Forced Convection Hot Air Drying Of Hardened Egg Slices

Mecha Peter, Nyaanga Daudi M.,Njue Musa R.

Abstract: The aim of the study was to test and select thin layer drying models for egg drying under forced convection. To achieve it, an experimental forced convection was used to provide airflow rate of $0.15m^3/s$ with temperature ranging from 35-45 ^oC to dry a 0.03m thick layer of hardened eggs. The eggs were dried and retrieved every 20 minutes to determine the moisture content and moisture ratio respectively. The resulting experimental moisture ratios were fitted to Newton, Page, Modified page, Henderson and pabis, Logarithmic, Simplified Fick's diffusion Equation modified page equation11, Demir *et.al*, and Aghbashlo *et.al*. Among the nine models, the Page model best described the forced convection hot air drying of hardened egg slices. It was also observed that an increase in air temperature significantly reduced the drying time with falling rate period. The average values of effective diffusivities of hardened egg in the drying process at 35–45 ^oC varied in the range of 3.10×10^{-07} to 6.38×10^{-07} m^2/s with increase in temperature. An Arrhenius relation with an activation energy value of 58.729kJ/mol for the whole drying process of eggs was found. This showed the effect of varying temperature on moisture diffusivity in eggs increased with temperature.

Index Terms: Activation energy,Diffusivity,Forced convection, Hardened eggs, Models, Thin layer drying, Shelf life.

1.0 INTRODUCTION

Eggs normally gain a lot of demand because it is one of the most versatile and near perfect foods in nature. It is rich in protein, amino acids, vitamins and most mineral substances. The yolk and white components are all of high biological value and are readily digestible. They are known to supply the best proteins besides milk [1]. It is also one of the most consumed foods worldwide and an important commodity in international trade [2]. Chicken egg, whole and hard-boiled, for instance contains 12.6 g/100g protein, 10.6 g/100 g fat, 1.12 g/ 100 g carbohydrate and 647KJ/100 g energy [3]. All these good properties of eggs make it to have high demand by people more so those under malnutrition. It thus calls for a need to come up with new techniques of processing the eggs in a cheaper and easily affordable manner by the poultry farmer especially simple and cheaper methods of drying. Dried egg products like egg white powder is a highly stable product with a shelf life of over two years, almost fat free, and can be efficiently functionalized by heat treatment into high foam or high gel powders [4]. The boiling of egg before drying them and grinding them to get powder is likely to offer a solution to reduce on the post-harvest losses of the product especially in the case of spray drying and ohmic drying.It can also reduce time and energy costs that are the case in freeze and foam-mat drying. Egg powders are widely used in food processing including emulsification, adding colour, tenderness and flavour.

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These powders are preferred due to their microbiological safety and reduced volumes [4]. Eggs products especially powder are found in foods like mayonnaise, bakery products and custards among others. The existing methods for dried egg production include: Spray drying; ohmic heating; freeze and foam-mat drying that is energy and time intensive; and direct solar drying which does not allow easy control of the drying parameters. The usage of spray-dried egg yolk in commercial food processing is rather limited [5]. In addition, majority of these methods are rarely available to small-scale poultry farmers and if available, then they are expensive for them. To compete with other functional ingredients, eggs powder products are often specifically designed for customers' formulations, a technique greatly enhanced by the ingredient's diverse technical possibilities [4]. This therefore, indicates that the demand for egg powder is increasing as the population of people rises in the world. Consequently, there is need to improvise more techniques and scientific knowledge that can lead to solving these challenges. One of the ways to dry the hardened eggs is through forced convection. This is a type of heat transfer where fluids are forced to move in order to increase the heat and mass transfer from one point to another. This forcing is achieved through using a fan, a pump, suction device among other devices especially flow rate controllers. It has the advantage of fastening drying rate and enabling control of the drying process through regulation of temperature and the airflow rate. From these benefits, it can be successively be used in studying the drying process of egg thus leading to the best conditions for drying of the eggs. Thin layer drying models for describing the drying phenomenon of agricultural products are usually based on liquid diffusion theory, and the process can be explained by the Fick's second law **[6]**. The process of drying which includes a thin layer of sample particles is called thin-layer drying **[7]**. Thin layer drying equations are important tools in mathematical modelling of food drying. They are practical and give sufficiently good results **[8]**. According to **[9]**, thin layer drying models mainly fall into three categories: empirical, semi-empirical and theoretical. They have used in drying most of agricultural and animal products [6, 10-12]. Most of the researches done on the aforementioned method have little information on the thin layer model that can describe the drying process of hardened eggs under forced convection drying. This leads to lack of a set of mathematical equations that can satisfactorily explain the system thus posing more challenges in the calculation of the process parameters that is a function of time at any point in the dryer. It is due to this that the present research seeks to investigate the best model for describing the drying process of hardened eggs by maintaining air flow rate and layer thickness and varying the drying air temperature.

2.0 MATERIALS AND METHODS

2.1 Development of drying system

An experimental dryer system shown in (Fig 2.1) was used in the experiment. It comprised of a centrifugal fan that was used to push the desired drying airflow rate to the system; electrical heaters that were used to heat the drying air at varying temperature in the drying chamber. The heated air was forced through the dryer using the centrifugal fan whose airflow was controlled by use of an airflow control valve. The drying chamber was used to dry the various slice thickness of hardened eggs at the varying drying temperatures and airflow rates. The area of the chamber was 0.0025m^2 while the various pulley sizes were 11 cm diameter (smaller), 13 cm diameter (medium) and 15 cm diameter (larger). The air-drying temperature was controlled using proportional, integral and derivative control (PID) sensors while airflow was controlled by using different pulley sizes and then directed to the drying chamber that had a constant drying area. The relative humidity of the drying air was measured using hygrometer PCE-555 type.

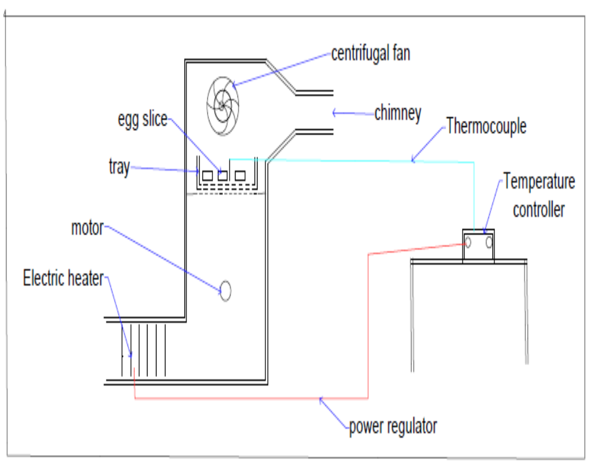

Fig 2. 1 *Forced convection drying system*

2.2 Sample preparation

Two-day old grade1 (an egg without any blood spot, oval shaped and not shrunken) hen eggs were purchased from the Egerton University Tatton Farm. They were then candled to confirm their freshness. Cleaning was then done by washing and then dipped in water for boiling them for 17 min at a water boiling temperature for hardening them. They were then removed and their average weight measured using digital weighing balance (Model: Precisa310M). Thereafter, they were dishelled and their average weight determined again. Then, using a sharp knife, they were sliced into a 0.01m thickness.

2.3 Drying procedure

The slices were then arranged into three layers and then subjected to constant drying flow rate of 0.15m^3/s at varying temperature of 35 to 45^{o}C. They were retrieved after every 20 minutes to determine their moisture content using equation (1) and then converted to dry basis using equation (2). Moisture ratio was determined using equation (3).

$$M_{wb} = \frac{W_w - W_d}{W_t} * 100 \quad (1)$$

$$M_{db} = \frac{M_{wb}}{1 - M_{wb}} \quad (2)$$

$$MR = \frac{M - M_e}{M_0 - M_e} \quad (3)$$

2.4 Thin layer modelling of the hardened sliced eggs

The results obtained from experimental MR as calculated in equation 3 were fitted to the nine thin layer models (Table 2.1).

Table 2. 1 *Mathematical models widely used to describe the drying kinetics*

S/No	Model name	Model equation	Reference
1)	Newton	$MR = \exp(-kt)$	**[13]**
2)	Page	$MR = \exp(-kt^n)$	**[14]**, **[15]**,**[16]**.
3)	Modified Page	$MR = \exp-(kt)^n$	**[13]**
4)	Henderson and Pabis	$MR = a\exp(-kt)$	[17].
5)	Logarithmic	$MR = a\exp(-kt) + c$	**[18]**, **[19]**, **[13]**.
6)	Simplified Fick's Diffusion Equation	$MR = a\exp-k\left(\frac{t}{L^2}\right)$	**[20]**. **[21]**
7)	Modified page equuation11	$MR = \exp\left[-k\left(\frac{t}{L^2}\right)^n\right]$	[14, 21, 22]
8)	Demir *et.al*	$MR = a\exp(-kt)^n + c$	[10, 14, 15, 21, 22]
9)	Aghbashlo *et.al*	$MR = \exp\left[\frac{-k_1 t}{1+k_2 t}\right]$	[10, 14, 18, 21, 22]

* a, b, c and n are drying coefficients, t is drying time (hours) k, k_0 and k_1 are drying constants and L is the layer thickness

The following statistical indicators were used to select the most appropriate drying models as reported in the literature include R^2, x^2, RMSE whose equations are indicated in 4,5 and 6. The higher the values of R^2 of a particular model the better the model is in predicting the drying behaviour of particular product. Similarly, the lower the values of x^2 and RMSE of a particular model the more suitable the model is in predicting the drying kinetics of the particular product [17].

$$R^2 = \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pre,i}\right)\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)}{\sqrt{\left[\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pre,i}\right)\right]^2\left[\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)\right]^2}} \quad (4)$$

$$RMSE = \left[\frac{1}{z}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)^2\right]^{1/2} \quad (5)$$

$$x^2 = \frac{\sum_{i=1}^{n}\left(MR_{\exp,i} - MR_{pre,i}\right)}{N - z} \quad (6)$$

Where, N and z represent the number of observations and constants respectively, while $MR_{\exp,\ i}$ are the experimental moisture ratio and $MR_{pre,\ i}$ the predicted moisture ratio).

Modelling and calculation of the constants was carried out using the Microsoft Excel spreadsheet (Microsoft Office 2010, USA).

2.5 Effective diffusivity and Activation energy

The hardened egg slices took the form of slab and the Fick's second law of diffusion for slab object became appropriate. Accordingly, equations (7) and 8 were used to determine the diffusivity and the activation energy. They were derived from the Arrhenius type equation [23]:

$$MR = \left(\frac{8}{\pi^2}\right)\exp\left(\frac{\pi^2 D_{eff}\, t}{4L^2}\right) \tag{7}$$

This is linearized as,

$$\ln MR = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}\, t}{4L^2}\right) \tag{8}$$

Then in plotting, a graph of *ln*MR versus time (t) gives the slope that is used to determine the diffusivity of the hardened egg during drying as expressed below

$$D_{eff} = \left(\frac{4L^2 Xslope}{\pi^2}\right) \tag{9}$$

From the equation (9), the activation energy was determined as shown in the equation 10:

$$D_{eff} = D_0 \exp\left(\frac{-E_a}{RT}\right) \tag{10}$$

Equation (10) was linearized to equation (11)

$$\ln D_{eff} = \ln D_0 - \left(\frac{E_a}{R}\right)\left(\frac{1}{T}\right) \tag{11}$$

The activation energy is

$$E_a = Rxslope \tag{12}$$

3.0 RESULTS AND DISCUSSION

3.1 Drying kinetics of egg slices

The drying kinetics of the egg slices dried under a forced convection system is shown in Fig 3.1. The initial moisture content of the egg before drying was 227% (d.b.). As expected, the drying temperature had a significant effect on the drying kinetics of the hardened eggs at the constant airflow rate and layer thickness. The moisture content decreased continuously with time and an increase in temperature resulted in reduced drying time as can be observed from the Fig 3.1. For instance, to reduce the moisture content of the hardened egg from 227 % d.b to about 24 % d.b, the 35^{o}C, 40 ^{o}C and 45 ^{o}C temperature took 620, 480 and 360 minutes respectively. The reduction in moisture content at varying temperature over a given time was due to the residual heat inside the hardened egg slices that removed moisture from the intermolecular spaces within the egg and secondly, moisture gradient that existed between the intermolecular spaces and the air-product interface. This explains why drying rate was higher at the initial stage since there was high moisture content that created high moisture gradient. This resulted to more driving force to drive moisture from inside the product to the outer surface from where it transportation by the flowing air occurred. **[24]** reported similar observation in drying characteristics of red chilli where moisture diffusivity was higher at higher moisture content as compared to those at lower moisture content. The high temperature gradient at the interface of the drying egg slice caused more heat transfer to the intermolecular spaces energising the moisture molecules causing mass transfer to the surface hence high drying rate. This moisture was removed from the surface by the airflow leading to more drying of the product.

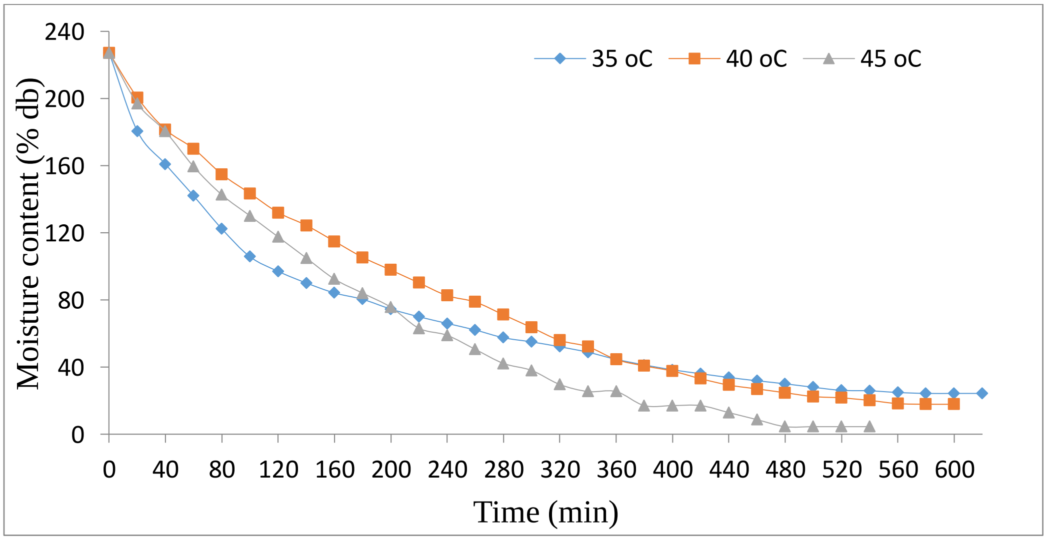

Fig 3.1 *Moisture content in percentage (d.b) change with time*

3.2 Modelling of dried egg slices

The experimental moisture ratio (MR) data observed in the hardened egg drying process under different conditions fitted to the nine commonly used thin-layer drying models (Table 2.1) and their results shown in Table 3.1. From the Table, the best model describing the thin layer-drying characteristic of hardened eggs was selected based on the one with the highest R^2 values, the lowest x^2 and RMSE values. In all cases, the R^2, x^2 and RMSE values ranged from 0.6141 to 0.9990, 0.0001 to 0.5429 and 0.0012 to 0.5708 (Table 3.1), respectively. The page model presented the highest R^2 values (0.9991), the lowest x^2 (0.0001) and the lowest RMSE (0.0012) values in all three drying temperatures

Table 3.1 *Model parameters and statistics for thin layer drying of egg slices at various temperatures*

Model No.	Model name	Temperature (^{o}C)	Coefficients and constants	R^2	χ^2	RMSE
1	Newton	35	k= 0.0036	0.9794	0.0159	0.1239
		40	k= 0.0045	0.9985	0.0003	0.0172
		45	k= 0.0074	0.9856	0.0038	0.0641
2	Page	35	k= 0.03154, n= 0.6716	**0.9991**	**0.0001**	**0.0012**
		40	k= 0.00644, n= 0.9351	0.9985	0.0004	0.0183
		45	k= 4.56E-03, n= 1.0578	0.9975	0.0005	0.0221
3	Modified Page	35	k= 0.00582, n= 0.6716	**0.9991**	**0.0001**	0.0116
		40	k= 0.00454, n= 0.9351	0.9985	0.0004	0.0183
		45	k= 6.13E-03, n= 1.0578	0.9975	0.0005	0.0221
4	Henderson and Pabis	35	a= 10.707867, k =0.0034	0.6141	0.0985	0.0638
		40	a= 1.0085, k =0.0045	0.9985	0.0003	0.0177
		45	a= 1.2687, k =0.0074	0.9856	0.0071	0.0809
5	Logarithmic	35	a= 0.1979, k= 0.0019, c= 0.6299	0.6311	0.2609	0.4855
		40	a= 0.16051, k= 0.003, c= 0.7748	0.6912	0.3377	0.5513
6	Simplified Fick's Diffusion Equation	35	a= 0.70787, k= 3E-06	0.9735	0.0045	0.0646
		40	a= 1.00874, k= 4.05E-06	0.9985	0.0003	0.0178
		45	a= 1.2687, k= 7.0 E-06	0.9794	0.0071	0.0813
7	Modified Page equation*11*	35	k= 5.24E-06,n= 0.6716	0.6705	0.5429	0.7127
		40	k= 9.44E-08,n= 1.2993	0.9913	0.0026	0.0495
		45	k= 7.40 E-09,n= 1.3477	0.9937	0.0018	0.0407
8	Aghbashlo et al.	35	k1= 7.14E-3, k2= 1.42E-3	0.9963	0.0009	0.0295
		40	k1= 0.00398, k2= -0.000279	0.9990	0.0004	0.0182
		45	k1= 0.00459, k2= -0.00082	0.9990	0.0005	0.0209
9	Demir et al.	35	a= 0.16094, c= 0.83906,k= 2.46E-3, n= 0.8091	0.6928	0.4897	0.6531
		40	a= 0.1704, c= 0.7748,k= 0.00292, n= 1.1024	0.6951	0.3565	0.5559
		45	a= 0.18862, c= 0.7476, k= 0.00886, n= 1.0331	0.6021	0.3502	0.5462

3.3 Simulation of the drying process

In order to take into account the effect of drying temperature variation on drying rate, the constant and coefficients of the Page model, namely *k* and *n*. The experimental Moisture ratio values were substituted into the quadratic polynomial equation. The input variable was time (minutes) and the output was predicted Moisture ratio that was useful to determine the moisture content at a given time. The comparison between experimental moisture ratio at different temperature conditions and that predicted by the Page model at the same temperature conditions are shown in Fig 3.2. The predicted values are in good agreement with the experimental ones, indicating that the drying process of hardened egg slices is well predicted and described by the Page model. Therefore, the regression equations of these parameters against drying temperature, T (^{o}C), and the accepted Page model are as follows:

$$MR = \exp(-kt^n) \tag{13}$$

Where *k*=0.0315*;* *n*=0.6716

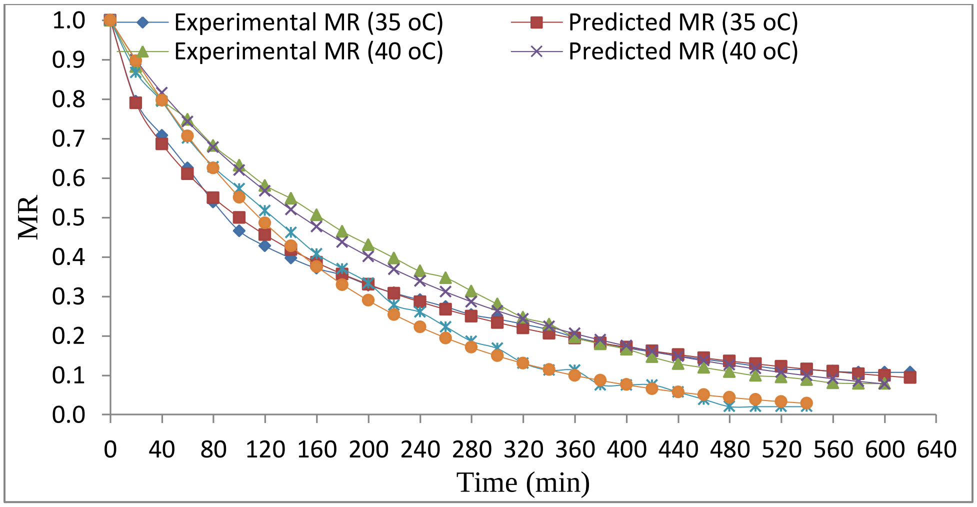

Fig 3.2 *Comparison of the page model predicted moisture ratio and experimental moisture ratio at 35, 40 and 45 °C*The consistency of the Page model and the drying temperature constants was evident with R^2= 0.9991, x^2 = 0.0001, RMSE= 0.0012. Thus, the moisture ratio of hardened egg at any time during thin layer forced convection drying process can be estimated more accurately by using these expressions.

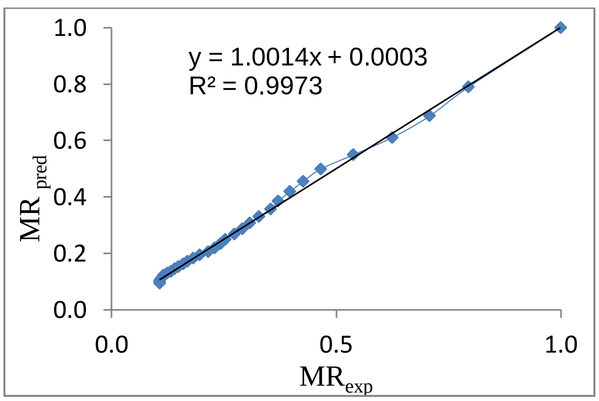

Fig 3.3 *Predicted moisture ratios against experimental moisture ratio at 35 °C*

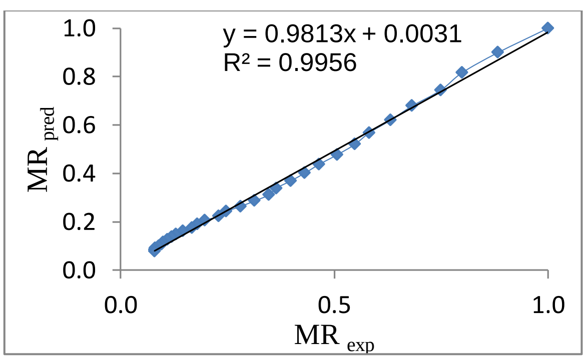

Fig 3.4 *Predicted moisture ratio against experimental moisture ratio at 40 °C*

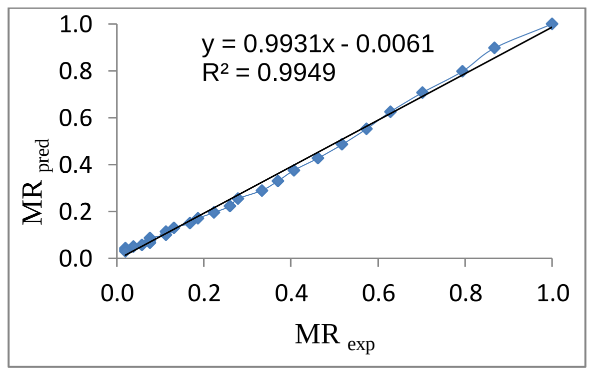

Fig 3.5 *Predicted moisture ratio against experimental moisture ratio at 45 °C*

Fig 3.3-5 shows the correlation between the experimental and predicted values of hardened egg drying process. In all the three Figs, there is a close banding at the final stages of drying and that it attracts linear relationship with R^2 > 0.99, demonstrating good agreement between the predicted and the experimental values of moisture ratio. Thus, the Page model accurately predicts the moisture ratio of hardened egg drying process during forced convection hot air drying. Comparison of the moisture ratios predicted by the Page model and the actual values for the hardened egg slices shows that there was no distinct difference between the predicted and the actual moisture ratio values for all the three drying temperature conditions.

3.4 Effective diffusivity

The values of effective diffusivity at different drying temperatures were obtained by using equations 8-13 appropriately. The average values of effective diffusivities of hardened egg in the drying process at 35–45 °C varied in the range of 3.10 x 10^{-07} to 6.38 x 10^{-07} m^2/s as shown in Table 4.31. From the table, the values of effective diffusivity increased with the increase in the drying temperature. These increase of effective diffusivity as the drying air temperature increase are in agreement with those of other food materials **[6, 11]**.

Table 3.5 *Diffusivity results of hardened egg drying at various drying temperatures*

Temperature (°C)	Slope	Effective Diffusivity (m^2/s)	R^2
35	0.0034	3.10E-07	0.9721
40	0.0045	4.10E-07	0.9954
45	0.0070	6.38E-07	0.9692

In this study, a single falling rate period was observed in each of the three-temperature variation (Fig 3.1), each corresponding to an approximately constant slope from which the different effective diffusion coefficients were determined. However, as previously mentioned, there the drying rate was high for the first 20 minutes and therefore the single falling phase started stabilising at 200 % (d.b) moisture content. This corresponded to 1.555, 1.777 and 1.817 g/g.min drying rate for 35, 40 and 45°C drying air temperature respectively. This is conquers with conclusions that the rate of diffusion is proportional to the sample temperature variation **[25]** and that the value of effective diffusivity increases as drying time goes on **[26]**.

3.5 Activation energy determination

The values of activation energy are calculated by Arrhenius-type equation **[6]**. In this relationship, the natural logarithm of effective diffusivity as a function of the reciprocal of absolute temperature was plotted in the Fig 3.7. The result shows a linear relationship derived from the Arrhenius-type equation. From the line slope the values of activation energy was found to be 58.729kJ/mol for the whole drying process of eggs. [27] found the activation energy (Ea) for the egg white protein to be 56.89kJ/mol. However, our value was slightly high than that of [27] because the hardened egg continued to dry thus affecting it surface shape and structure. This led to more energy for one to initiate the drying process in hardened egg than the liquid egg white protein. The activation energy determines the energy consumption by electrical motor and also the mechanical damages to product **[28]**. This may also be supported be fig. 3.6 from which it can be seen that egg white has high drying rate as compared to egg yolk. This may be due to high fat content in the egg yolk that hinders movement of moisture. In this study, a single falling rate period was observed in each of the three-temperature variation (Fig 3.1), each corresponding to an approximately constant slope from which the different effective diffusion coefficients were determined. However, as previously mentioned, there the drying rate was high for the first 20 minutes and therefore the single falling phase started stabilising at 200 % (d.b) moisture content. This corresponded to 1.555, 1.777 and 1.817 g/g.min drying rate for 35, 40 and 45°C drying air temperature respectively. This is conquers with conclusions that the rate of diffusion is proportional to the sample temperature variation **[25]** and that the value of effective diffusivity increases as drying time goes on **[26]**.

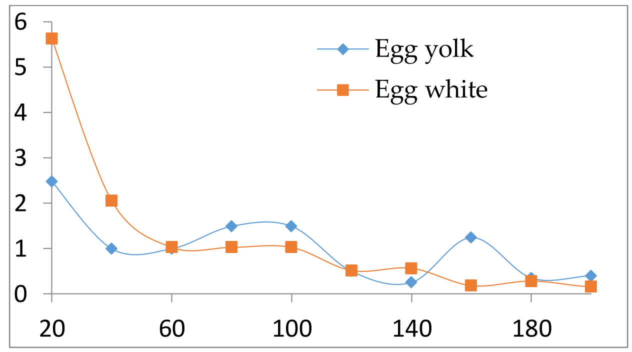

Fig 3.6 *Comparison of drying rate of egg white and yolk with time*

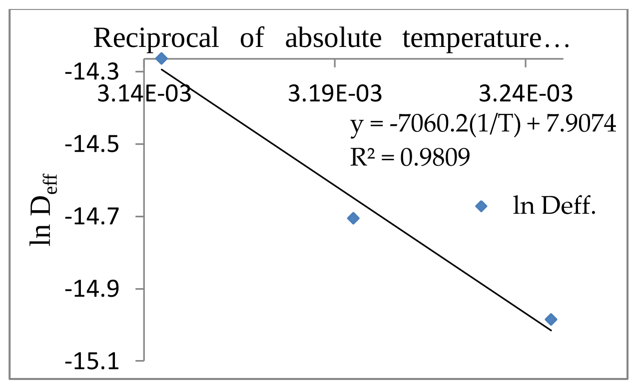

Fig 3.7: *Relationship between effective moisture diffusivity and absolute temperature*

The value of activation energy is relatively high for most agricultural crops as can be deduced from [6, 11, 13, 15, 18, 28, 29]. This is because the egg dries faster at the surface making the bound to use more heat to be evaporated due to its closer connection to the materials. It is evident that from Fig 3.7, the effective moisture diffusivities of hardened egg can be expressed as follows:

$$D_{eff} = 2748\exp\left(-\frac{7064}{T}\right)(R^2 = 0.98)$$

4.0 CONCLUSION

The Comparison of the coefficient of determination (R^2), root mean square error (RMSE) and reduced chi-square (x^2) for both experimental moisture ratio and prediction moisture ratio showed that the Page model best described thin layer drying of hardened eggs in forced convection drying. The Page model had the highest R^2 (0.9991) and lowest values of RMSE (0.0012) and x^2 (0.0001). This result therefore, confirms the supremacy of the page model over the other models. The average values of effective diffusivities of hardened egg in the drying process at 35–45 ^{o}C varied in the range of 3.10 x 10^{-07} to 6.38 x 10^{-07} m^2/s while the activation energy was 58.729kJ/mol. This research work will be helpful in designing a better-forced convection dryer for drying hardened eggs to retain their quality during storage and transportation in addition to increasing the shelf-life of eggs.

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