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Modeling Kinetic Parameters for Thin Layer Drying of Beans

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***Abstract*— *The removal of a liquid from a solid by evaporation is known as the process of drying. It can also be termed the reduction or loss of moisture content. Preservation of nutritive values and extension of the shelf life of foods are reasons why drying is important. The process of drying takes place under optimum operating conditions and efficient drying rate. This research work aimed at determining the kinetic parameters for thin-layer drying of beans under constant drying conditions necessary for the design of industrial dryer. An experimental work was carried out using an oven drying method which observed the drying of beans to be in the falling rate periods between 45oC to 65oC. The rate of drying was found to have a direct relationship with moisture content and temperature but an inverse relationship with time. The experimental data for beans could fairly be predicted by the Page equation. The values of A and B from the Page equation were found to be functions of temperature rather than mere constants as were used in the model and these are for A between 8.41E-05 and 2.4E-03 for the given temperatures while for B it was between 0.668 and 0.966. Temperature, therefore, is an important parameter to be manipulated in any dryer design especially for hygroscopic grains like beans.*

***Keywords*— *Beans, mathematical modelling, drying rate, moisture content, temperature and drying time.*

I. Introduction

The word "bean" have existed in common use in West Germanic languages since before the 12th century (Merriam-Webster's Collegiate Dictionary), referring to broad beans and other pod-borne seeds. The term has long been applied generally to many other seeds of similar form, (American Heritage Dictionary of the English Language) such as Old World soybeans, peas, chickpeas (garbanzo beans), etc. Thus the term "bean" in general usage can mean a host of different species. Seeds called "beans" are often included among the crops called legumes (Merriam-Webster's Collegiate Dictionary), although a narrower prescribed sense of legumes reserves the word for leguminous crops harvested for their dry grain. Beans were an important source of protein throughout Old and New World history, and still are today. Beans are high in protein, complex carbohydrates, folate, and iron. Beans also have significant amounts of fiber and soluble fiber. Many edible beans, including broad beans and soybeans contain oligosaccharides a type of sugar molecule also found in cabbage.

Drying is the removal of liquid from a solid by evaporation. Heat is applied under controlled conditions during the process. In agricultural work, drying refers to the removal of moisture until the moisture content of the product is such that decrease in quality from molds, enzymatic activity and insects will be negligible. The main purpose of dehydration is to extend the shelf life of foods by a reduction in water activity which inhibits microbial growth; however, the processing temperature is not normally sufficient to cause inactivation, hence, care needs to be taken with the product on subsequent rehydration. Drying causes deterioration in the eating quality and nutritive value of foods being dried and so the design engineer must design a plant which will minimize such detrimental effects while obtaining efficient drying rates (Yliniemi, 1999).

Farmers especially in Nigeria have over the years adopted the traditional drying system of using the solar energy for grains. Grains are allowed to dry naturally after maturation to a certain reduction in moisture content before being harvested. While in the field, the grains are exposed to adverse weather conditions which reduce or even destroy the germination properties of seed, reduce food quality and increase field loss of grains due to weather, insect, rodents etc. This method causes much delay and when finally harvested, grains are either hung in the chimney or spread on the floor under uncontrolled heat temperatures (Talbot, 2001). This is unhygienic and ineffective as they are still being infected by micro-organisms. The process is labour intensive, causes food wastage and prone to deterioration by biochemical reactions or microbiological or insect infestation. It does not allow for long term storage. Available techniques have not been able to adequately bring solutions to this problem especially in West African Region.

The gap between harvesting and processing of beans needs to be bridged. This can be achieved through the design of an appropriate dryer with efficient drying rate and optimum operating temperature. The design of this dryer is possible only when the kinetic parameters for drying is accurately determined. However, to achieve this purpose, there is a need to develop mathematical models which can predict accurately the drying behavior of sample in the dryer. Therefore, a mathematical model anchored on drying kinetics which is based on the physical mechanisms of internal heat and mass transfer to the material being dried which controls the process resistance as well as on structural and thermodynamic assumptions must be considered. Sun drying under natural convection is widely used as the conventional method of drying. It has a low cost heating source (Doymaz and Ismail, 2011) but having some inherent disadvantages (Khawas *et al*. 2013) such as slowness of the process, weather uncertainties especially long rainy seasons, high man power costs, large area requirement, insects' infestation and contamination with foreign materials are prominent draw backs of sun drying. The drying characteristic curves of most of these food materials were modeled using different drying models such as the Newton model (O'Callaghan *et al*., 1971), Page model (Akpinar *et al*., 2003, Iminabo *et al*., 2018), Henderson and Pabis model (Karathanos and Belessiotis, 1999), logarithmic model (Yaldiz *et al*., 2001), two term exponential model (Akpinar *et al*., 2003). For example, the page model was found to be best in describing the drying behavior of potato, red pepper, plantain chips, corn and tomato under hot air drying (Akpinar *et al*., 2003; Simal *et al*., 2005; Iminabo *et al*., 2018; Dagde *et al*, 2018; Doymaz, 2007). Hence, this research seeks to model the kinetic parameters for thin-layer drying of beans for the design of industrial dryer.

II. MATERIALS AND METHOD

2.1 Experimental Investigation

Thin-layer drying test was performed in the laboratory of the Department of Chemical/Petrochemical Engineering of the Rivers State University Laboratory using fresh white beans.

2.1.1 Raw materials

Fresh white beans sample was obtained from the Mile 3 market, Port Harcourt. The species of beans used was the locally harvested white beans type.

2.1.2 Procedure

- A gravity-convection oven was used to dry the beans at 45°C, 50°C, 55°C, and 65°C.
- The sample material was first shelled and cleaned of dirt and other impurities.
- The moisture cans were dried, weighed and the samples placed in them and reweighed. And the weight of the sample was taken.
- The oven was set at a specified temperature and when stabilized, the sample was placed in there and allowed to dry for 30 minutes.
- The sample was brought out of the oven after 30 minutes, cooled in desiccators without a drying agent and weighed, then placed back into the oven.
- Subsequent weighing and drying at every 30 minute internal was done till weight lost became negligible at that particular temperature. It was then left in the oven overnight to get the bone dry weight at the point where equilibrium moisture content is zero.
- This was done at the various temperatures of tests (45°C, 50°C, 55°C, and 65°C).
- Knowledge of the weight of the sample at the different drying times and its dry matter weight, allowed the construction of the sample drying curve. During the thin layer drying tests, the temperature was monitored.

2.2 Mathematical Modelling

The beans drying model was developed based on fundamental principles and experimental results. The model for solids described the drying characteristics of the solids and predicted the drying rate as a function of moisture in the solids and the temperature and humidity of the drying air.

2.2.1 Assumptions

- The initial moisture content of material sample is uniform.
- The temperature gradient within kernel is negligible.
- The dryer walls are adiabatic and no heat losses.
- The airflow is plug type and constant.
- The kernel-to-kernel condition is negligible
- The volumetric shrinkage of beans is negligible

2.2.2 Drying kinetics

The drying of beans in thin layers where each and every kernel is fully exposed to the drying air was expressed thus: Proctor (1994).

$$M_R = f\ (T, h, t) \quad (1)$$

$$M_R = \frac{M_C - M_{C_e}}{M_{C_o} - M_{C_e}} \quad (2)$$

where:
M_R = Moisture Reduction Ratio
M_C = Moisture content of the grain at any level and at any time, % dry bases $(\%db)$
M_{C_e} = Equilibrium moisture content $(\%db)$
M_{C_o} = initial moisture content of the wet grain $(\%db)$
T = air temperature (°C)
h = air relative humidity and
t = drying time

Relationship between drying rate and air conditions for the beans' thin-layer drying was first developed by the Page model (1949), used by Sharaf-Eldeen (1980), and recommended in ASAE standards (2000a). The model is:

$$M_R = \frac{M_C - M_{C_e}}{M_{C_o} - M_{C_e}} = \exp(-At^B) \quad (3)$$

where:
A and B are used as constants in their model.
Simplifying equation (3) to determine their values thus:

$$In\, M_R = -At^B \quad (4)$$

$$In\,(-In\, M_R) = InA + BInt \quad (5)$$

A plot of $In\,(-In\, M_R)$ against Int gives a straight line graph with a high relational coefficient which shows a perfect relationship (Figures 1- 4), from the slope and intercept of the graph values of A and B can be determined.
Rearrangement of equation (3) gives:

$$M = (M_{C_o} - M_{C_e})exp\,[-A(T)t^B(T)] \quad (6)$$

Using an appropriate curve fitting technique, the dependence of A and B on air temperature is obtained with a perfect correlation coefficient of $R_2 = 1$.
From equation (3)

$$M_C - M_{C_e} = (M_{C_o} - M_{C_e})exp\,(-At^B) \quad (7)$$

Using;

$$t = \frac{x}{u} \quad (8)$$

substituting (8) into (7) and rearranging, we have

$$M_C = M_{C_e} + (M_{C_o} - M_{C_e})exp\,(-A\left(\frac{x}{u}\right)^B)$$

Let $z = A\left(\frac{x}{u}\right)^{B}$ (9)

Hence, simplifying further and taking differential with respect to z we have:

$$\frac{dM_C}{dz} = -\frac{A*B(M_{C_o} - M_{C_e})}{U^B} x^{B-1} exp\left[A\left(\frac{x}{u}\right)^{B}\right] \quad (10)$$

In summary, the form of the thin layer drying equation used for the development of the model is the Page (1949), Sharaf-Eldeen model (1980) which was recommended in ASAE standards (2000a). To validate the equilibrium moisture content equation of Sharaf-Eldeen *et al.,* (1980), the temperature of the oven was recorded during the processes.

The drying kinetics data obtained from the experiment was used to plot graphs of drying rate against moisture contentwhich showed a common trend for all the items.

Drying was found to be in the falling rate period for the beans sample since the initial moisture content, Mc, is less than the critical moisture content, Cr. Rate of drying was found to have a direct relationship with moisture content and temperature but an inverse relationship with time.

III. RESULT AND DISCUSSION

3.1 Results

The results of the experiment are presented in Tables 1-4 for 45^{o}C, 50^{o}C, 55^{o}C and 65^{o}C respectively. Drying curves of drying rate over drying period were constructed to depict drying profile graphically. The plots of $In\,(-InM_R)$ against Int for each of the temperature values are shown in Figures 1 – 4. Also, the graph of drying curve for each of the temperatures are presented in Figures 5 - 12 which shows the moisture content variation with drying rate.

TABLE 1. Result of Drying Kinetics Data for Beans at 45^{O}C

Drying Time (sec)	Mass of Sample (g)	Moisture Content (db g/g)	Drying Rate (g/g.sec)
0	10.1867	0.0699	
1800	10.1340	*0.0644*	0.0000031
3600	10.1014	0.0610	0.0000019
5400	10.0705	0.0577	0.0000018
7200	10.0448	0.0550	0.0000015
9000	10.0244	0.0529	0.0000012
10800	10.0073	0.0511	0.0000011
12600	9.9893	0.0492	0.0000011
14400	9.9779	0.0480	0.0000007
16200	9.9579	0.0459	0.0000012
18000	9.9424	0.0442	0.0000009
19800	9.9323	0.0432	0.0000006
21600	9.9215	0.0420	0.0000007
23400	9.9110	0.0410	0.0000006
76500	9.7639	0.0255	0.0000003
80100	9.7549	0.0245	0.0000003
83700	9.5212		0.0000068

Bone Dry Mass = 9.5212g

TABLE 2. Result of Drying Kinetics data for Beans at 50°C

Drying Time (sec)	Mass of Sample (g)	Moisture Content (dbg/g)	Drying Rate (g/g.sec)
0	10.1458	0.0699	
1800	10.0682	0.0617	0.0000046
3600	10.0248	0.0571	0.0000026
5400	9.9871	0.0532	0.0000022
7200	9.9575	0.0500	0.0000018
9000	9.9275	0.0469	0.0000017
10800	9.8988	0.0438	0.0000017
12600	9.8747	0.0413	0.0000014
14400	9.8514	0.0388	0.0000014
16200	9.8360	0.0372	0.0000009
18000	9.8222	0.0358	0.0000008
19800	9.8103	0.0345	0.0000007
21600	9.7987	0.0333	0.0000007
90000	9.5900	0.0305	0.0000003
93600	9.5851	0.0276	0.000003
99000	9.4830		0.000002

Bone Dry Mass = 9.4830g

TABLE 3. Result of Drying Kinetics Data for Beans at 55°C

Drying Time (sec)	Mass of Sample (g)	Moisture Content (dbg/g)	Drying Rate (g/g.sec)
0	10.0160	0.0699	
1800	9.9499	0.0628	0.0000039
3600	9.9089	0.0585	0.0000024
5400	9.8344	0.0505	0.0000044
7200	9.8067	0.0475	0.0000017
9000	9.7874	0.0455	0.0000011
10800	9.7654	0.043 1	0.0000003
12600	9.7489	0.0414	0.0000009
14400	9.7325	0.0396	0.0000001
16200	9.7109	0.0379	0.0000009
18000	9.7009	0.0362	0.0000009
19800	9.6959	0.0357	0.0000003
21600	9.6828	0.0343	0.0000008
23400	9.6724	0.0332	0.0000006
25200	9.6566	0.03 15	0.0000009
27000	9.4641	0.0285	0.0000067
79680	9.3617	0.0249	1.3495E-06

Bone Dry Mass = 9.3617g

TABLE 4. Result of Drying Kinetics Data for Beans at 65°C

Drying Time (sec)	Mass of Sample (g)	Moisture Content (db g/g)	Drying Rate (g/g.sec)
0	10.2072	0.0699	
1800	10.0935	0.0580	0.0000066
3600	10.0333	*0.0517*	0.0000035
5400	9.9817	0.0463	0.0000030
7200	9.9407	0.0420	0.0000024
9000	9.9068	0.03 84	0.0000020
10800	9.8747	0.0350	0.0000019
12600	9.8499	0.0324	0.0000014
14400	9.8279	0.0301	0.0000013
16200	9.8072	0.0280	0.0000012
18000	9.7888	0.0260	0.0000011
19800	9.7682	0.0239	0.0000012
70200	9.5404	0.0000	0.0000005

Bone Dry Mass = 9.5404g

Figures 1 – 4 are straight line graphs showing the variation of $\ln(-InM_R)\,against\,lnt$ with a high relational coefficient which shows a perfect relationship. Using the curve fitting technique, the dependence of A and B on air temperature is obtained with a perfect correlation coefficient of R_2 = 0.999 for each temperature values.

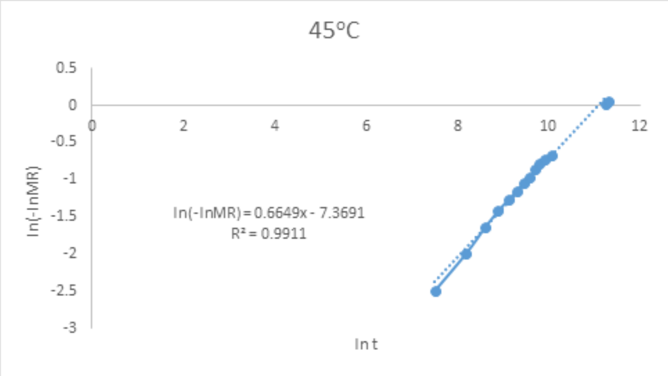

Fig. 1. Plot of $In(-lnM_R)$ against In t at 45°C

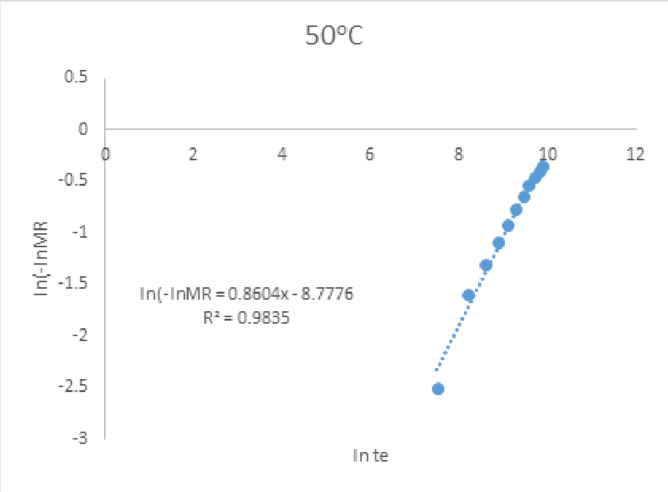

Fig. 2. Plot of $In(-lnM_R)$ against ln t at 50°C

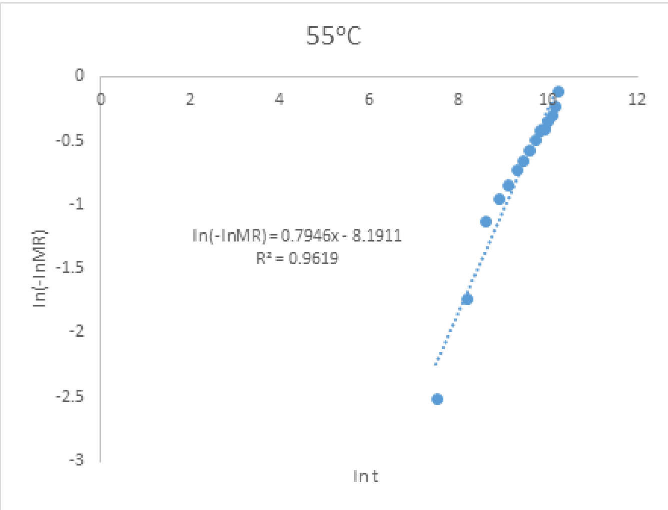

Fig. 3. Plot of $In(-lnM_R)$ against ln t at 55°C

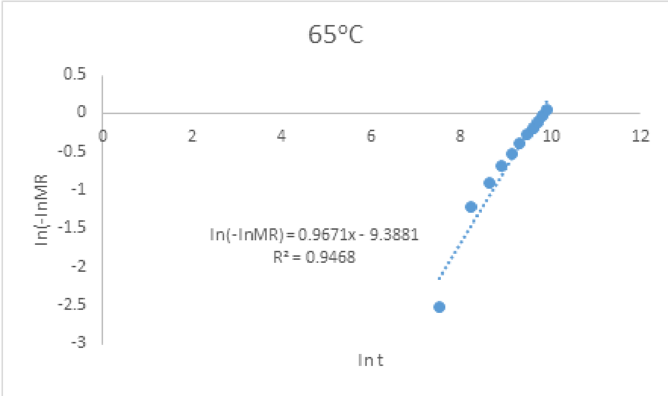

Fig. 4. Plot of $In(-lnM_R)$ against ln t at 65°C

Figures 5 - 8 shows the variation of Drying rate with Moisture Content at temperatures of 45°C, 50°C, 55°C and 65°C respectively. From Figures 5 and 6, it is seen that the drying rate increases with an increase in moisture content of the sample at temperatures of 45°C and 50°C. Figures 7 and 8, depicts that the drying rate is inversely proportional to the moisture content at temperatures of 55°C and 65°C.Hence, it can be concluded that the moisture content and the drying rate are both functions of temperature.

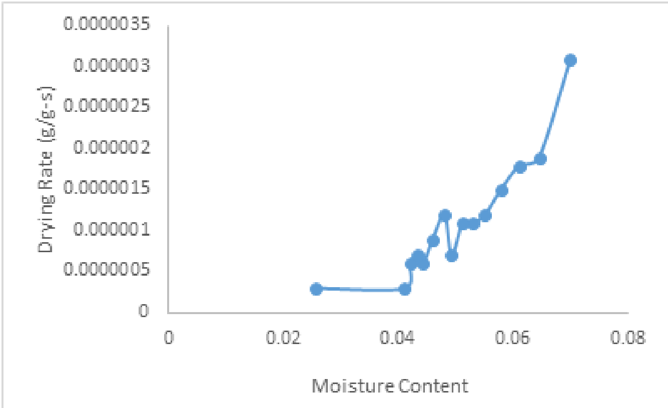

Fig. 5. Variation of Drying rate with Moisture Contentat 45°C

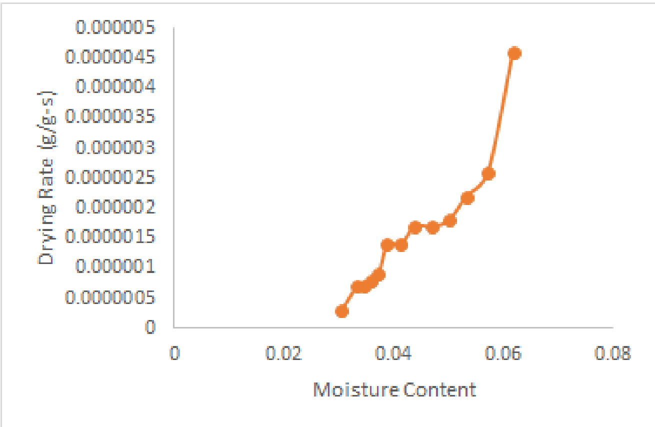

Fig. 6. Variation of Drying rate with Moisture Content at 50°C

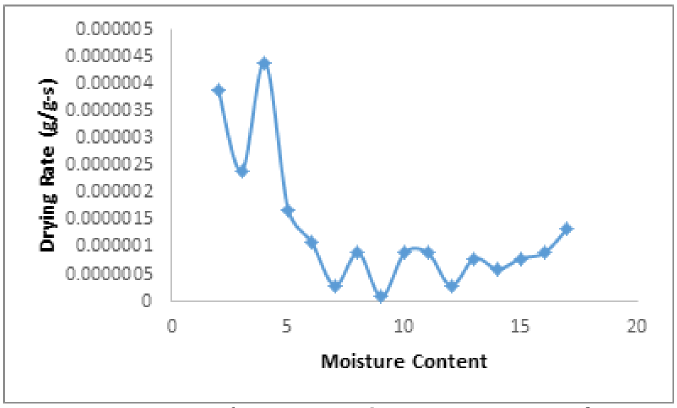

Fig. 7. Variation of Drying rate with Moisture Content at 55°C

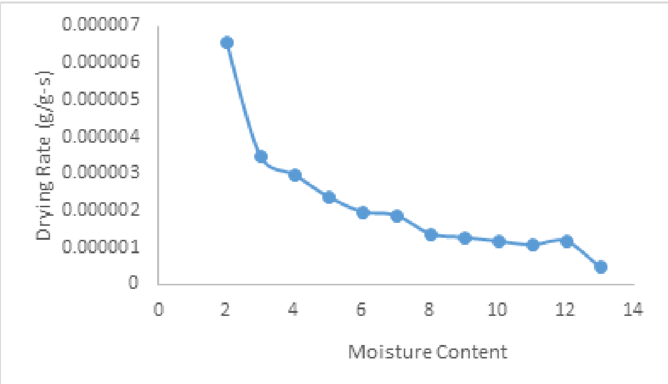

Fig. 8. Variation of Drying rate with Moisture Content at 65°C

Figures 9 - 12 depicts the variation of Drying Rate against Drying Time at 45°C, 50°C, 55°C and 65°C respectively. From the plots, it is seen that the drying rate decreases with an increase in drying time which is as a result of increased residence time of the sample in the oven. It was observed also, that the drying rate increases with an increase in temperature as shown in Figures 9 - 12 for temperatures 45°C - 65°C. Hence, it can be concluded that the drying rate is a function of temperature and it is inversely proportional to the drying time.

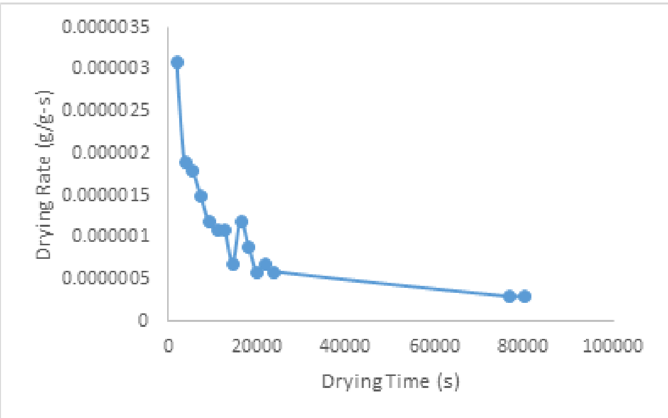

Fig. 9. Variation of Drying Rate and Drying Time at 45°C

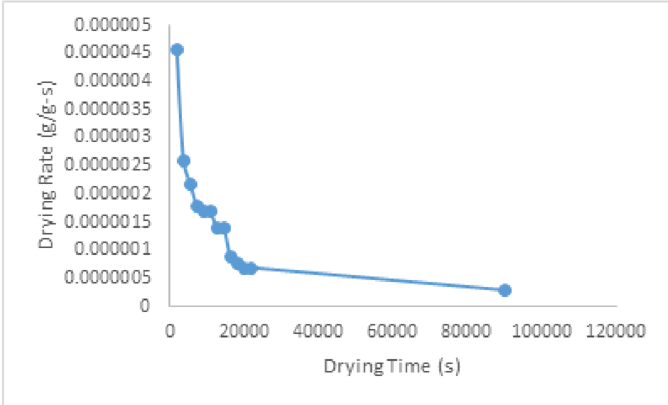

Fig. 10. Variation of Drying Rate and Drying Time at 50°C

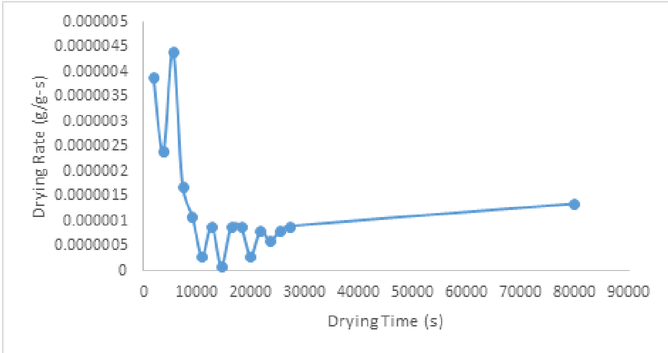

Fig. 11. Variation of Drying Rate and Drying Time at 55°C

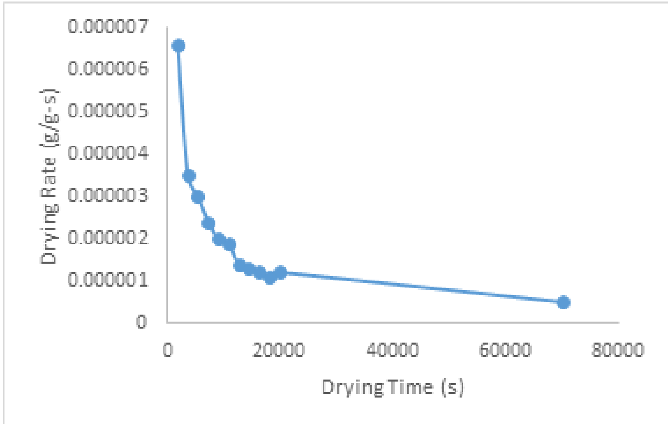

Fig. 12. Variation of Drying Rate with Drying Time at 65°C

IV. CONCLUSION

The purpose of drying is achieved when an optimum operating condition and efficient drying rate is determined. This work has achieved this objective through the investigation of the kinetic parameters for the thin layer drying of beans for further purposes under constant drying conditions. The drying of the beans sample was observed to be in the falling rate period. The experimental data for beans could fairly accurately be predicted by the Page equation. The values of A and B for beans respectively are:

T°C	A	B
45	0.000613	0.6686
50	0.002408	0.5519
55	8.41E-05	0.7944
65	0.000278	0.9666

The contribution of this work to knowledge is the discovery of the dependence of A and B on air temperature which can be used in the design of industrial dryers for corn under constant drying conditions and also enable the development of dryer models over a wide range of temperatures.

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