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Determination of moisture diffusivity and activation energy in the convective drying of fish

Clement Adekunle Komolafe^{1*}, Iyiola Olusola Oluwaleye², Akinfoye O. Daniel Adejumo³, Mufutau Adekojo Waheed⁴, Sidikat Ibiyemi Kuye⁴

¹ Department of Mechanical Engineering, Landmark University, P.M.B. 1001, Omu Aran 251101, Nigeria

² Department of Mechanical Engineering, Ekiti State University, P.M.B. 5363, Ado Ekiti 360001, Nigeria

³ Department of Agricultural Engineering, Federal College of Agriculture, P.M.B. 5092, Ibadan 200272, Nigeria

⁴ Department of Mechanical Engineering, Federal University of Agriculture, P.M.B. 2240, Abeokuta 110253, Nigeria

Corresponding author E-mail: komolafe.adekunle@lmu.edu.ng

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ABSTRACT

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Tilapia fish, convective drying, moisture diffusivity, activation energy

The moisture diffusivity and activation energy of three tilapia fish varieties were determined under convective drying process (CDP). A locally fabricated drying system was used for the experiment at 60, 90/60 and 90 °C drying air temperatures. The drying rate showed falling rate period for all the drying processes with no sign of constant rate period. The moisture diffusivity values which increased with the increase in drying air temperature varied from 7.821×10^{-11} to $4.591 \times 10^{-10} \text{ m}^2/\text{s}$. The predicted Arrhenius constant and activation energy were $2.221 \times 10^{-10} \text{ m}^2/\text{s}$ and 23.79 kJ/mol respectively.

1. INTRODUCTION

Fish, due to its high protein content and nutritional value is being considered a crucial food component in people's meal all over the world [1]. Reduction of moisture content from 80 to 25% will reduce autolytic activity and also prevent bacteria from surviving. However, further reduction of moisture content to 15% or less will stop mould growth during storage [2].

Traditionally, drying of fish is usually done in the open sun on the rack or on a raised smoking platform or three stone stove where control of heat is difficult and at times impossible [3]. The traditional technique is characterized with shortcomings such as weather dependency, insect infestation, etc. and the result is usually unsatisfactory end products. However, if acceptable and suitable drying temperature(s) are adopted under a controlled environment, post-harvest losses incurred as a result of under-drying and over-drying would be greatly reduced.

Heat and mass transfer, moisture diffusion and activation energy are the basic physical and thermal properties of agriculture materials necessary for ideal dryer design [4]. Moisture diffusivity is strongly dependent on temperature and the moisture content [5]. The level of dependency of temperature on the diffusivity is usually described by the Arrhenius equation, and that of moisture content on diffusivity can be introduced in the Arrhenius equation by considering either the activation energy or the Arrhenius factor as an empirical function of moisture [5]. Designing and modelling of mass transfer processes such as dehydration, adsorption and desorption of moisture during storage needs knowledge of moisture diffusivity [6].

Drying methods (simplified, regular regime and numerical solution methods) are one of the various techniques for determining experimentally moisture diffusivity in solids [5]. Moisture diffusivity is a transport

property related to solid's drying or dehydration phenomena. Diffusion in solids during drying may involve the following: molecular diffusion, capillary flow, Knudsen flow, hydrodynamic flow, or surface diffusion. Moisture diffusivity if accurately predicted can lead to optimization of the drying process [7]

Several studies have been reported on modelling of drying kinetics, heat and mass transfer, moisture diffusivity and activation energy of fish [8,9,10, 11], other agricultural products under different drying conditions such as ginger [12], tomato [13], tomato leathers [14], grape leaves [15], olive pomace [16], rough rice [17], rumbutan seed [18], star fruit slices [19], cocoyam slice [20], pomegranate arils [6] and surface building materials [21]. However, no work seems to have been reported on the moisture diffusivity and activation energy of three tilapia fish varieties (mackerel, pilchard and herring) under a locally developed convective drying system. This study was therefore undertaken to determine the drying kinetics, moisture diffusivity and activation energy of three common tilapia fish varieties in Nigeria markets namely: *mackerel* (*Scomber scomber* spp.), *pilchard* (*Sardina pilchardus* spp.) and *herring* (*Clupea harengus* spp.) during convective drying process.

2. MATERIALS AND METHODS

2.1 Experimental set-up

A locally fabricated convective drying system (shown pictorially and schematically as in Figures 1 and 2) capable of operating at desired drying temperature and blower speed was used for the study. Major components of the drying system are well insulated drying chamber, drying cage with tray (made from stainless steel wire mesh of 2.8 mm diameter), a blower (to push the heated air into the drying

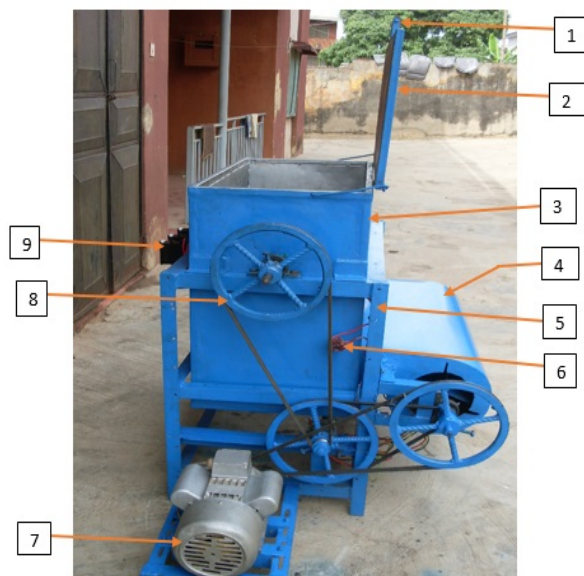
chamber) and a thermostat with sensor.

2.2 Sample preparation

Three common varieties of fresh tilapia fish in Nigeria market namely: Mackerel, Pilchard and Herring obtained from local fish market at Ibadan, Nigeria were used for the study. The frozen fish samples brought to the laboratory were washed thoroughly, head were cut-off. Later, the body without head was pre-treated by soaking in brine solution following the method described by [22]. Thereafter, the pre-treated samples were thoroughly rinsed with clean water to prevent the salt crystal from depositing on fish surface as drying process progresses. The pretreated fishes were then arranged in single layer inside the pre-weighted mesh tray outside the drying chamber and left to drain for five minutes [23].

2.3 Drying procedure

The drying experiments were conducted at Ibadan, Nigeria, latitude $7^{\circ} 22.5^{\circ} \text{N}$ and Long $3^{\circ} 50.5^{\circ} \text{E}$ at constant drying chamber temperature of 60, 90/60 (i.e. drying at high temperature at initial stage and later at lower temperature) [24] and 90°C . Selection of these temperatures was based on the submission of Raham [24] that the drying temperature of fish must be at or above 60°C to avoid microbial risk in the product. Each fish variety already pretreated and weighed was dried at constant drying time of 8 hrs (8 a.m to 4 p.m) [25] on separate day at 60, 90/60 and 90°C . In order to control drying air temperature, a thermostat with sensor (probe) was fixed to the wall of the drying chamber. At intervals of 30 minutes in each experiment, the tray was taken out and weighed quickly to measure moisture loss.



1. Wooden handle 2. Drying chamber cover 3. Drying chamber 4. Blower housing 5. Supporting frame 6. Thermostat 7. Electric motor 8. Drying cage pulley 9. Electric switch

Figure 1. Pictorial diagram of the convective drying system

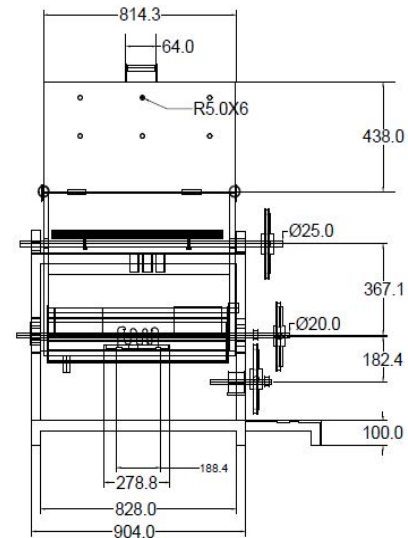


Figure 2. Schematic front view of the convective drying system

2.4 Drying kinetics

The moisture content on wet basis (M_t) was calculated according to [26] as:

$$M_t = \frac{W_i - W_{bd}}{W_i} \quad (1)$$

where M_t is the moisture content (% w.b.); W_i the initial weight of the sample (g) and W_{bd} the final weight of sample (g).

The dimensionless variable of moisture ratio (MR) of fish was calculated according to [27] using:

$$MR = \frac{M_t - M_e}{M_o - M_e} \quad (2)$$

where M_t , M_o and M_e are the moisture content measured at time t , initial moisture content, and equilibrium moisture content respectively. The value of M_e is very small compared to M_t or M_o for long drying time. Thus eqn. (2) can be simplified according to [28] as

$$MR = \frac{M_t}{M_o} \quad (3)$$

The drying rate (DR) of fish was expressed using eqn. (4) [29, 30] as:

$$DR = \frac{M_t - M_{t+dt}}{dt} \quad (4)$$

where M_{t+dt} is moisture content (g water/g wet solid) at $t + dt$, t is the drying time (hr) and dt is change in time (hr).

The drying rate is defined as moisture diffusion from the inside to the outside layer. This can be explained by Fick's second law of diffusion for unsteady state diffusion.

2.5 Moisture diffusivity

The moisture diffusivity is a general property of moist involving the following: liquid diffusion, vapour diffusion, hydrodynamic flow and other possible mass transfer mechanism [31]. Assume fish in the form of approximated slab, the Fick's second law of diffusion adopted to fit the

experimental data for determining moisture diffusivity is expressed according to [15] as:

$$\frac{\partial M}{\partial t} = D_{eff} \nabla^2 \quad (5)$$

The analytical solution of eqn. (5) for slab geometry using the following assumptions: uniform initial moisture distribution, negligible external resistance, constant diffusivity and negligible shrinkage [32] is given as:

$$MR = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{2n-1} \exp\left(\frac{(2n-1)^2 \pi^2 D_{eff} t}{4L^2}\right) \quad (6)$$

where L is sample's half-thickness (m), t is the drying time (s), n is a positive integer and D_{eff} is the moisture diffusivity. Linearizing eqn. (6) [29, 33] as follows:

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 t D_{eff}}{4L^2}\right) \quad (7)$$

The slope of the curve from the plots of $\ln MR$ data against time data is constant of the above linear equation (eqn.7) and the moisture diffusivity was calculated using:

$$D_{eff} = \text{slope} \times \frac{4L^2}{\pi^2} \quad (8)$$

The moisture diffusivity can also be calculated using the Arrhenius equation:

$$D_{eff} = D \exp\left(-\frac{E}{RT}\right) \quad (9)$$

where D is the pre-exponential factor of the Arrhenius equation (Arrhenius constant) (m^2/s), E is activation energy (kJ/mol), R is universal gas constant (8.314 J/mol.K), T is absolute temperature (K).

2.6 Activation energy

The Microsoft Excel SOLVER tool was used for the prediction of the Arrhenius constant and activation energy.

3. RESULTS AND DISCUSSION

3.1 Drying kinetics

Figures. 3-5 show variation in moisture content with the time during the convective drying experiments of three tilapia fish species at 60, 90/60 and 90 °C drying temperature. From the Figurers, the moisture content continuously decreases as drying process progresses. At 60 °C, the initial moisture content of mackerel, pilchard and herring within 8 hrs of drying, reduced from 66.3, 67.3 and 66.2% w.b. to 13.0, 16.5 and 14.7% w.b respectively. Similarly, at 90/60 °C and 90 °C, the initial moisture content of the three tilapia fish species reduced within the same period (8 hrs) from 73.0, 70.6 and 65.2% w.b.; and 68.3, 71.1 and 66.1 w.b. to 16.3, 17.9 and 13.5%; and 12.4, 14.6 and 12.3% respectively. The drying curves indicate absence of constant rate drying period. The drying process dominantly occurred under falling rate period. The continuous decrease in moisture content is an indication that diffusion is the physical mechanism governing the internal

mass transfer. This is in congruent with the results of study on silverside fish [4], prawn and chelwa fish [22] and pomegranate arils [6].

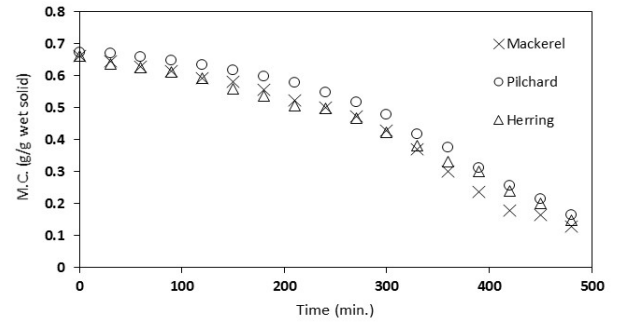


Figure 3. Moisture content as a function time at 60°C drying temperature

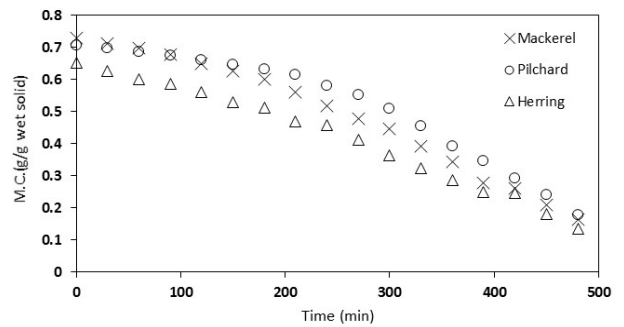


Figure 4. Moisture content versus drying time at 90/60°C drying temperature

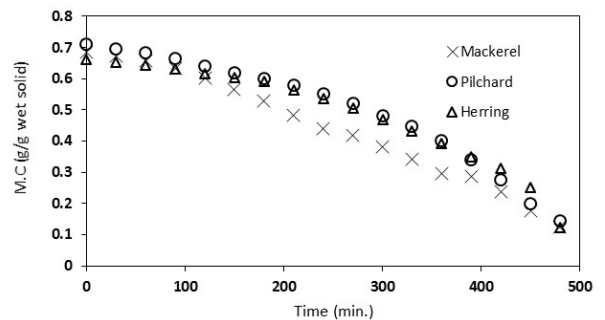


Figure 5. Moisture content versus drying time at 90°C drying temperature

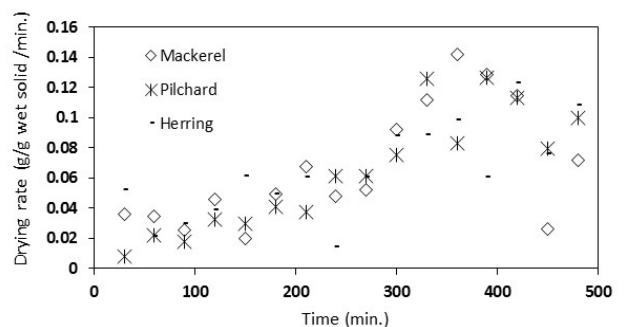


Figure 6. Drying rate as a function time at 60°C drying temperature

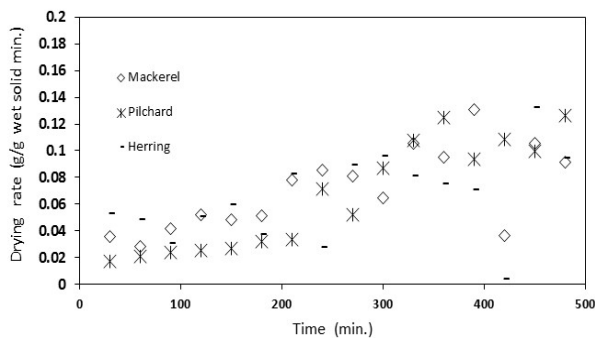


Figure 7. Drying rate as a function of time at 90/60°C drying temperature

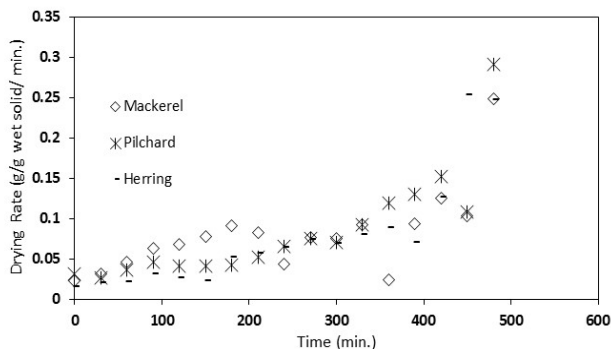


Figure 8. Drying rate as a function of time at 90°C drying temperature

Figures 6-8 depict the relationship between the drying rate and time. The highest drying rate curves were observed in Figure 8 (i.e. at 90°C drying temperature) as compared to two other Figures (Figure 6 and 7). The highest drying rates obtained at 90°C drying temperature were 0.291, 0.253 and 0.246 g/g wet solid min. for pilchard, herring and mackerel respectively. The interpretation of the results is that the higher the drying temperature, the faster the drying rate.

3.2 Moisture diffusivity and activation energy

Figures 9-11 present the variation of logarithm of moisture ratio with drying time at 60, 90/60 and 90 °C drying air temperature. From the Figures, the logarithm of moisture ratio decreased with the increase in drying time. The coefficient of determination (R^2) at 60, 90/60 and 90 °C drying air temperature for the three tilapia fish species (mackerel, pilchard and herring) were 0.982, 0.971 and 0.994; 0.997, 0.969 and 0.996; and 0.903, 0.811 and 0.746 respectively. The calculated effective diffusivities for the fish species are shown in Table 1. It is clearly evident from Table 1 that the increase in drying temperature resulted to increase in moisture diffusivity. The calculated moisture diffusivity value ranged between 7.821×10^{-11} and $4.591 \times 10^{-10} \text{ m}^2/\text{s}$. The values of D_{eff} obtained from this study are within the general range 10^{-12} to 10^{-8} for drying of food materials [34]. The predicted Arrhenius constant and activation energy were $2.221 \times 10^{-10} \text{ m}^2/\text{s}$ and 23.79 kJ/mol respectively. The moisture diffusivity and activation energy values were in reasonable agreement with 0.11 and $0.25 \times 10^{-9} \text{ m}^2/\text{s}$ and 20.32 kJ/mol for fish; 1.7×10^{-10} and $1.15 \times 10^{-9} \text{ m}^2/\text{s}$ and 29.35 to 33.78 kJ/mol for apricot fruit; 7.14×10^{-9} and $3.70 \times 10^{-8} \text{ m}^2/\text{s}$ and 11.797 to 33.318 kJ/mol for

asparagus root reported by [35], [36] and [37]. Also, the predicted activation energy falls within the range 12.7 to 110 kJ/mol reported by [38] for various foods. The sum of square error SSE and root mean square error RMSE of the calculated and predicted moisture diffusivity were 3.8756×10^{-39} and $1.1142 \times 10^{-10} \text{ m}^2/\text{s}$.

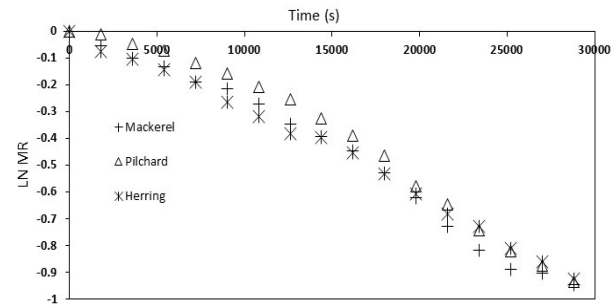


Figure 9. Variation of ln MR with time at 60 °C drying temperature

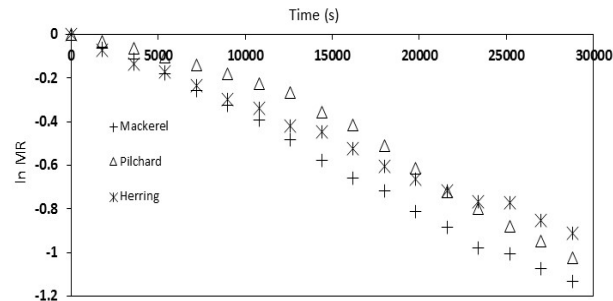


Figure 10. Variation of ln MR with time at 90/60°C drying temperature

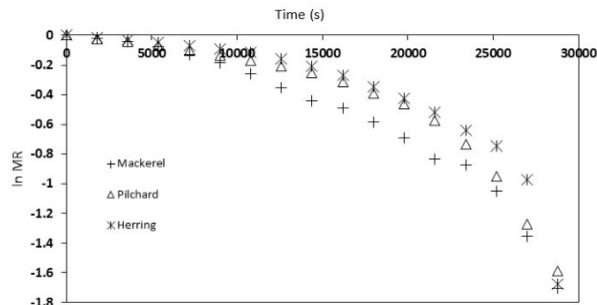


Figure 11. Variation of ln MR with time at 90°C drying temp

Table 1. Calculated moisture diffusivity D_{eff} (m^2/s)

Fish species	Drying temp. °C	Moisture diffusivity m^2/s
Mackerel	60	$1.133\text{E}-10$
Pilchard	60	$1.159\text{E}-10$
Herring	60	$7.821\text{E}-11$
Mackerel	(90/60)	$2.561\text{E}-10$
Pilchard	(90/60)	$1.961\text{E}-10$
Herring	(90/60)	$2.397\text{E}-10$
Mackerel	90	$4.591\text{E}-10$
Pilchard	90	$3.183\text{E}-10$
Herring	90	$2.397\text{E}-10$

Also, the moisture diffusivity values obtained lie within

the range 5.997 and $3.358 \times 10^{-10} \text{ m}^2/\text{s}$, 5.997 and $3.358 \times 10^{-10} \text{ m}^2/\text{s}$, 5.18 and 6.58×10^{-10} ; 11.11 and $8.708 \times 10^{-11} \text{ m}^2/\text{s}$; 4.13×10^{-10} and $1.83 \times 10^{-9} \text{ m}^2/\text{s}$ and 3.43×10^{-10} and $29.19 \times 10^{-10} \text{ m}^2/\text{s}$ reported by [10], [11], [6], [39], [15] and [40] during solar drying of salted catfish; Microwave heating of sardine fish, microwave-vacuum drying of pomegranate arils, open sun drying of fish, cabinet drying of grapes leave and microwave drying of pomegranate arils respectively.

4. CONCLUSION

Moisture diffusivity and activation energy of three locally available tilapia fish species in Nigeria market were investigated and determined under three different drying temperatures. The following results were drawn from the experiments.

- The highest drying rates were observed during the convective drying process at 90 °C drying temperature.
- The calculated moisture diffusivity value ranged between 7.821×10^{-11} and $4.591 \times 10^{-10} \text{ m}^2/\text{s}$.
- The predicted Arrhenius constant and activation energy were $2.221 \times 10^{-10} \text{ m}^2/\text{s}$ and 23.79 kJ/mol respectively.

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NOMENCLATURE

Deff	moisture diffusivity (m ² /s)
D	Arrhenius constant (m ² /s)
DR	drying rate (g H ₂ O/g wet solid h)
E	activation energy (kJ/mol)
L	half thickness of slab (mm)
M	moisture content (%)
MR	moisture ratio (dimensionless)
R	Universal gas constant (8.314 J/mol.K)
T	temperature (K)
W	weight of sample (g)

Subscripts

dt	change in time (hr)
e	equilibrium
f	final
i	initial
m	moisture
t	drying time (hr)