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Effective Moisture Diffusivity, Activation Energy and Specific Energy Consumption in the Thin-Layer Drying of Potato

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Abstract: **Thin-layer drying of sweet potato (*ipomoea batatas*) using hot-air convectional dryer was studied in order to determine the effective moisture diffusivity, activation energy and the specific energy consumption. The effects of variables such as slice thickness, temperature and air speed on the drying of sweet potato was studied. Increase in air speed and temperature increased the drying rate. The effective moisture diffusivity obtained ranged from 3.52 x 10^{-10} to 6.76 x 10^{-10} m^2/s for different air speed and temperature. The activation energy varied from 28.06 to 37.36 KJ/mol while the specific energy consumption ranged from 166.72 to 232.70 KWh/Kg. The data obtained in this study will be useful in designing industrial dryers.**

Keywords: **Drying, Potato, Effective Moisture Diffusivity, Activation Energy and Specific Energy Consumption.**

1. INTRODUCTION

Sweet potato (*Ipomoea batatas*) is a dicotyledonous plant that has large starchy roots. The young leaves and shoots are sometimes eaten as greens. It has great yield potential and high nutritive value. It is rich in carbohydrates, proteins, phosphorus, calcium etc. the ratio of protein to carbohydrate is higher in potato than in many cereals and other tuber crops (Marwaha et al, 1999). It is a very important food crop and constitutes nearly half of the world's annual output of all root and tuber crops (Shahzad et al, 2013). Raw foods have high amounts of moisture and thus perishable. Due to lack of suitable storage and transportation facilities, about 30% of fresh crop is wasted by respiration and microbial spoilage (Sharma et al, 2009).

The reduction of moisture in food products is one of the oldest techniques for food preservation (Amina et al, 2011). Most food crops contain more than 80% water at harvest and are therefore highly perishable if stored or left for long in that state. These can lead to unavailability of essential nutrients, vitamins and minerals which they supply to human diet in high proportion (Nwajinka et al, 2014). Hence, after harvesting, moisture content must be reduced to an acceptable level that inhibits microbiological activity. Drying greatly increases storage life, product diversity and leads to substantial volume reduction (Amiri et al, 2011). Drying has been proved to be the most common technique used to reduce micro-biological activity and to improve the stability of moist materials. This is done by reducing their moisture content to a certain value (Torki-Harchegani et al, 2015). Many applications of drying have been used to decrease physical, biochemical and microbiological deterioration of food products as the moisture content is reduced to a certain level that will allow safe storage for a long time. This will also lead to substantial reduction in weight and volume, minimize packaging, storage as well as transportation costs (Zielinska and Markowski, 2010).

Drying involves heat and mass transfer mechanism and hence an understanding of the engineering properties of the food crops will be useful in the design of dryers and optimization of the process conditions and that of energy recovery systems. They are important in quantitative evaluation of energy requirements and energy losses in drying systems (Mohsen, 2016). These engineering properties which are crop specific include the effective moisture diffusivity, activation energy and specific energy consumption. The knowledge of diffusion properties is very relevant to understand the behavior of food crops during drying (Hadami et al, 2004). The optimization of the drying operation leads to an improvement in the quality of the output product, a reduction in the cost of processing as well as the optimization of the throughput (Majid et al, 2011).

The purpose of this research work is dry potato slices using hot air convectional dryer and to investigate the effects of slice thickness, air speed and temperature on the moisture content reduction as well as determine the effective moisture diffusivity, activation energy and the specific energy consumption in drying potato.

2. MATERIALS AND METHODS

Preparation of samples

The potato tubers were sourced from Eke Awka market in Anambra State, Nigeria. The cocoyam tubers were washed, peeled, sliced to the appropriate thickness and then washed again to remove dirt.

Experimental procedure

The conventional hot-air dryer was designed and fabricated in Faculty of Engineering, Nnamdi Azikiwe Univeristy, Awka, Nigeria. One of its features is that the temperature and air velocity can be regulated. Three replicates of the experiments were conducted to reduce experimental error. 100g of the sample was used for each run of the experiments. The fan and heater were started and the drying temperature and air flow were allowed to run without load until stabilized condition was observed, when all the indicators are steady at a set value. Thereafter, the drying chamber was loaded with the samples for the experiments. The sample was weighed every fifteen minutes for the first one hour, then every thirty minutes for subsequent measurements. Drying was continued until the moisture content of the sample reached equilibrium with the drying air. This state was observed when two or three consecutive weighing showed no significant variation or change in value. The drying air temperatures, drying air velocity and sample weight were continuously measured and recorded during the drying experiments. The speed of the air was measured by a speed meter (hot wire anemometer, model 20004 AHYK), with the precision of 0.01m/s, while the temperature was measured by digital thermometer and the mass of the sample was obtained using a digital weighing balance.

There were three temperature levels (50^{o}C, 60^{o}C, 70 ^{o}C) and slice thickness (2.0, 4.0 and 6.0 mm) and four drying air speeds (2.0, 2.5, 3.0, 4.0 m/s) used in this work. The data were analyzed and used for determination of the drying parameters.

Determination of Moisture content

The moisture content determinations were conducted in duplicate by the oven method in accordance with AOAC (2000). This method was used for both cocoyam and potato in all the methods

$$MC_{db} = \frac{M_1 - M_2}{M_2}\, x\, 100 \qquad (1)$$

Where

MC_{db} is the moisture content of the sample in dry basis; M_1 is the initial mass before drying; M_2 is the mass after oven drying

For any weight of the sample at any time, the moisture content at that weight is determined using equation 2:

$$M_{t(db)} = M_{o(db)} - \left(\frac{100(W_o - W_t)}{(1 - M_{o(wb)})W_o}\right) \qquad (2)$$

Where,

$M_{t(db)}$ =Moisture content at any time in dry basis (%), $M_{o(db)}$ = initial moisture content in dry basis (%), $M_{o(wb)}$ = initial moisture content in wet basis (%), W_t = mass of sample at any time, g, W_o = initial mass of sample, g

After each drying experiment, the sample moisture content was determined and termed the final moisture content.

Determination of moisture ratio

In determining moisture ratio, it is assumed that the material layer is thin enough or the air velocity is high so that the conditions of the drying air (humidity and temperature) are kept constant throughout the material. Moisture ratio values can be calculated for the drying using the moisture contents at the initial time, equilibrium time and at that particular time:

$$MR = \frac{M_t - M_e}{M_i - M_e} \qquad (3)$$

where,

MR is the moisture ratio (dimensionless),

M_t is the moisture content at any given time (kg water/ kg solids),

M_e is equilibrium moisture content (kg water/kg solids) and

M_i is the initial moisture content.

The value of M_e is relatively small compared with M_t and M_o especially for food materials (Junling et al, 2008).

Therefore, M_e can be assumed to be zero, hence the MR can be simplified to equation below

$$MR = \frac{M_t}{M_o} \qquad (4)$$

Determination of drying rate (D_r)

Drying rate of the agricultural products can be calculated using the following equation (Akpinar et al., 2003);

$$D_r = \frac{M_{t+dt} - M_t}{dt} \qquad (5)$$

Where D_r is the drying rate (g/mins)

dt is the time interval

The drying rate was obtained by calculating the time to remove a given quantity of moisture from the food product. The drying rate normally decreases with an increase in the drying time and an increase with temperature.

Determination of effective moisture diffusivity

Drying of most food materials regularly take place in the falling rate period, which meant that the moisture transfer during drying was controlled by internal diffusion. The internal diffusion occurring during the falling rate period for most food materials is described by Fick's second law of diffusion (Nwajinka et al , 2014).

$$\frac{\partial M}{\partial t} = D\,\nabla^2 M \qquad (6)$$

Where, D= diffusivity.

The analytical solution of Fick's second law of diffusion for slab-shaped material is with the assumptions of moisture transfer by diffusion, negligible shrinkage, and constant diffusion coefficients and temperature.

Therefore, on the assumption that the initial moisture-concentration (M_i) is uniform, the average moisture-content, M(t), of the product, after a drying time t, can be given by an analytical solution of the form,

$$\frac{\bar{M}(t)-M_e}{M_I-M_e} = \frac{8}{\pi^2}\left(\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-\left(\frac{(2n+1)\pi}{2H}\right)^2 D_{eff}\,t\right]\right) \quad (7)$$

where: D_{eff} = the effective moisture diffusion (m^2/s),

t = the drying time (s),

H = half-thickness of the slab (m).

But if $\frac{\bar{M}(t)-M_e}{M_i-M_e}$ is defined as moisture ratio (MR), then the equation can be written as:

$$MR = \frac{8}{\pi^2}\left(\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-\left(\frac{(2n+1)\pi}{2H}\right)^2 D_{eff}\,t\right]\right) \quad (8)$$

Expansion of the first three terms (n = 0, 1 and 2) will produce equation 9:

$$MR = \frac{8}{\pi^2}\left\{exp\left[-\left(\frac{\pi}{2H}\right)^2 D_{eff}t\right] + \frac{1}{3^2}exp\left[\left(\frac{3\pi}{2H}\right)^2 D_{eff}t\right] + \frac{1}{5^2}exp\left[-\left(\frac{5\pi}{2H}\right)^2 D_{eff}t\right] + \cdots\right\} \quad (9)$$

This equation is derived on the assumption that D_{eff} and M_e are constants, but in reality D_{eff} varies with temperature and moisture-content, while M_e also varies with temperature. As supported by the observations of Sacilik (2007), it is noticeable that the first term of the series solution in Equation 9 will dominate the other terms.

Also, for long period of drying (t is sufficiently large), only the first-term in the series in the equation is significant (with D_{eff} $t/4H^2 > 0.02$, the error is less than 3 %) and hence,

$$MR = \frac{8}{\pi^2}\left\{exp\left[-\left(\frac{\pi}{2H}\right)^2 D_{eff}t\right]\right\} \quad (10)$$

Taking the natural logarithm of the equation gives

$$\ln MR = \ln\frac{8}{\pi^2} - \left(\frac{\pi}{2H}\right)^2 D_{eff}t \quad (11)$$

that is

$$\ln MR = \ln(0.81057) - 2.4674\left[\frac{D_{eff}t}{H^2}\right] \quad (12)$$

Hence, in the study, the effective moisture diffusivity D_{eff} will be determined by plotting the experimental data in terms of ln (MR) against drying time (t) and then using the slope in equation given

$$D_{eff} = \frac{-slope}{\left[\frac{2.4674}{H^2}\right]} \quad (13)$$

Activation energy of the drying process

The activation energy and rate of a reaction are related by the Arrhenius equation:

$$k = A\exp(-E_a/RT) \quad (14)$$

where *k* is the rate constant, *A* is a temperature-independent constant (often called the frequency factor), E_a is the activation energy, *R* is the universal gas constant, and *T* is the temperature.

Because the relationship of reaction rate to activation energy and temperature is exponential, a small change in temperature or activation energy causes a large change in the rate of the reaction.

In drying process the effective moisture diffusivity (D_{eff}) is analogous to the rate constant (k).

Temperature dependence of the effective moisture diffusivity can be presented by an Arrhenius relationship.

$$D_{eff} = D_o exp\left[-\frac{E_a}{RT}\right] \qquad (15)$$

where: D_o = the pre-exponential factor of the Arrhenius equation in m^2/s,

Ea = the activation energy in kJ/mol, R = the universal gas constant (8.314 kJ/mol K), T = the absolute air temperature (°K).

Linearizing the equation by taking the natural logarithm gives

$$\ln D_{eff} = \ln D_o - \frac{E_a}{R}.\frac{1}{T} \qquad (16)$$

The pre-exponential factor of the Arrhenius equation and the corresponding activation energy were determined by using the data of effective moisture diffusivities and absolute air temperatures to plot ln (D_{eff}) against 1/T (Nwajinka et al, 2014).

The Activation energy Ea is calculated using the slope of the line as follows

$$E_a = -(\text{slope x R}) \qquad (17)$$

Specific energy consumption (SEC)

Specific Energy Consumption is the energy required to eliminate 1 kg of water (moisture) from wet materials during heated-air drying. The total energy consumption, E_t was calculated using the relation

$$E_t = (A.V.\rho_a.C_a.\Delta T).t \qquad (18)$$

Where

A is the area of drying tray, V is the drying air speed, ρ_a is the air density, C_a is the specific heat capacity of air, ΔT is the temperature difference and t is the time of drying. (Motevali et al, 2012; Mohsen, 2016).

The Specific Energy consumption, SEC, was calculated using the relation

$$SEC = \frac{E_t}{M} \qquad (19)$$

Where M is the mass of water removed.

3. RESULTS AND DISCUSSION

Effect of slice thickness on the moisture content

The effect of slice thickness on the moisture content is given in Fig 1. The rate of drying was found to be dependent on the thickness of the sample as the moisture content decreased with increase in slice thickness. With the 2mm thick slices, equilibrium moisture content was attained fastest with the 2mm thick slice and slowest with the 6mm thick slice. This is because at low slice thickness, the free moisture can be easily removed from the surface. The thicker the slice, the slower the approach to equilibrium moisture content and the slower the drying rate (Etoamaihe and Ibeawuchi, 2010). This is probably because as the product's thickness increase, the moisture dissipation and subsequent departure from the food material faces more resistance, hence prolonging the drying time (Mohammad et al, 2013). Aremu et al (2013) when investigating the effect of slice thickness reported that the drying time increased as the slice thickness increase.

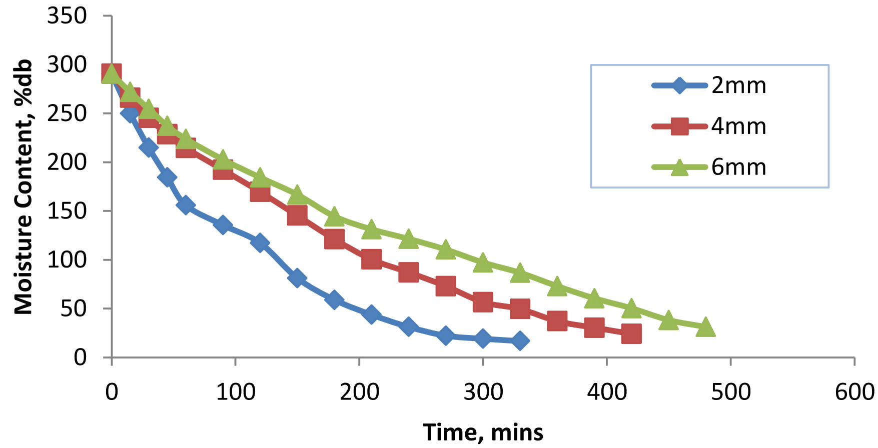

Fig 1: Effect of slice thickness on moisture content against time

Effect of temperature and air speed

The potato slices were dried at 50 ^{o}C, 60 ^{o}C, and 70 ^{o}C with air speed of 2.0, 2.5, 3.0 and 4.0 m/s. From Figures 2 to 4, it is seen that both increase in temperature and air speed reduces the drying time. Increased temperature of drying caused a faster attainment of equilibrium moisture content (Etoamaihe and Ibeawuchi, 2009). This means that the drying time was decreased as the temperature increased. This is due to the fact that as the temperature increased, the average kinetic energy of the moisture increases making it easier for them for the moisture to diffuse out of the products. Wankhade et al (2012) and Saeed et al (2008) reported that air temperature had a significant effect on the moisture content of samples. Increasing the temperature brings about a decrease in drying time because both the thermal gradient inside the object and the evaporation rate of the product increase (Mohammad et al, 2013).

With increase in the air speed, there is decrease in the moisture content, hence an increase in the drying rate of the products. When the hot dry air absorbs water from the surface of the drying product, it needs to be quickly moved on so that another set of air can repeat the process. The faster this process, the faster the drying process will be. Hence, it is seen that the drying time is decreased as the air speed increased.

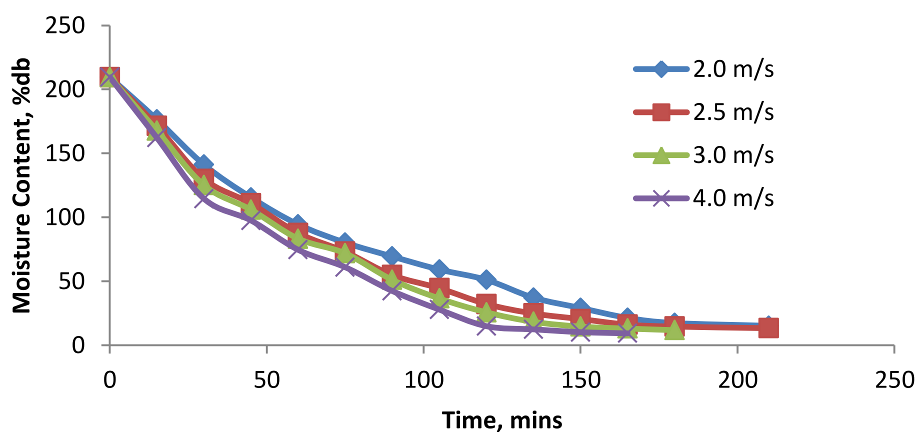

Fig 2: Effect of speed on moisture content against time at 50^{o}C

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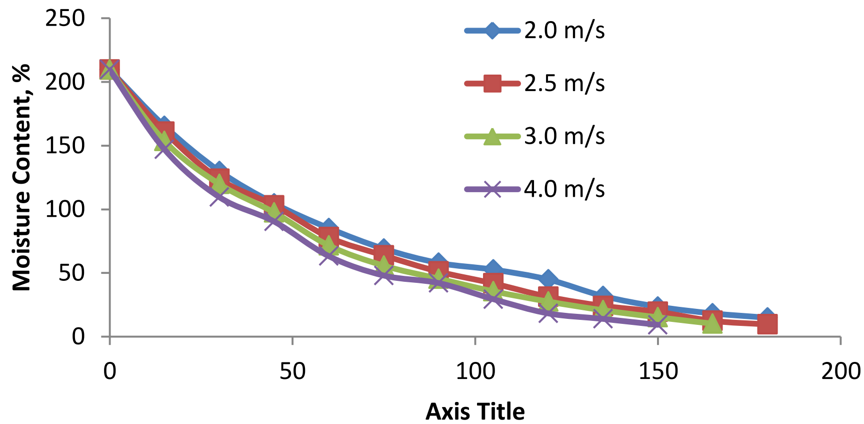

Fig 3: Effect of speed on moisture content against time at 60°C

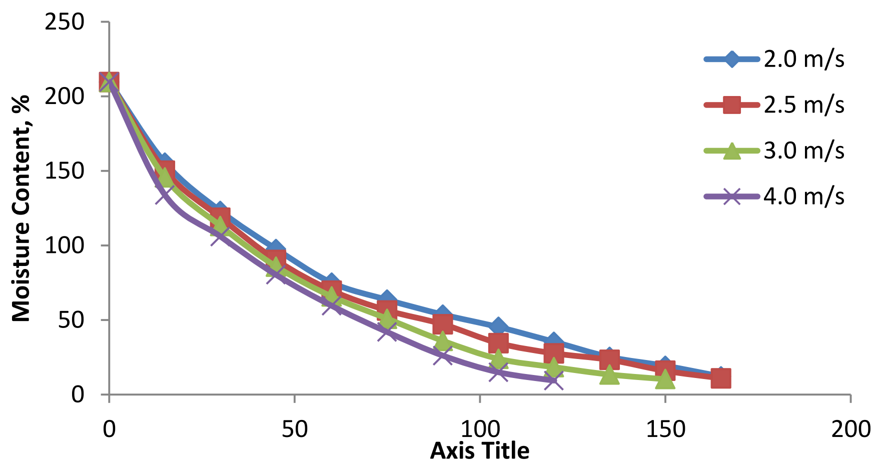

Fig 4: Effect of speed on moisture content against time at 70 °C

Drying rate

The drying rate was evaluated as the decrease of the water concentration during the time interval between two subsequent measurements divided by time interval (Anna et al, 2014). Figures 5 to 7 show the variations of drying rate with the experimental factors. The drying rate decreased as the slice thickness increased but increased as the temperature and the air speed increased. After 15 minutes, the drying rate of the 2 mm, 4mm and 6mm thick slices were 0.586 g/g.min, 0.507g/gmin and 0.313 g/g.min respectively. The main factor that controls the drying rate is the rate that moisture can move from the interior of a piece of food to the surface. Therefore the shorter the distance that moisture has to travel, the faster the drying rate will be.

In thin-layer drying, the effect of temperature on drying time is more significant relative to the air speed (Mirzaee et al, 2009; Divine et al, 2013). The drying process that occurs at higher air speed and higher temperature has the fastest drying rate and hence reached the equilibrium moisture content more quickly than others (Ndukwu, 2009). The drying rate was higher at the beginning of the drying operation and later decreased with decreasing moisture content (Anna et al, 2014; Ndukwu, 2009). The drying rate helps to determine the time the food should spend in the dryer before the moisture content is low enough to prevent spoilage by micro-organisms. The high drying rate at high drying temperature could be due to more heating energy which speeds up the movement of water molecules and results in higher moisture diffusivity (Junling et al, 2008).

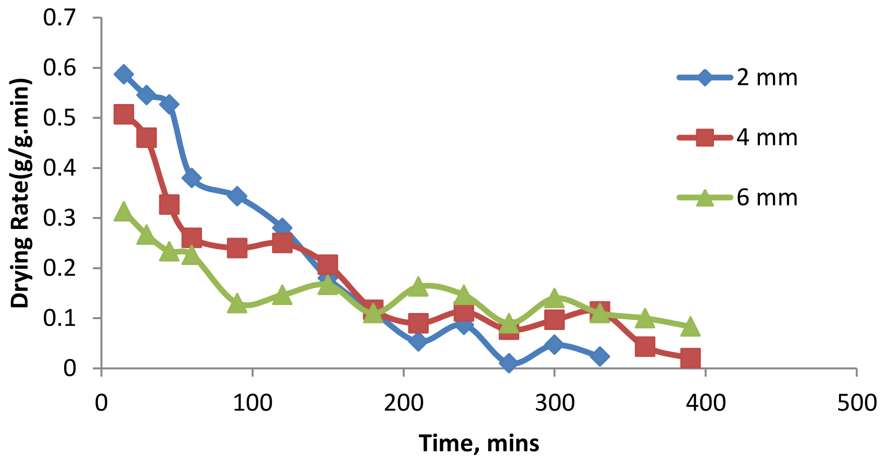

Fig 5. Effect of slice thickness on drying rate against time

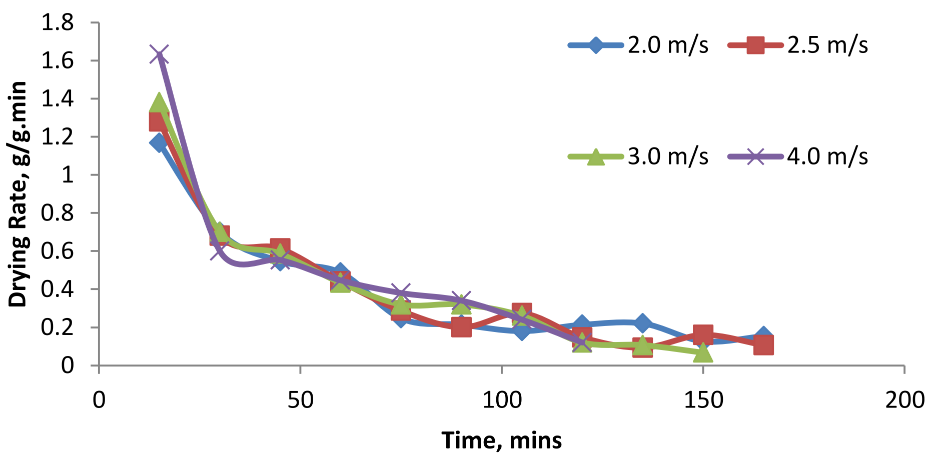

Fig 6. Effect of air speed on drying rate against time at 70 ^{o}C

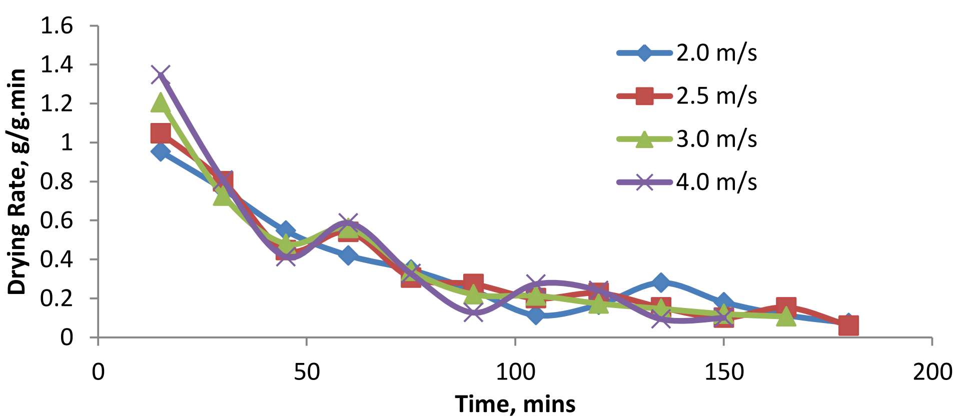

Fig 7. Effect of air speed on drying rate against time at 60 ^{o}C

Effective Moisture Diffusivity

Drying process of food materials generally occurs in the falling rate period. The result showed that the effective moisture diffusivity values were in the range of 5.404 x 10^{-11} to 2.432 x 10^{-10} m^2/s which are generally within the range of 10^{-11} to 10^{-6} m^2/s given for food materials' moisture diffusion coefficient (Moshen, 2016; Baballs and Belessiotis, 2014; Aghbashlo et al, 2008).

The Table 1 shows that the minimum value of effective moisture diffusivity was obtained at the minimum slice thickness used and that increase in slice thickness increases the value of effective moisture diffusivity at constant drying temperature. This trend is consistent with that reported by Tinuade et al, (2014). This is probably because the moisture gradient of the sample increased. The effective diffusion constant of a material is affected by the shorter distance that moisture needs to travel before the evaporation to the surroundings (Amira et al, 2014).

Table 1: Effect of slice thickness on the effective moisture diffusivity

Size	D_{eff} (m^2/s)	R^2
2 mm	5.404 x 10^{-11}	0.985
4 mm	1.621 x 10^{-10}	0.991
6 mm	2.432 x 10^{-10}	0.989

Table 2 shows the variation of temperature and drying air speed with effective moisture diffusivity. The minimum effective moisture diffusivity was 6.76 x 10^{-10} m^2/s which was obtained at a temperature of 70°C and air speed of 4.0 m/s. It was seen that both temperature and air speed do not inversely affect the effective moisture diffusivity. The same trend was reported by Moshen (2016). The moisture diffusivity in these slices was affected by the drying temperature because the drying temperature affected the internal mass transfer during drying (Nwajinka et al, 2014). This is due to the increased heating energy which would increase the activity of the water molecules leading to higher moisture diffusivity when samples were dried. Equally, effective moisture diffusion constant increases with temperature because at higher temperature, the water molecules are loosely bound to the food matrix and hence less energy is required to remove the moisture than at lower temperature (Amira et al, 2014). The knowledge of effective moisture diffusivity helps in designing a low cost but efficient dryer for drying agricultural products.

Table 2: Variations of effective moisture diffusivity in the Hot air dryer for Potato

Temperature	Air speed (m/s)	D_{eff} (m^2/s)	R^2
50 °C	2.0	3.5178 x 10^{-10}	0.990
	2.5	4.0528 x 10^{-10}	0.996
	3.0	4.5878 x 10^{-10}	0.989
	4.0	5.3984 x 10^{-10}	0.982
60 °C	2.0	3.7773 x 10^{-10}	0.9742
	2.5	4.3284 x 10^{-10}	0.981
	3.0	4.8634 x 10^{-10}	0.9684
	4.0	5.9500 x 10^{-10}	0.9772
70 °C	2.0	4.0529 x 10^{-10}	0.9548
	2.5	4.5878 x 10^{-10}	0.9842
	3.0	5.3984 x 10^{-10}	0.982
	4.0	6.7602 x 10^{-10}	0.972

Activation energy in the hot-air conventional dryer

The variation of different air speed on the activation energy was obtained by plotting the graph of ln D_{eff} against 1/T as shown in Figures 8.

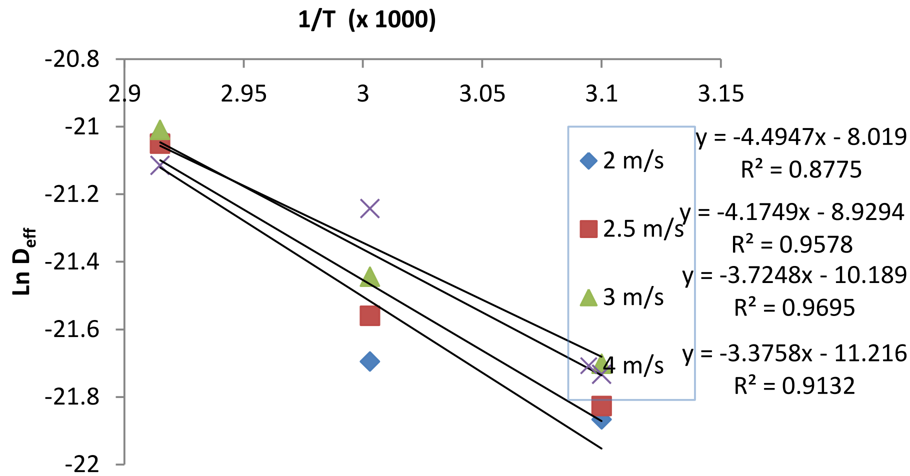

Figure 8: Plot of ln D_{eff} against 1/T at different air speeds

The coefficients of determination of the fitted lines with experimental data were mostly close to unity indicating a good correlation. The activation energy was calculated and presented in Table 4. It was observed that the magnitude of the activation energy is affected by the drying air speed. The minimum activation energy was 28.06 KJ/mol while the maximum was 37.367 KJ/mol. The range of activation energy obtained was in agreement with the general range of activation energy of 12.7 KJ/mol to 110 KJ/mol (Aghbashlo et al, 2008).

The study on the activation energy revealed that as the air speed increased, the activation energy progressively decreased. This is due to the fact that activation energy being energy that must be overcome before a process starts, is reduced as the drying air speed increases. If the air speed of the system is increased, the average heat energy is increased; a greater proportion of collision between reactants result in reaction and the reaction proceeds more rapidly. Nwajinka et al (2014) and Mirzaee et al (2009) reported similar trends in activation energy. In the thin-layer drying of Russian olive, the activation energy decreased from 63.83 KJ/mol to 48.18 KJ/mol as the drying air speed increased from 0.5 m/s to 1.5 m/s (Abbasazadeh et al, 2012). The values of the frequency factors calculated in Table 3 are similar to that reported by Amira et al (2014).

The linear regression of the relationship between drying air speed and activation energy is given in equation 20 with a correlation coefficient of 0.958

$$E_a = -4.694V + 46.26 \qquad (20)$$

Table 3: Activation Energy in Hot air conventional drying of potato

Velocity (m/s)	Activation Energy (KJ/mol)	$D_o \times 10^{-3}$ (m^2/s)	R^2
2.0	37.363	0.329	0.887
2.5	34.703	0.133	0.957
3.0	30.961	0.0379	0.969
4.0	28.060	0.0135	0.913

Variations of slice thickness with total energy consumption and specific energy consumption

The plots of the total energy consumed in drying the slices at different thicknesses were presented in Fig. 9 while the specific energy consumptions are shown in Fig. 10. The total energy increased from 10.67 KWh to 14.89 KWh as the slice thickness increased. The maximum and minimum values of specific energy consumption were 166.72 KWh/kg and 232.70 KWh/kg respectively. The highest total energy needed was obtained for the thickest slice sample while the lowest energy was observed least thick sample. This is probably due to the fact that the energy utilized to transfer heat to the internal regions of the slice is higher since the heat transfer distance is higher (Tinuade et al, 2014).

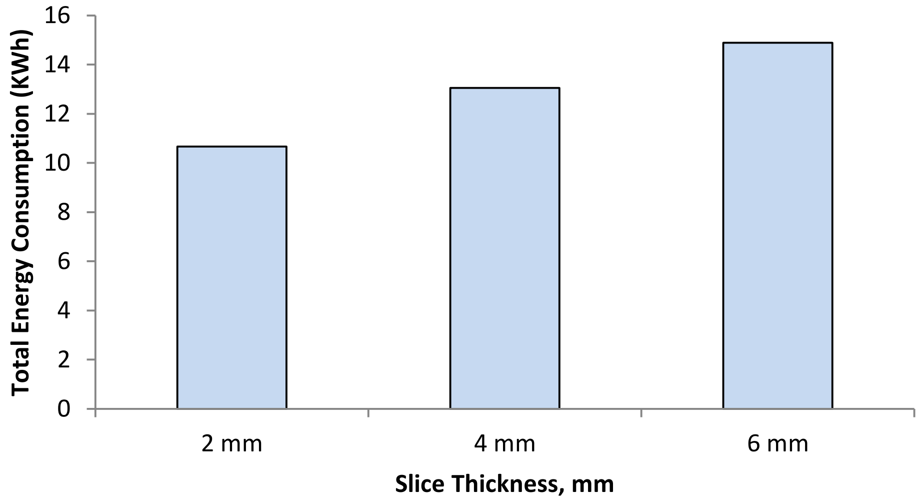

Fig 9. Effect of slice thickness on the total energy consumption

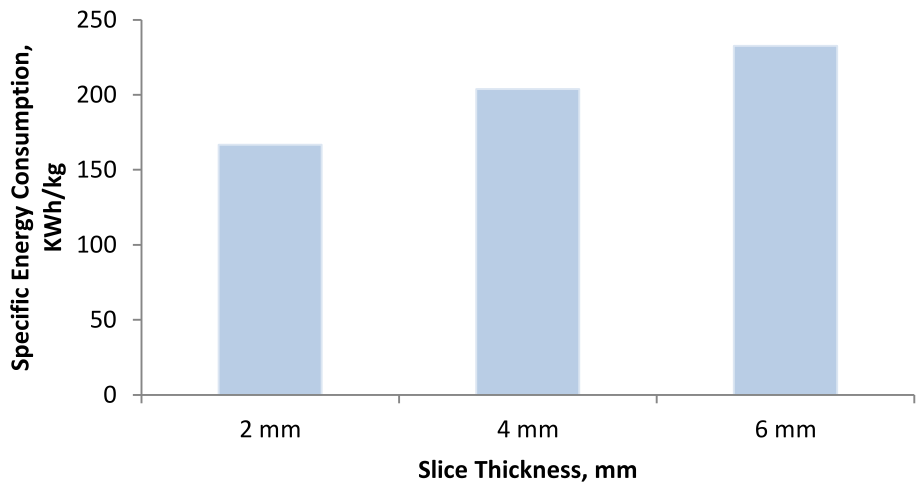

Fig 10. Effect of slice thickness on the specific energy consumption of SDP

4. CONCLUSION

In this study, potato slices were dried in a hot-air convectional dryer and the effects of some factors such as slice thickness, drying air speed and temperature were investigated. The results obtained indicated that as the slice thickness increased, the time to attain the equilibrium moisture content and the drying rate decreased. The effective moisture diffusivity increased with increase in temperature because at a high temperature, the water molecules are loosely bound to the food matrix. The activation energy increased progressively as the air speed decreased. Equally, the specific energy consumption was observed to vary with slice thickness. The hot air convectional dryer was effective in drying potato slices.

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