be conducted to ascertain the influence of temperature and variable thickness on the heat sensitive food nutrient such as vitamin c.

IV. CONCLUSION

In conclusion, increasing air temperature significantly reduced the drying time of the banana slices for all thicknesses. The smaller the thickness the faster the moisture removal rate. Diffusion was found to be the main driving force influencing the drying. The entire drying process occurred in the falling rate period. While temperature had a great influence on effective diffusivity, that of slice thickness was relatively lower. Effective diffusivity fell within range as cited in this work. Rate of drying decreased with decreased moisture content and below 0.2 kg/kg (db) no significant difference existed between drying rates at different slice thicknesses for all temperatures. Activation energy ranged between 23-28.7 kJ/mol K. The Lewis model was selected as having the goodness of fit for describing the experimental drying data.

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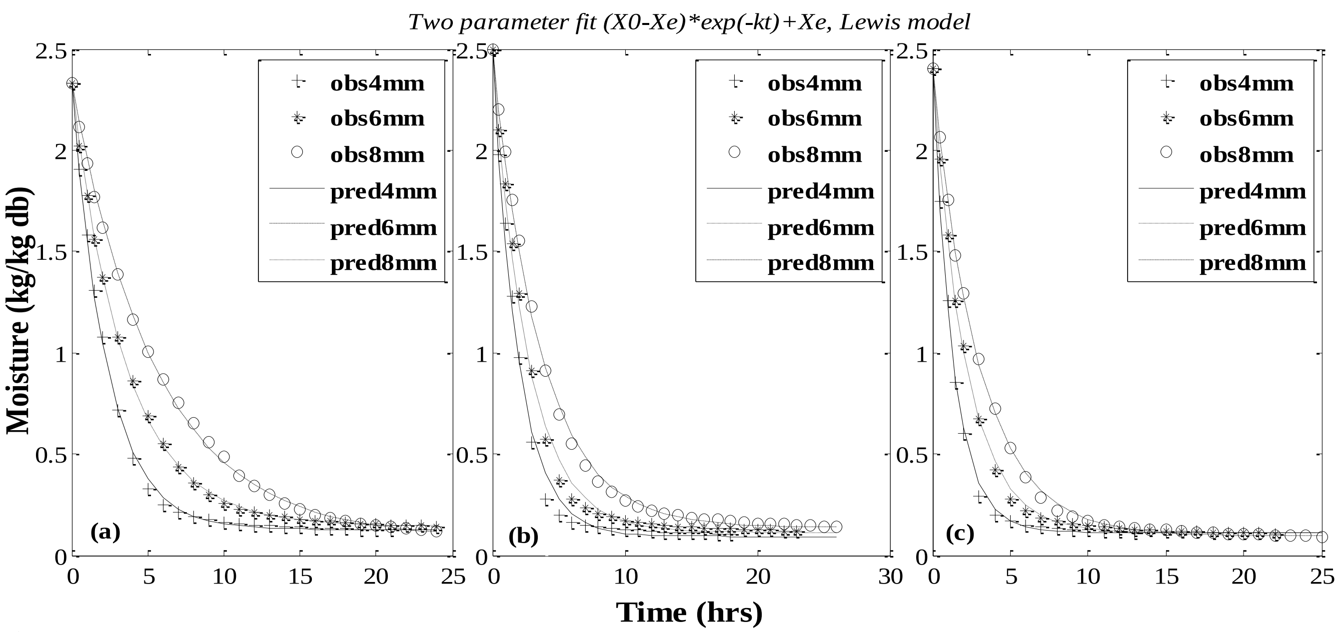

Fig. 1

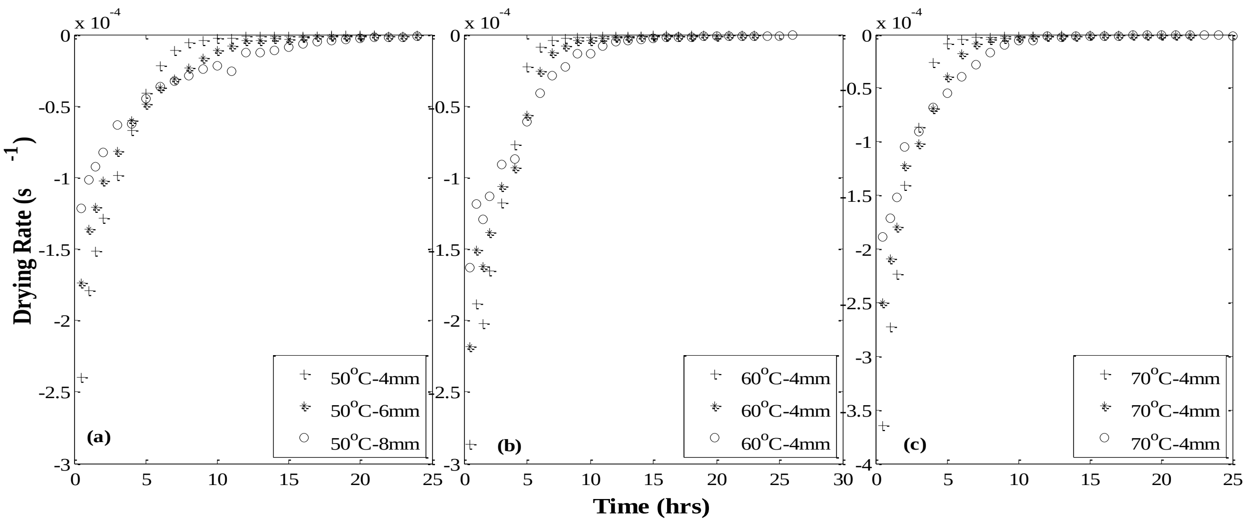

Fig. 2

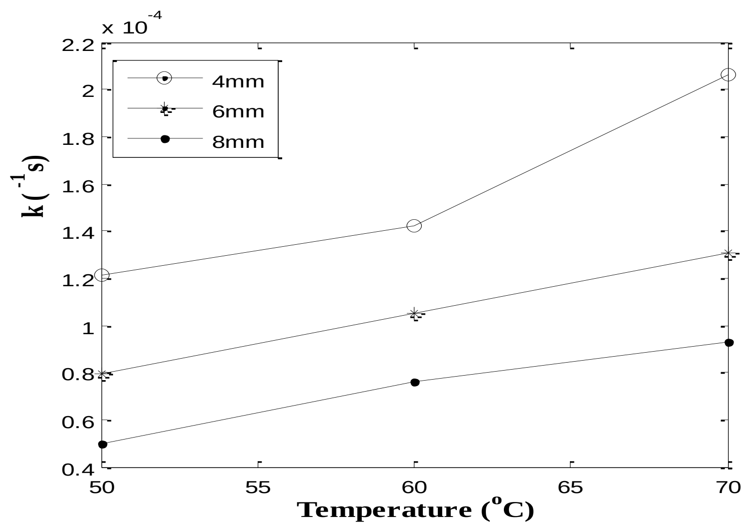

Fig. 3 Rate constant at different temperatures and thicknesses

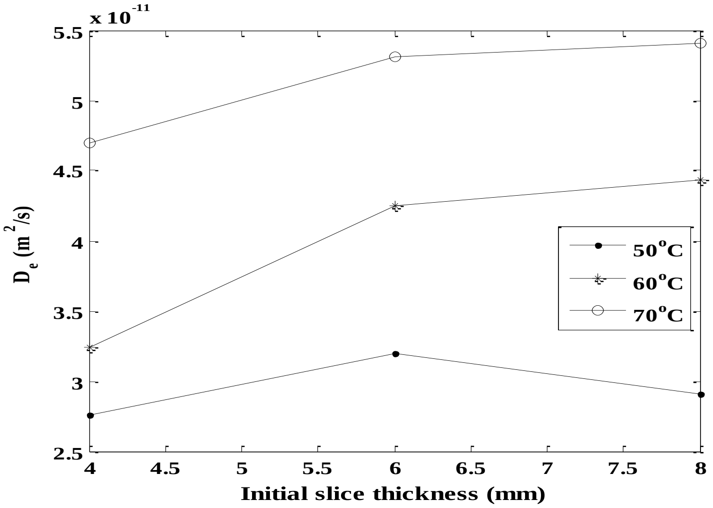

Fig. 4 Effective diffusivity as a function of initial slice thickness

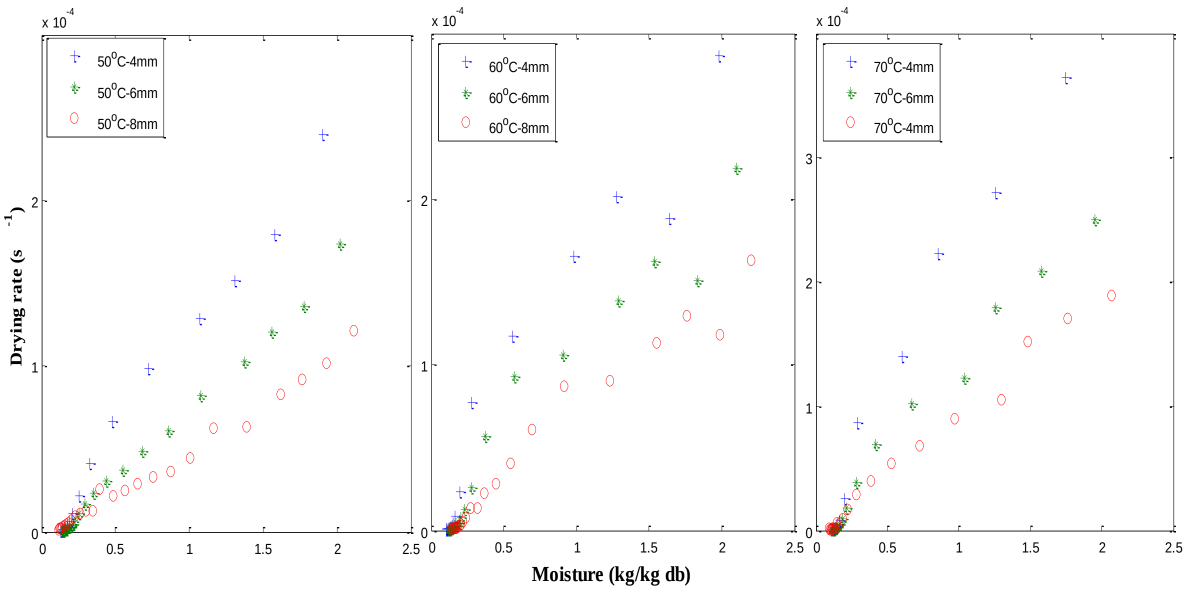

Figure 5: Oven drying at (a) 50oC, (b) 60oC and (c) 70oC respectively with drying rate (s-1) against moisture (kg/kg db.)

Table Ia Parameters at different temperatures and thicknesses, mean square error (MSE) and coefficient of determination (R^2) for various models

		k	k^1	k^2	a	b	n	Me	MSe	R^2
Lewis										
50 ºC	4mm	$1.21*10^{-4}$						0.1266	$3.40*10^{-4}$	0.9991
	6mm	$7.94*10^{-5}$						0.1439	$9.04*10^{-5}$	0.9998
	8mm	$4.99*10^{-5}$						0.0858	$3.38*10^{-4}$	0.9993
60 ºC	4mm	$1.42*10^{-4}$						0.0934	$2.30*10^{-3}$	0.9954
	6mm	$1.05*10^{-4}$						0.1136	$1.70*10^{-3}$	0.9964
	8mm	$7.60*10^{-5}$						0.1369	$7.29*10^{-4}$	0.9985
70 ºC	4mm	$2.06*10^{-4}$						0.1126	$1.24*10^{-4}$	0.9997
	6mm	$1.31*10^{-4}$						0.1112	$8.22*10^{-5}$	0.9998
	8mm	$9.28*10^{-5}$						0.0956	$2.34*10^{-5}$	0.9999
Henderson and Pabis										
50 ºC	4mm	$1.23*10^{-4}$			1.0096			0.1277	$3.10*10^{-4}$	0.9992
	6mm	$7.87*10^{-5}$			0.9938			0.1426	$7.64*10^{-5}$	0.9998
	8mm	$4.85*10^{-5}$			0.9844			0.0772	$2.17*10^{-4}$	0.9995
60 ºC	4mm	$1.46*10^{-4}$			1.0250			0.0960	$2.00*10^{-3}$	0.9959
	6mm	$1.09*10^{-4}$			1.0262			0.1169	$1.50*10^{-3}$	0.9969
	8mm	$7.80*10^{-5}$			1.0200			0.1407	$5.67*10^{-4}$	0.9988
70 ºC	4mm	$2.10*10^{-4}$			1.0155			0.1140	$7.24*10^{-4}$	0.9984
	6mm	$1.33*10^{-4}$			1.0129			0.1133	$3.24*10^{-4}$	0.9992
	8mm	$9.36*10^{-5}$			1.0060			0.0965	$2.03*10^{-4}$	0.9995
Two term exponential										
50 ºC	4mm	0.0206			0.0058			0.1279	$4.08*10^{-4}$	0.9990
	6mm	0.0059			0.0131			0.1423	$6.40*10^{-5}$	0.9998
	8mm	0.0018			0.0265			0.0710	$1.40*10^{-4}$	0.9997
60 ºC	4mm	0.0329			0.0042			0.0959	$2.40*10^{-3}$	0.9951
	6mm	0.0332			0.0030			0.1159	$2.10*10^{-3}$	0.9957
	8mm	0.0197			0.0038			0.136	$7.95*10^{-4}$	0.9984
70 ºC	4mm	0.0003			1.6295			0.1260	$1.21*10^{-4}$	0.9997
	6mm	0.0288			0.0045			0.1135	$4.47*10^{-4}$	0.9989
	8mm	0.0142			0.0065			0.0957	$2.52*10^{-4}$	0.9994

Table Ib Parameters at different temperatures and thicknesses, mean square error (MSE) and coefficient of determination (R^2) for various models

		k	k^1	k^2	a	b	n	Me	MSe	R^2
					Verma (Diffusion)					
50 ºC	4mm		$1.21*10^{-4}$	$1.21*10^{-4}$	0.3847			0.1266	$3.40*10^{-4}$	0.9991
	6mm		$7.92*10^{-5}$	$1.03*10^{-5}$	1.0043			0.1486	$9.02*10^{-5}$	0.9998
	8mm		$4.67*10^{-4}$	$3.98*10^{-4}$	0.9519			0.0659	$1.15*10^{-4}$	0.9998
60 ºC	4mm		$1.42*10^{-4}$	$1.42*10^{-4}$	0.1759			0.0934	$2.30*10^{-3}$	0.9954
	6mm		$7.14*10^{-5}$	$7.14*10^{-5}$	1.0262			0.1550	$1.10*10^{-3}$	0.9977
	8mm		$7.60*10^{-5}$	$7.60*10^{-5}$	0.4353			0.1367	$7.00*10^{-4}$	0.9985
70 ºC	4mm		$2.06*10^{-4}$	$2.06*10^{-4}$	0.0919			0.1126	$8.23*10^{-4}$	0.9982
	6mm		$1.31*10^{-4}$	$1.31*10^{-4}$	0.3616			0.1120	$3.77*10^{-4}$	0.9991
	8mm		$9.29*10^{-5}$	$9.28*10^{-5}$	0.0378			0.0965	$2.16*10^{-4}$	0.9995
					Two Term					
50 ºC	4mm		$1.23*10^{-4}$	$1.23*10^{-4}$	0.5048	0.5048		0.1277	$3.10*10^{-4}$	0.9992
	6mm		$7.87*10^{-5}$	$7.87*10^{-5}$	0.4969	0.4969		0.1426	$7.64*10^{-5}$	0.9998
	8mm		$4.67*10^{-5}$	$4.03*10^{-4}$	0.9600	0.0406		0.0659	$1.15*10^{-4}$	0.9998
60 ºC	4mm		$1.46*10^{-4}$	$1.46*10^{-4}$	0.5125	0.5125		0.0960	$2.00*10^{-3}$	0.9959
	6mm		$1.09*10^{-4}$	$1.09*10^{-4}$	0.5131	0.5131		0.1169	$1.50*10^{-3}$	0.9969
	8mm		$7.80*10^{-4}$	$7.80*10^{-4}$	0.5100	0.5100		0.1407	$6.00*10^{-4}$	0.9988
70 ºC	4mm		$2.10*10^{-4}$	$2.10*10^{-4}$	0.5078	0.5078		0.1140	$7.25*10^{-4}$	0.9984
	6mm		$1.33*10^{-4}$	$1.33*10^{-4}$	0.5065	0.5065		0.1133	$3.24*10^{-4}$	0.9992
	8mm		$9.36*10^{-5}$	$9.36*10^{-5}$	0.5030	0.5030		0.0965	$2.03*10^{-4}$	0.9995
					Page					
50 ºC	4mm	$6.98*10^{-5}$					1.0621	0.1342	$1.51*10^{-4}$	0.9996
	6mm	$8.94*10^{-5}$					0.9871	0.1400	$8.00*10^{-5}$	0.9998
	8mm	$8.21*10^{-5}$					0.9469	0.0500	$1.54*10^{-4}$	0.9997
60 ºC	4mm	$2.87*10^{-5}$					1.1822	0.1134	$6.38*10^{-4}$	0.9987
	6mm	$2.64*10^{-5}$					1.1524	0.1331	$4.93*10^{-4}$	0.9990
	8mm	$3.17*10^{-5}$					1.0935	0.1551	$1.85*10^{-4}$	0.9996
70 ºC	4mm	$7.01*10^{-5}$					1.1278	0.1262	$1.41*10^{-4}$	0.9997
	6mm	$7.04*10^{-5}$					1.0697	0.1198	$1.44*10^{-4}$	0.9996
	8mm	$7.05*10^{-5}$					1.0301	0.1000	$1.60*10^{-4}$	0.9996

Table II Effective diffusivity at various temperatures and thicknesses

Thick	50 ºC	60 ºC	70 ºC
		De (m2/s)	
4mm	$2.76*10^{-11}$	$3.24*10^{-11}$	$4.70*10^{-11}$
6mm	$3.20*10^{-11}$	$4.25*10^{-11}$	$5.31*10^{-11}$
8mm	$2.91*10^{-11}$	$4.43*10^{-11}$	$5.41*10^{-11}$

Table III Ea and D_eo at various thicknesses

Thick	Ea (kJ/mol)
4mm	24.39
6mm	23.31
8mm	28.67