International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249-8958 (Online), Volume-7 Issue-1, October 2017

Determination of Physical and Chemical Properties of Okra During Convective Solar Drying

Germain Wende Pouiré Ouedraogo, Boureima Kaboré, Sié Kam, Dieudonné Joseph Bathiébo

Abstract*-Convective solar drying of okra was carried out for three different types of cuts. Using the variation of the reduced water content or the moisture content of okra as a function of time, we were able to determine the diffusion coefficient of okra. And the mass transfer coefficient. The diffusion coefficient of okra varies from 6.16×10^{-10} to 47.8×10^{-10} m^2s^{-1} depending on the shape of the cut. By applying the Arrhenius relation dependent on the temperature of the drying air, the energy of activation of the okra obtained varies from 20.497 to 39.864 kJ.mol-1.

***Index Terms:* okra, diffusion coefficient, mass transfer coefficient, activation energy, convective solar drying.**

I. INTRODUCTION

Okra is one of the most important vegetables grown in tropical regions and warmer parts of the temperate climatic zone [1]. The okra of scientific name *Abelmoschus Esculentus* is grown for its fibrous pods containing seeds [2]. It contains proteins, vitamins C and A, iron, calcium, dietary fiber and low saturated fats [3]. The okra seeds have an oil content of 15% to 19% and their proteins are of good quality [4]. The freshly harvested okra has a very high moisture content (88-90% wet) with a safe moisture content for storage (10% wet basis) [5]. Due to its high moisture content, its shelf life is short [6] because it is subject to rapid deterioration, resulting in chemical, physical and biological changes. Thus, in order to preserve their crop, the growers proceed to the drying of the product. Drying food is an important method of preservation and can be applied to several products. In countries where weather permits, food is often dried outdoors by sun exposure. The main objective of drying agricultural products is to reduce the moisture content to a level that allows safe storage for an extended period of time [7]. In Burkina Faso, okra drying is mainly carried out in the open air, where okra cut into several sizes is exposed directly to solar radiation and more rarely by solar dryers. The purpose of this study is to carry out convective solar drying of okra by using an indirect solar dryer called a solar tower dryer for three types of cuts. Thanks to the experimental results, we will determine the diffusion and mass transfer coefficients as well as the activation energy of okra.

Manuscript published on 30 October 2017.
* Correspondence Author (s)

Germain Wende Pouiré Ouedraogo, Laboratory of Renewable Thermal Energy, University Ouaga I Pr Joseph KI-ZERBO, Burkina Faso.
Boureima Kaboré, Laboratory of Renewable Thermal Energy, University Ouaga I Pr Joseph KI-ZERBO, Burkina Faso.
Sié Kam, Laboratory of Renewable Thermal Energy, University Ouaga I Pr Joseph KI-ZERBO, Burkina Faso.
Dieudonné Joseph Bathiébo, Laboratory of Renewable Thermal Energy, University Ouaga I Pr Joseph KI-ZERBO, Burkina Faso.

II. EXPERIMENTAL PROTOCOL

A. Product Preparation

The okra used is the Indiana variety. It was bought in the market of Toukin (district of the city of Ouagadougou).
After the purchase, we sorted the okra according to their lengths, diameters and morphologies (healthy external surface). Then we washed, stirred and spread on a glass table for ten minutes so that the water on the surface (water used for washing) evaporates.
We performed three different okra cutouts commonly practiced in Burkina Faso.

- The okra is cut into a cylindrical shape with a height of 1 cm. The radius of the slices varies from one slice to another, but the difference of the order of 0.1 cm to 0.2 cm is considered negligible (Fig. 1). This cutting results in mass losses of the seeds of the order of 1%.

Fig.1. Cylindrical cutting of okra

- The okra is cut in the longitudinal direction by dividing it into two equal parts (Fig.2). The length considered is 4 cm. For this cutting, the mass losses of the seeds are estimated at 3%.

Fig.2. Longitudinal cut-out of okra

- The okra is cut in the longitudinal direction into four equal parts of length 4 cm (Fig.3). It is a cut which causes the greatest loss of seeds, (about 8%) of its initial mass.

Fig.3. Four-dimensional cutting of okra

Finally we weighed them and introduced them into the room to be dried.

B. Materials

The different weightings were possible thanks to an electronic balance of precision 0,1g. The dryer used is an indirect dryer with four racks called a solar tower dryer (Fig.4).

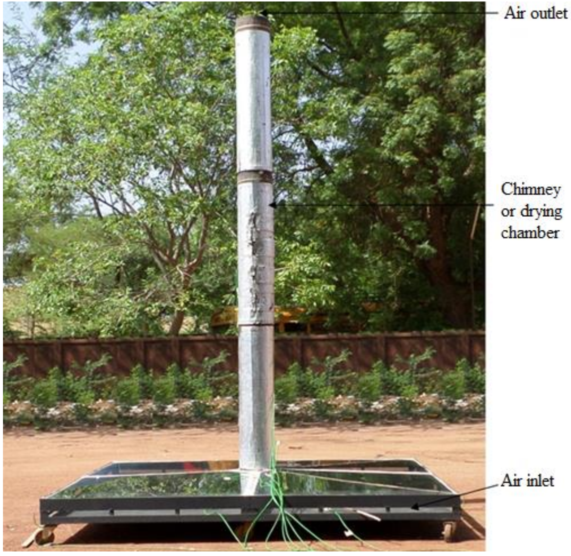

Fig. 4: Solar tower dryer

C. Procedure

The initial mass of the product to be dried is set at 200 g at each rack whatever the cut. The drying process begins at 9am and stops at 5pm for the first day but continues the next day at the same time because it is at this time that one has good solar radiation. The drying time of the okra observed during our experiments varies between 10h and 17h depending on the cutting. The okra of each rack is weighed every fifteen minutes (15 min) for an hour and then every thirty minutes (30 min) until the end of the first day. At the end of the first day, the trays removed from the dryer are stored in a cabinet with an air temperature between 33.8 ° C and 31.5 °C with a relative humidity of between 52% and 66%. On the second day, before placing the products in the dryer, we weigh them. Then the weightings are carried out every thirty minutes (30 min) for two hours and then every one hour until reaching the final wet mass (m_{hf}); that is to say the mass which no longer varies according to two successive weightings.

These experiments were carried out at drying air temperatures between 36 °C and 62 °C with relative humidity ranging from 42% to 67%.

III. MATHEMATICAL MODELING

A. Diffusion Coefficient

The diffusion coefficient is a physical quantity whose equation depends on the shape of the product. It will be determined by adopting the cylindrical shape for the first cut and the form assimilated to an infinite plate for the two longitudinal cuts. The experimental results obtained during the solar drying of okra are analyzed by applying the second Fick law depending on the shape of the product:

- Product having a cylindrical shape

$$\frac{\partial \chi}{\partial t} = \frac{1}{r}\left(\frac{\partial}{\partial r}\left(D_{eff}\, r \frac{\partial \chi}{\partial r}\right)\right) + \frac{\partial}{\partial z}\left(D_{eff}\, r \frac{\partial \chi}{\partial z}\right) \qquad (1)$$

where χ is the moisture content (kg water/kg dry basis), D_{eff} is the diffusion coefficient ($m^2 s^{-1}$), t is the time and r is the radius of okra (m)

Along a cylinder, the majority of water transfers are radial, so equation (1) gives equation (2) [8].

$$\frac{\partial \chi}{\partial t} = \frac{1}{r}\left(\frac{\partial}{\partial r}\left(D_{eff}\, r \frac{\partial \chi}{\partial r}\right)\right) \qquad (2)$$

- Product having a form assimilated to an infinite plate

$$\frac{\partial \chi}{\partial t} = D_{eff} \frac{\partial^2 \chi}{\partial x^2} \qquad (3)$$

The analytical solution of Eq. (2) and Eq. (3) is given by equations Eq. (4) and Eq. (5) according to the shape of the product [9]:

- Product having a cylindrical shape

$$MR = \frac{\chi_t - \chi_{eq}}{\chi_0 - \chi_{eq}} = \frac{4}{\beta^2} \exp\left(-\frac{\beta^2 D_{eff}\, t}{r^2}\right) \qquad (4)$$

- Product having a form assimilated to an infinite plate

$$MR = \frac{\chi_t - \chi_{eq}}{\chi_0 - \chi_{eq}} = \frac{8}{\pi^2} \exp\left(-\frac{\pi D_{eff}\, t}{4\, l^2}\right) \qquad (5)$$

Where MR is the water content ratio or moisture ratio, χ_t is the moisture content of the product at time t (kg water/kg dry basis), χ_0 is the initial moisture content (kg water/kg dry basis), χ_{eq} is the equilibrium moisture content (kg water/kg dry basis), l is the half -thickness of product (m) and t is the time (s).

The diffusion coefficient is determined by following the following steps:

- Calculating MR from the experimental drying data at each instant t
- Plot the curve of ln(MR) as a function of the time expressed in second and then determine the equation of the straight line in the form ln(MR) = A + B.t where A is the intersection and B the slope.

- For the cylindrical shape, β is determined from the intersection A and then reintroduced into the slope B for the calculation of the diffusion coefficient.
- For the other form, the Fourier humidity number $F_0 = D_{eff}\frac{t}{l^2}$ must be entered in Eq. (5) and we obtain:

$$F_0 = \frac{4}{\pi}\left(\ln\left(\frac{8}{\pi^2}\right) - \ln(MR)\right) \qquad (6)$$

Then

$$D_{eff} = \frac{F_0}{(t/l^2)_{exp}} \qquad (7)$$

The diffusion coefficient D_{eff} was calculated by substituting the positive values of F_0, the drying time and half average thickness of okra in Eq. (7).

Finally, we perform the arithmetic mean of the different values of D_{eff} to determine the diffusion coefficient of the product.

B. Mass transfer coefficient

Thin layer drying models assume that changes in water content during drying are related to certain parameters. Parameters such as drying constant $k(s^{-1})$ or delay factor k_0 (dimensionless). They take into account the combined effects of various transport phenomena during drying.

Considering analytic Eq. (4) and Eq. (5), the Henderson and Pabis model given by Eq. (8) is analogous to these equations.

$$MR = k_0 \exp(-k\,t) \qquad (8)$$

The different correspondences of the coefficients are given in Table I.

Table. I. Correspondence of Coefficients of Analogous Equations.

Model of Henderson and Pabis	k_0	k
Cylindrical product	$\frac{4}{\beta^2}$	$\frac{\beta^2 D_{eff}}{r^2}$
Product of longitudinal shape	$\frac{8}{\pi^2}$	$\frac{\pi D_{eff}}{4 l^2}$

The values of k_0 and k will be used in the determination of the mass transfer coefficient.

Thus the convective mass transfer coefficient $h_m(m.s^{-1})$ and the diffusion coefficient are linked by the Biot number (B_i) which is a dimensionless number. The Biot number expression also depends on the shape of the product:

- Product having a cylindrical shape

$$B_i = \frac{h_m\, r}{D_{eff}} \qquad (9)$$

Where r is the radius of the okra cut into cylindrical shape (m)

- Product having a shape assimilated to a plate.

$$B_i = \frac{h_m\, l}{D_{eff}} \qquad (10)$$

l is the half thickness of the okra cut longitudinally (m).

These Eq. (9) and Eq. (10) are valid for a Biot number greater than 0.1 and allow estimation of the mass transfer coefficient if Bi is known [10].

The determination Bi is made from Eq. (11), linking the number of Dincer to the Biot number. This relation is called Dincer's correlation and has as expression:

$$B_i = 28{,}848 D_i^{-\frac{3}{8}} \qquad (11)$$

$$\text{with } D_i = \frac{U}{k\,r} \quad \text{ou } D_i = \frac{U}{k\,l} \qquad (12)$$

Where $U(m.s^{-1})$ is the drying air flow velocity and k (s^{-1}) is the drying constant.

The determination of the mass transfer properties was carried out in accordance with the following steps:

- From the experimental drying data at each instant t, determine the diffusion coefficient D_{eff}
- Determine k and k0 by combining Eq. (4) and Eq. (9) for okra having a cylindrical shape or Eq. (5) and Eq. (9) for okra having a longitudinal shape.
- Calculate D_i and B_i by applying Eq. (12) and Eq. (11) respectively.
- Deduce from the Eq. (10), the mass transfer coefficient h_m.

C. Activation Energy

The activation energy corresponds to the quantity of energy that must be supplied to the product to initiate the transfer of water into the product. It is a function of the temperature and the diffusion coefficient. The activation energy is expressed by the Arrhenius equation:

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{R(T+273{,}15)}\right) \qquad (13)$$

Where D_0 is the pre-exponential factor of the Arrhenius equation ($m^2.s^{-1}$), E_a is the activation energy ($kJ.mol^{-1}$), T is the drying temperature (°C) and R is the perfect gas constant ($kJ.mol^{-1}.K^{-1}$).

The preceding equation (13) can be written in the following form:

$$\ln(D_{eff}) = \ln(D_0) - \frac{E_a}{R(T+273{,}15)} \qquad (14)$$

To determine the activation energy, it is sufficient to:

- Calculate D_{eff} values for the different experiments
- Plot the curve of the diffusion coefficients as a function of the inverse of the temperatures and this according to the cutting mode of the okra.
- Then deduce the energies of activation through the slopes of the straight lines described by the Arrhenius equation.

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

IV. RESULTS AND DISCUSSION

A. Diffusion Coefficient

The convective solar drying of okra slices yielded experimental results for the determination of the diffusion coefficient.

The Fig.5 gives the shape of ln (MR) = f (t) and its linearization for the okra cut in cylindrical form.

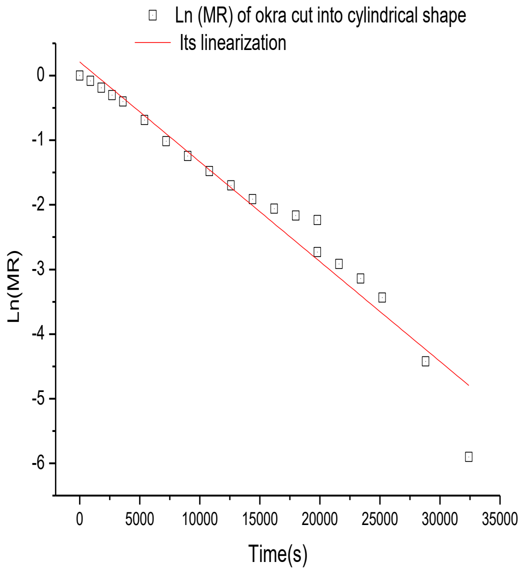

Fig.5: Linearization of the function ln (MR) = f (t) of the okra cut into cylindrical shape.

This Fig.5 makes it possible to determine the slope (B) and the intersection of the linearization line whose values are written in the Table II with a regression which tends towards 1.

Table.II. Linearization characteristics

Okra carved	Intersection (A)	slope (B)	R²
In cylindrical shape	0,21265	-1,54536.10^{-4}	0,94992

The diffusion coefficients determined from the values of the linearization and the number of Fourier moisture is 47.8×10^{-10} $m^2 s^{-1}$, 6.16×610^{-10} $m^2 s^{-1}$ and 8.99×10^{-10} $m^2 s^{-1}$ respectively for the okra cut into cylindrical form, longitudinally in two, and longitudinally in four.
Table III shows the different values obtained.

Table.III. Diffusion coefficients and dimensions of okra

Okra carved	$D_{eff} \times 10^{-10} (m^2.s^{-1})$	R ou l (m)	β
In cylindrical shape	47,8	0,01	1,798265
Longitudinally in two	6,16	0,0025	
Longitudinally in four	8,99	0,0025	

We observe that the okra cut into cylindrical shape has a diffusion coefficient higher than the okra cut longitudinally. This seems to indicate that the okra cut into cylindrical shape allows the best transfer of water in the product and accelerates the drying process.
The diffusion coefficient of the whole Okra, determined by K.H. Ouoba et al. [9], is equal to 2.81×10^{-10} $m^2.s^{-1}$for a temperature of 70°C. This value is lower than the diffusion values obtained in this study. Using the correlation number of Biot-Dincer number, Dincer et al [11] estimated the diffusion coefficient of okra cut into cylindrical shape at 5.67×10^{-10} $m^2.s^{-1}$. However, the diffusion coefficient values of okra determined by Gökçe Dadalı in 2007 [12] vary between 20.52×10^{-10} $m^2.s^{-1}$ and 86.17×10^{-10} $m^2.s^{-1}$ depending on the power of the microwave used. Kaymak-Ertekin in 2002 [13] has obtained values of diffusion coefficients of okra on the order of 4.27×10^{-10} $m^2.s^{-1}$ to 13.0×10^{-10} $m^2.s^{-1}$for an air temperature range between 50 and 70 ° C.
Certainly the values of the diffusion coefficients of okra that we have calculated are more or less higher or lower than those found in the literature. But this is explained by the fact that none of these authors worked under variable conditions such as solar drying. Because the applied drying mode influences the diffusion coefficient.

B. Mass transfer coefficient

The results obtained are given in Table IV.

Table. IV. Calculated parameters to determine the mass transfer coefficient

Okra carved	k_0	$k \times 10^{-5}$ (s^{-1})	D_i	B_i	$h_m \times 10^{-8}$ $(m.s^{-1})$
In cylindrical shape	1.2369	15.457	323478.03	0.2476	11.84
Longitu-dinally in two	0.8105	7.741	2583712.28	0.1136	2.801
Longitu-dinally in four	0.8105	11.297	1770381.52	0.1309	4.708

The mass transfer coefficient of okra cut longitudinally in two is 2.801×10^{-8} $m.s^{-1}$, that of okra cut longitudinally in four is 4.708×10^{-8} $m.s^{-1}$, and that of okra cut into cylindrical shape is 11.84×10^{-8} $m.s^{-1}$. The value of the mass transfer coefficient of the cut-out okra in cylindrical shape is greater than the other mass transfer coefficient. This shows that the transfer of water in this okra is fast compared to the okra cut longitudinally.
The mass transfer coefficient of okra cut into cylindrical shape, determined by Dincer et al. [11] is estimated at 1.6098×10^{-8} $m.s^{-1}$ for a okra radius corresponding to 3mm. This value is less than that which we have determined for the same form of cutting. However, the difference in value may depend on the variety of the product and on the drying conditions which are different.

C. Activation Energy

Fig.6 gives the influence of the drying air temperature on the diffusion coefficient of the okra as a function of the cuts.

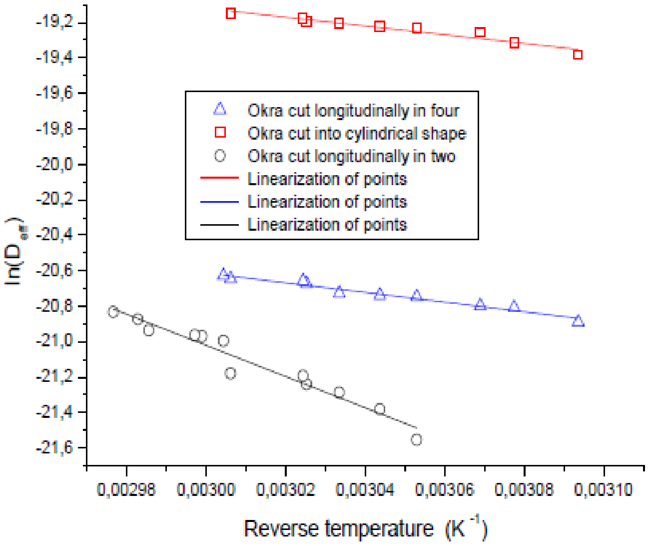

Fig.6. Linearization of functions ln (D_{eff}) = f (1 / T) for each cut.

Using the linearization of the different points of the diffusion coefficient of okra obtained as a function of the inverse of the temperature of the drying air, we were able to calculate the energies of activation and the pre-exponential factors. These values are grouped in Table V.

Table.V. The calculation results of the activation energy of okra

Okra carved	$D_0 \times 10^{-7}$ ($m^2.s^{-1}$)	$E_a(kJ.mol^{-1})$	R^2
In cylindrical shape	80.917	20.497	0.9213
Longitudinally in two	7.7352	39.864	0.9446
Longitudinally in four	39.603	22.653	0.9622

The transfer of water in okra cut longitudinally in two requires activation energy of 39.864 $kJ.mol^{-1}$ while that cut into four requires only activation energy of 22,635 $kJ.mol^{-1}$. Finally, okra cut in cylindrical form is the one which, in our study, requires lower activation energy (20.497 $kJ.mol^{-1}$). However, the last two values are in the order of magnitude of the results found by Lam Van Mana et al in 2012 [14]. They claim that the okra activation energies calculated for temperatures of 50 °C, 60 °C and 70 °C are respectively 21.4 $kJ.mol^{-1}$, 24.5 $kJ.mol^{-1}$ and 26.1 $kJ.mol^{-1}$.

V. CONCLUSION

The okra drying experiments were carried out under varying conditions of drying air temperature and humidity; that is to say in the solar drying conditions. From the results obtained, it is noted that the okra cut into a cylindrical shape has the largest diffusion coefficient ($47.8 \times 10^{-10}\ m^2.s^{-1}$). This okra having this form of cut also has the largest mass transfer coefficient, ie $11.84 \times 10^{-8}\ m.s^{-1}$ and the smallest value of the activation energy, (20.497 $kJ.mol^{-1}$). Therefore, it is necessary to reduce the energy of the okra cut into cylindrical shape to allow the extraction of its moisture.

The higher the diffusion and mass transfer coefficients, the more rapid the moisture transfer from inside to outside. Thus, the final wet mass of okra cut into cylindrical form is obtained faster than the final wet mass of the other cuttings of okra.

REFERENCES

1. B. Sankar, J.C. Abdul, P. Manivannan, A. Kishorekumar, R. Somasundaram, and R. Panneerselvam, "Relative Efficacy of Water Use in Five Varieties of Abelmoschus esculentus (L.)" Moench. under Water-Limited Conditions Colloids and Surfaces. Biointerfaces, 2008, 62, pp. 125-129.
2. D. Kumar, S. Prasad, and G.S. Murthy, "Optimization of microwave assisted hot air drying conditions of okra using response surface methodology". Journal of Food Science and Technology, 2011.
3. M. Camciuc, M. Deplagne, G. Vilarem, and A. Gaset, Ocra (Abelmoschus esculentus L. Moench.) a Crop with Economic Potential for Set Aside Acreage in Frances Industrial. Crops and Products, 1998, vol. 7, pp. 257-264.
4. I. Doymaz, Drying characteristics and kinetics of okra. Journal of Food Engineering, 2005, Vol. 69, pp. 275-279.
5. U.S. Shivhare, A. Gupta, , A.S Bawa and P. Gupta, "Drying characteristics and product quality of okra". Drying Technology, 2000, Vol. 18, Number 1 & 2, pp.409-419.
6. D. Kumar, and S. Prasad, Microwave-convective drying characteristics of okra. An ASABE Meeting Presentation, 2010.
7. E.K. Obiakor, Experimental evaluation of mechanical dehydration of Nigerian cocoa beans. Nigerian Journal of Technology, 1975, Vol. 1, No. 1, pp. 12-18.
8. J. Crank, The mathematics of diffusion second edition, London,UK: Oxford University Press, 1975.
9. K. H. Ouoba, H. Desmorieux, F. Zougmore et B. Naon, Caractérisation du séchage convectif du gombo, influence de la découpe et de ses constituants, Afrique Science 2010, 06(2), pp. 37 – 48.
10. A. Z. Sahin, I. Dincer, B. S. Yilbas and M. M. Hussain, “Determination of drying times for regular multi-dimensional objects,” International Journal of Heat and Mass Transfer, April 2002, vol. 45,no. 8, pp. 1757–1766.
11. I. Dincer and M. M. Hussain, “Development of a new Bi–Di correlation for solids drying,” International Journal of Heat and Mass Transfer, July 2002, vol. 45, no. 15, pp. 3065–3069.
12. G. Dadalı, D. K. Apar, and B. özbek, "Estimation of Effective Moisture Diffusivity of Okra for Microwave Drying", Drying Technology, 2007, 25(9), pp. 1445-1450.
13. F. Kaymak-Ertekin, ‘Drying and Rehydrating Kinetics of Green and Red Peppers’, Journal of Food Science, 2002, Vol. 67, N°1, pp. 168 – 175.
14. L. V. Mana, T. Orikasab, Y. Muramatsuc and A. Tagawaa, "Impact of Microwave Drying on the Quality Attributes of Okra Fruit", Food Processing & Technology, 2012.

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)