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A Study on Drying Kinetics of Shrimps

A.S. Ajala[1] and F.A. Ajala[2]

[1]Department of Food Science and Engineering, Ladoke Akintola University of Technology,
P.M.B. 4000, Ogbomoso, Nigeria

[2]Department of Computer Science and Engineering, Ladoke Akintola University of Technology,
P.M.B. 4000, Ogbomoso, Nigeria

ABSTRACT: In this study, samples of shrimps were dried in a convective tunnel dryer at 60°C, 70°C and 80°C. Moisture kinetics was investigated and fitted into various models based on Fick's second law of diffusion. Logarithmic model had the best fit for the drying condition and effective moisture diffusivity increased as drying temperature increased. The activation energy was found to be 33.851kJ/mol.

KEYWORDS: Drying Kinetics, Shrimps.

1 INTRODUCTION

Shrimp, any of about 2,000 species of small, aquatic animals related to crabs, lobsters, and crayfish. It ranges in size from animals not much bigger than a fingernail to ones over 20 cm (8 in) long **(**De-Grave *et al.,* 2008; Christian 2011**)**. Shrimp lives in a wide variety of freshwater and saltwater habitats, including lakes, coral reefs, and the depths of the sea. Some shrimp are good swimmers and spend nearly their entire life swimming in open water. But many species are bottom-dwellers and swim only occasionally. These shrimps crawl over submerged rocks, sand, or mud on the lake or ocean floor.

Shrimp has become increasingly popular in many part of Nigeria. Over the past decades, interest in the demand of this animal has again increased due to health benefit accrued from nutritional standpoint in that shrimp meat is high in protein but low in fat, which makes it a highly nutritious food (Ajala and Oyategbe 2013). Shrimp by-products have been identified as an animal protein source of great potential; also, as an important source of chitin and asthaxanthin (Shahidi and Synowiecki, 1991).

Various methods abound for preservation of shrimps. Such methods include freezing, canning and drying (Rungtip *et al.,* 2005; Lourdes *et al.,* 2007). Canning and freezing are viable options to preserve shrimp in advanced economy. However, in developing economy such as in Nigeria, drying is prefer option due to its lower cost compared to canning and freezing. Furthermore, most drying of shrimps is done by spreading it on mat in open sun (Rungtip *et al.,* 2005, Nwanna *et al.,* 2004). This resulted in poorly dried shrimps; some are fermented before drying is accomplished. Because of this problem, there is need to develop a better and efficient drying method which can accurately drying this product. This is accomplishable by means of studying the drying behaviour of the shrimps to determine amount of energy needed to dry the samples. Then, mathematical models can then be used to design an efficient drying process using tunnel dryer. Therefore the objectives of this study are (i) to study the effect of temperatures on the drying characteristics of the shrimps (ii) to determine the effective diffusivity and activation energy of the samples in the dryer using Fick's law of diffusion (iii) to fit in the experimental drying curve data into seven mathematical models.

2 MATERIALS AND METHODS

2.1 DRYING EXPERIMENT

A sample of fresh white shrimp (*Penaeus vannamei*) was obtained from Sasi Lagoon Resort, Lagos State. Nigeria. The shrimps were immediately placed in ice with an ice/ shrimp ratio of 2:1 (w/w) for 6 hrs. The samples were prepared for drying by beheading, washing and draining the shrimps. The drying experiment was performed in a tunnel dryer built in the Department of Food Science and Engineering, Ladoke Akintola University of Technology, Ogbomoso Nigeria. The dryer was operated at air temperature of 60^0C, 70^0C and 80^0C at constant air velocity of 1.5 m/s. The dryer was installed in an environmental condition of 48% relative humidity and 29^0C ambient temperature. The temperature and the air velocity in the dryer were at steady state before samples were introduced into the dryer. Rounded and spherical shape shrimps were selected for the drying operations. The shrimps had average radius of 5.00 mm measured with a micrometer screw guage. The samples were placed in the dryer and removed manually every 1 hour to determine weight loss of the sample. The drying experiment was stopped when three consecutive sample weights remained constant.

2.2 MATHEMATICAL MODEL

In this work, Fick's second law of moisture diffusion in porous media was adapted for the drying operation. This is as represented in equation 1

$$\frac{\partial m}{\partial t} = D\frac{\partial^2 m}{\partial t^2} \qquad 1$$

Where *m* = moisture content (kg water/kg solid); t = time (s); D = diffusion coefficient for moisture in solids (m^2/s).

To solve this equation for certain geometries or shapes, the following assumptions were made;

- free water content at the surface is zero and moisture is evenly distributed
- the shape and size of the sample remain constant during drying i.e negligible shrinkage
- heat transfer proceeds very quickly (negligible internal and external heat transfer effect)

To investigate the drying behaviour of the shrimps, the experiment data were fitted into seven different models as presented in Table 1. These models described the relationship between moisture diffusion and drying time with different coefficients attached to each model.

Table 1: Mathematical drying models

Models	Equation	References
Henderson and Pabis	MR=aexp(-kt)	Chinnman, (1984)
Midilli	MR=aexp(ktn) +bt	Togrul and Pehlivan, (2003)
Newton	MR=exp(-kt)	Kingly et al., (2007)
Page	MR=exp(-kt^n)	Karathanos and Belessiotis, (1999)
Logarithmic	MR=aexp(-kt) +c	Togrul and Pehlivan, (2003)
Two-Term	MR=a exp(k_1t) + b exp(k_2t)	Hodge & Taylor, (1999)
Diffusion Approximation	MR=a exp(-kt) + (1-a) exp(kbt)	Sacilik *et al.,* (2005)

These models in Table 1 show relationship between moisture ratio and drying time. Moisture ratio (MR) during the thin layer drying was obtained using equation 2

$$MR=\frac{M_i - M_e}{M_O - M_e} \qquad (2)$$

Where MR= dimensionless moisture ratio, Mi = instantaneous moisture content (g water/g solid), Me =equilibrium moisture content (g water/ g solid), Mo = initial moisture content (g water/ g solid). However, due to continuous fluctuation of relative humidity of the drying air in the dryer, equation 2 is simplified in equation 3 according to Goyal *et al.,* (2007)

$$MR=\frac{M_i}{M_O} \qquad (3)$$

2.3 STATISTICAL ANALYSIS

The drying model constants were estimated using a non-linear regression analysis. The analysis was performed using Statistical Package for Social Scientist (SPSS 15.0 versions) software. The reliability of the models was verified using statistical criteria such as coefficient of determination (R^2), reduced chi-square (χ^2), root mean square error (RMSE) and mean bias error (MBE). The comparison criteria method can be determined as follows:

$$\chi^2 = \frac{\sum_{i-1}^{n}(MR_{(\exp,i)} - MR_{(pred,i)})^2}{N - z} \qquad (4)$$

$$MBE = \frac{1}{N}\sum_{i=1}^{n}(MR_{(pred,i)} - MR_{(\exp,i)}) \qquad (5)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{n}(MR_{(pred,i)} - MR_{(\exp,i)})^2\right]^{1/2} \qquad (6)$$

2.4 DETERMINATION OF EFFECTIVE DIFFUSIVITY

The simplified equation of Fick's second law was adapted to determine the moisture diffusion from the shrimp samples during the drying process. The analytical solution of the equation 7 represents the mass transfer in terms of specific geometrical representation of spherical shape (Azzouz, 2002 and Sacilik *et al.*, 2006)

$$MR = \frac{M - M_0}{M_0 - M_e} = \frac{6}{\pi^2}\sum_{n=1}^{n=\infty}\frac{1}{n^2}\exp\frac{-n^2\pi^2 D_{eff} t}{r^2} \qquad (7)$$

The effective moisture diffusivity (D_{eff}) was calculated from the slope of plot of ln MR against drying time (t) according to Doymaz (2007) and is represented in equation 8

$$k = \frac{\pi^2 D_{eff} t}{r^2} \qquad (8)$$

Where *k* represents the slope of the graph.

2.5 DETERMINATION OF ACTIVATION ENERGY

Arhenius equation describes the relationship between moisture diffusion and temperature of drying. This relationship is as shown in equation 9

$$D_{eff} = D_0 \exp\frac{-E_a}{RT} \qquad (9)$$

Where D_0 is the pre-exponential factor of the Arrhenius equation in m^2/s, E_a is the activation energy in kJ/mol, R is the universal gas constant in kJ/mol K and T is the absolute air temperature in K. The activation energy was calculated by plotting the natural logarithm of D_{eff} against inverse of the absolute temperature. Figure 3 shows the plot of the relationship between these parameters.

3 RESULTS AND DISCUSSION

The discussion entails studies on the effect of the drying temperature on the shrimps, statistical results of the model parameters, effective diffusivity and the activation energy.

3.1 EFFECT OF DRYING TEMPERATURES ON THE SHRIMPS

The drying pattern of the shrimps is as shown in Figure 1. The moisture loss exhibited falling rate profile which basically is the drying pattern of most agricultural products (Ramaswamy and Marcotte, 2006). Another observation from the graph is that it exhibited a second falling rate period mostly at the 2nd hr of drying which was as a result of the plane of evaporation which slowly receded from the surface and all evaporation occured at the interior of the food. At this stage, moisture is drastically reduced in the samples and the drying rate is controlled by internal resistance caused by moisture diffusion which is analogous to conductive heat transfer. Therefore, apart from temperature factor, changes in the external conditions such as air velocity no longer affected the rate of drying as reported by Ajala *et al.,* (2011), Ramaswamy and Marcotte (2006), Ivaldo and Gilson (2005). The same trend of drying is observed in figure 2

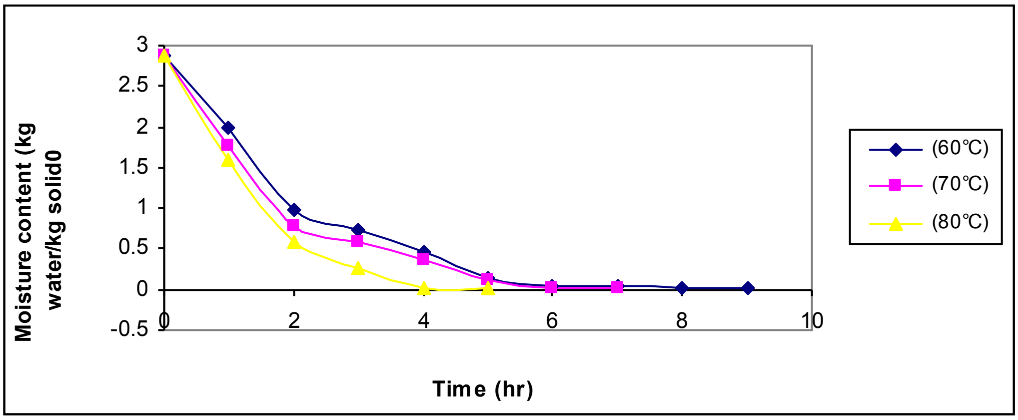

Figure 1: Moisture content against Time

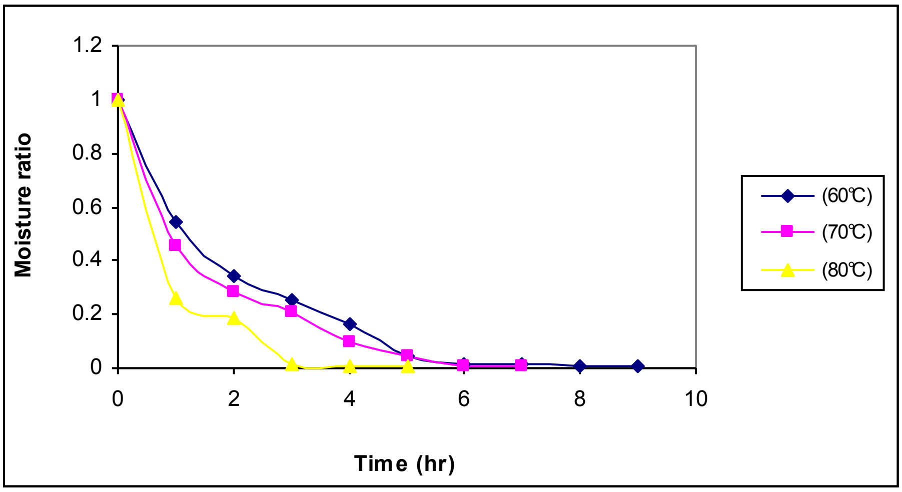

Figure 2: Moisture ratio against Time

3.2 STATISTICAL RESULTS AND CONSTANTS OF THE DRYING MODELS

Table 2 shows the values of statistical parameters used to test the models to evaluate the best fit. A good fit is said to occur between experimental and predicted values of a model when R^2 is high and χ^2, RMSE and MBE are lower (Demir *et al.,* 2004). From the table, careful analysis of the average R^2 for each is as follows: Handerson and Pabis; 0.992, Midilli; 0.815, Newton; 0.991, Page; 0.993, Logarithmic; 0.9943, Two-term; 0.992 and diffusion approximation; 0.994. These values showed that Logarithmic model had the highest average value of R^2. Hence, it can be deduced from the models that Logarithmic model had the best fit for the experimental drying of the shrimp samples. The constant values of different model are as shown in Table 3. Two-term model exhibited both the highest and lowest constant value of 61.126 and -21.399 respectively.

Table 2: Values of statistical parameters

Models	Temp	R^2	χ^2	MBE	RMSE
Henderson and	60	0.992	0.001061	0.007487	0.023675
Pabis	70	0.997	0.000628	0.007939	0.022454
	80	0.987	0.002604	0.012817	0.031395
	Average	0.992	0.001431	0.009414	0.025841
Midilli	60	0.747	0.040658	0.004487	0.014188
	70	0.805	0.041461	0.006689	0.018919
	80	0.893	0.040198	0.004484	0.010982
	Average	0.815	0.040772	0.00522	0.014696
Newton	60	0.992	0.000823	0.007487	0.023675
	70	0.997	0.000533	0.009189	0.02599
	80	0.986	0.002404	0.012817	0.031395
	Average	0.991	0.001253	0.009831	0.02702
Page	60	0.993	0.000885	0.009487	0.03
	70	0.997	0.000559	0.011689	0.033061
	80	0.990	0.002208	0.012817	0.031395
	Average	0.993	0.001217	0.011331	0.031485
Logarithmic	60	0.992	0.001049	-0.00051	0.001623
	70	0.997	0.000576	0.001689	0.004776
	80	0.994	0.001524	0.00115	0.002818
	Average	0.9943	0.00105	0.000776	0.003072
Two-Term	60	0.993	0.001065	0.006	0.018974
	70	0.996	0.000722	0.004189	0.011847
	80	0.989	0.003659	0.00615	0.015065
	Average	0.992	0.001815	0.005446	0.015295
Diffusion	60	0.992	0.001074	0.001487	0.004701
Approximation	70	0.996	0.000671	0.004189	0.011847
	80	0.994	0.001524	0.00115	0.002818
	Average	0.994	0.00109	0.002275	0.006455

3.3 EFFECTIVE DIFFUSIVITY AND ACTIVATION ENERGY

Effective diffusivity (D_{eff}) of a material is defined to describe the rate of moisture movement using transport mechanism such as liquid diffusion, vapour diffusion, Knudsen diffusion, surface diffusion and hydrostatic pressure differences. As shown from Table 4, the values of D_{eff} in this work fall within the range of food products (10^{-11} to 10^{-8} m/s^{-2}) as reported by Doymaz (2007). Moreover, the D_{eff} values reported in this work are less than the values for fish dried in microwave with values of 7.158×10^{-8} to 3.408×10^{-7} m^2/s as reported by Hosain *et al.,* (2012). Also the values are less than the values of clams dried in the cabinet with the values of 3.14 x10^{-9} to 11.0x10^{-9} m/s^2 as reported by Betty-Tello *et al.,* (2004). However, the values are comparable with that reported by Mehran *et al.* (2013) with values of 3.24-6.49x10^{-9}m^2/s for foam mat drying of shrimps. Moreover, the effect of temperatures on the effective moisture diffusivity is also observed in Table 4 which shows an increment from 1.27 x 10^{-9} m^2/s at 60^{o}C to 2.53 x 10^{-9} m^2/s at 80^{o}C. This clearly showed that moisture diffusivity increased as the temperature increased. This has been earlier observed by some authors such as Ajala, *et al,*. (2012), Guine *et al.,* (2009), Abraham et al., (2004) and Jaya and Das (2003). Besides, Jangham *et al.,* (2010) asserts that not only the temperature affects D_{eff} but also moisture content of the material being dried

Table 3: Values for model constants

Model	Temp	a	b	c	k	k_1	k_2	n
Henderson	60	0.985			0.521			
and Pabis	70	0.994			0.562			
	80	1.011			0.619			
Logarithms	60	0.997		-0.015	0.505			
	70	1.010		-0.023	0.523			
	80	1.110		-0.114	0.483			
Newton	60				0.528			
	70				0.565			
	80				0.613			
Page	60				1.000			-0.840
	70				0.582			0.967
	80				0.546			1.156
Logarithmic	60							
	70							
	80							
Two terms	60	0.099	0.901			-23.650	-0.489	
	70	-21.399	22.391			-0.651	-0.648	
	80	63.126	-62.129			-0.961	-0.969	
Diffusion	60	1.002	-0.487		0.528			
Approximation	70	4.845	1.022		0.630			
	80	1.060	0.996		-0.983			

Table 4: Values of effective moisture diffusivities at different temperatures

Drying air velocity (m/s)	Drying air temperature (^{0}C)	Effective moisture diffusivity (m^2/s) (D_{eff}x 10^{-9} m^2/s)
2.7	60	1.27
2.7	70	1.77
2.7	80	2.53

The activation energy which describes the influence of temperature on the diffusion coefficient of the materials is being derived from the plot of natural log of D against the inverse of the absolute temperatures at which the drying was carried out. In this study, the gradient of the curve produced the activation energy with the value of 33.851kJ/mol and diffusivity coefficient (D_0) of 2.57x$10^{-4}$$m^2$/s.This has a close value with the work of Mehran *et al.* (2013) on the study of foam mat drying characteristics of shrimps with the value of 32.16 kJ/mol.

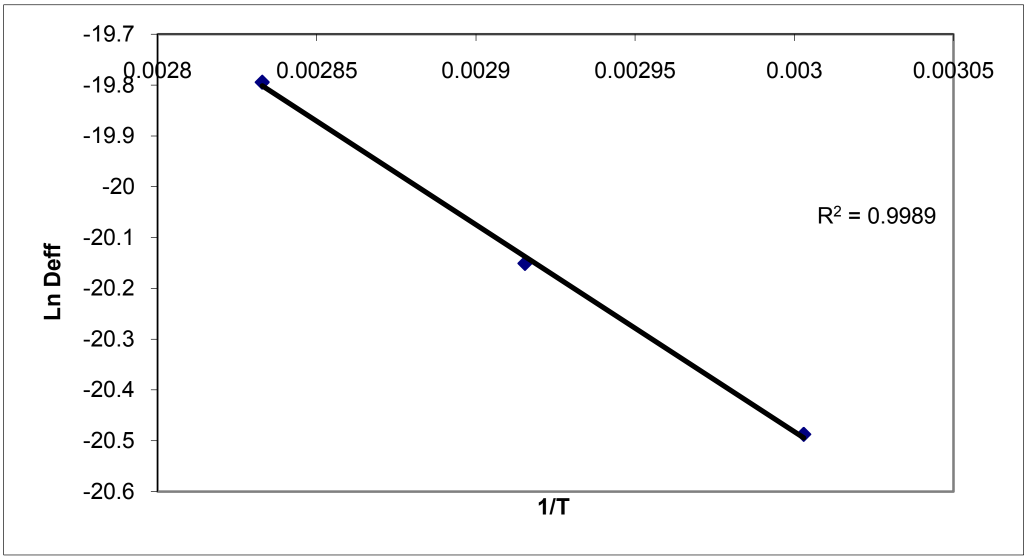

Figure 3: Plot of lnD$_{eff}$ against inverse of absolute temperature

4 CONCLUSIONS

Shrimps were dried at 60°C, 70 °C and 80 °C in a tunnel dryer. The moisture kinetics showed a second falling rate period and Logarithmic model gave the best fit for the experimental drying of the samples having the R^2 average value of 0.9943. The effective moisture diffusivity values were temperature dependent and values were comparable with other research work. The activation energy value was found to be 33.851kJ/mol.

NOMENCLATURE

a,b,c,k, k_1, k_2	Drying constant in the model
l	half of the thickness of the sample (m^2)
D_{eff}	effective diffusivity, m^2/s
D_0	pre-exponential factor, m^2/s
E_a	activation energy, kJ/mol
M_0	initial moisture content of the sample (g water/g solid)
M_i	instantaneous moisture content of the sample (g water/g solid)
M_e	equilibrium moisture content of the sample (g water/g solid)
MBE	mean bias error
MR	moisture ratio
MR_{exp}	experimental moisture ratio
MR_{pre}	predicted moisture ratio
n	drying constant in the model
N	number of observation
R	universal gas constant kJ/mol K
RMSE	root mean square error
R^2	coefficient of determination
t	drying time (hr)
χ^2	reduced chi square
z	number of constant in the models

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