Original Research Article

EXPERIMENTAL STUDY OF PAPAYA DRYING IN AN INDIRECT SOLAR DRYER IN NATURAL CONVECTION

ABSTRACT

Papaya is a fruit that is prized for its flavor and also for its different appearances. It is seasonal and easily perishable in our climatic conditions. This work is devoted to the improvement of conservation techniques such as drying. We conducted our experimental work in an indirect solar dryer in natural convection under real (random) climatic conditions and the curves are plotted and adapted using the MATLAB calculation software.

The results obtained show that for slices of papaya 1 cm thick dry less quickly than that of 0.5 cm thickness.

The Gaussian is the model that best adapts to drying curves. The effective diffusion coefficient for 1cm thickness is $Deff$=6.80.10−10m/s^2.

Keywords: papaya, drying kinetics, Gaussian, thickness, diffusion coefficient.

I-INTRODUCTION

Solar drying is a less expensive drying technique, therefore a technique well suited for Burkina Faso which has good sunshine. However, the natural factors accompanying solar drying are often difficult to predict. To avoid loss of time and loss of products often observed in drying, it is important to first proceed with experimental tests in order to make

account for the influence of certain parameters and adapt the drying kinetics to empirical or semi-empirical functions. Minh-Hue Nguyen et al [1] have shown that the greater the thickness, the greater the diffusion. Several authors have determined the diffusion coefficient for several products such as cassava, banana, pumpkin [2], okra [3] and have been able to show that it is a function of the water content and even of the thickness of the product [4]. The influences of temperature and/or drying air velocity have also been shown [5], [6], [7].

The influence of humidity was also determined. The lower the air humidity, the shorter the drying time [8].

For our part, parameters such as temperature, speed and humidity of the drying air take on random values during the process.

drying. Our drying device is a plane solar dryer equipped with fins. During our study, the evolution of the air temperature will be monitored at the level of the sensor (inlet and outlet), along the drying chamber and the evolution of the sunshine. The variation in the temperature of the product during drying and the variation in the relative humidity of the air in the drying chamber are also monitored. It is shown the influence of the thickness during drying on the kinetics of drying. A suitable drying model for the drying kinetics of papaya slices is determined and the effective diffusion coefficient calculated.

II. MATERIALS AND METHODS

II.1. The solar heating unit

It is an indirect dryer where the drying air is preheated by a flat collector. Air circulation is natural. The insolator used is the heating unit of an indirect dryer for food products. It is a flate insolator. The air passes between the absorber fitted with rectangular fins (19) and the insulation. The purpose of adding fins in the useful air stream is to increase the thermal performance of the insolator, more precisely the temperature at the entrance to the drying compartment. The insolator consists of a single glazing, it is inclined by about 12° and oriented towards the south. The pane used is a single pane (without selective coating) 5mm thick, 1x3m long and 1m wide. The absorber is a mild steel sheet with a length of 3m by a width of 1m and a thickness of 1mm. It is painted matt black to limit radiation towards the glass. Between the glass and the absorber is confined an air gap. On the rear face of the absorber are fixed the 19 fins in rectangular shape and spaced 5cm apart. The box is a structure in the form of a frame which consolidates everything and which has openings for the passage of the heat transfer fluid. The absorber plate is glued to 21 slats 5cm long and 3cm wide each. The height between the absorber and the bottom of the cabinet is 5cm. The sides and the bottom are protected by insulation which is none other than polystyrene. The box is covered by an aluminum sheet.

II.2. The drying cage

The drying chamber is parallelepipedic in shape. This chamber is constructed with heavy 25mm square tubing and thermally insulated with polystyrene. It is covered inside and out by an Alu-zinc sheet. In the enclosure of the chamber are placed four shelves spaced 20cm apart, built with 25mm aluminum angles on which will be placed racks of 1m^2 each. The racks are made of galvanized mesh to facilitate air-product contact. To evacuate the air laden with humidity after contact with the product or to facilitate its renewal, a chimney is built above the drying chamber on which can be placed a fan operating in direct current thanks to a solar panel.

- ✔ The stand is the third part of the dryer. It is made of 30mm thick heavy angle iron and

30mm diameter heavy round tubes. This support ends on six casters (06) facilitating its mobility when needed.

II.3. Measurement equipment

The results are obtained using some devices that we list below:

- ✔ a pyranometer (type SR03), measures the global solar radiation received on the plane of the sensor. The results obtained are displayed and recorded by a datalogger. The voltage value obtained is in millivolts (mV) and converted to (W/m2) using the sensitivity: 7.64µV/(W/m2).
- ✔ a GL200A datalogger to measure temperatures. This device has ten outputs where type K thermocouples are placed.
- ✔ a type recording hygrometer (RHT10), allows to measure the relative humidity of the air
- ✔ a PCE-Bs brand scale to measure the mass of the product during drying.

A drying product, the papayas chosen are ripe and firm. The fruits are washed, peeled, deseeded and then cut as desired.

<u>Math expressions</u>

The initial water content was determined from the formula:

$$X_0 = \frac{m_o - m_s}{m_s} \quad \textbf{(1)}$$

Avec :

X_0 **:** The initial water content (kgwater/kgdrymass)

m_o **:** The initial mass (kg)

m_s **:** The dry mass (kg)

The water content at each instant was determined by the formula:

$$X(t) = \frac{m(t) - m_s}{m_s} \quad \textbf{(2)}$$

Avec :

$X(t)$ **:** The water content at time t (kgwater/kgdrymass)

$m(t)$ **:** The mass at time t (kg)

m_s **:** The dry mass (kg)

Expression (1) made it possible to obtain an average value of the initial water content on a dry basis of the product of 6.7kgwater/kgms, i.e. 87.7%, this value is close to that found by Donald G. Mercer [9]. expression 1 made it possible to obtain an average value of the initial water content on a dry basis of the product of 6.7kgwater/kgms or 87.7% this value is close to that also found by Donald G. Mercer [9].

III. RESULTS

III.1. Changes in temperature and humidity of the drying air

We followed the evolution of the temperature from the inlet to the outlet of the sensor and that of the drying chamber as a function of time and sunshine.

Figure 1 shows the evolution of the temperature of the drying air at the inlet and at the outlet of the collector as a function of time and solar flux.

Figure 1: Evolution of the temperature of the drying air at the collector inlet and outlet as a function of time and solar flux

The solar flux evolves in the shape of a bell during the day. It reaches its maximum around 12h30min with a value of around 1000W/m^2. Air temperatures change according to solar flux.

The air temperature at the sensor inlet varies slightly and is approximately equal to the ambient temperature. The air temperature at the outlet increased and reached a maximum value of approximately 81°C around 12h30mins. Similar results are obtained by Boukaré et al [10].

Figure 2 presents the evolutions of the temperature of the papaya and that of the drying air during drying.

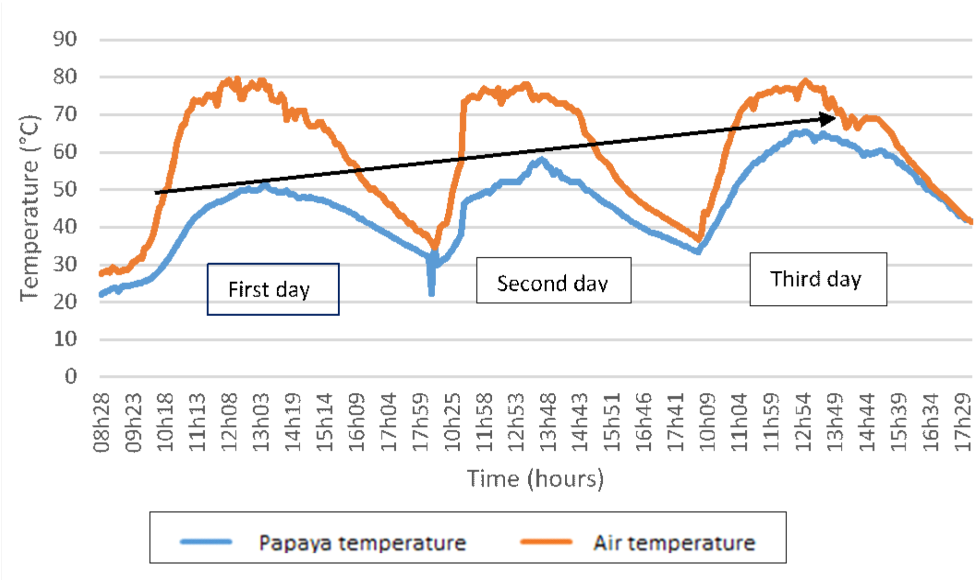

Figure 2: Changes in the temperature of the rack and that of the papaya during drying

On the first day of drying, the maximum temperature of the papaya slices is around 50.3°C and that of the rack is 79.2°C. On the second day of drying, the maximum temperature of the papaya slices is around 57.5°C and that of the rack is 78°C. On the third day of drying, the maximum temperature of the papaya slices is around 65.5°C and that of the rack is 78.3°C. We find that the maximum temperature of the product increases from the first to the third day of drying. This increase is explained by the decrease in the water content of the product during drying. In fact, the hot air is used to evaporate the water in the product and at the same time increase the temperature of the product. The temperature of 54°C on the third day is justified by the fact that the water content is now lower than on the first two days.

The temperature of the product tends towards the temperature of the drying air [11]

Figure 3 shows the variations in temperature and relative air humidity in the drying chamber.

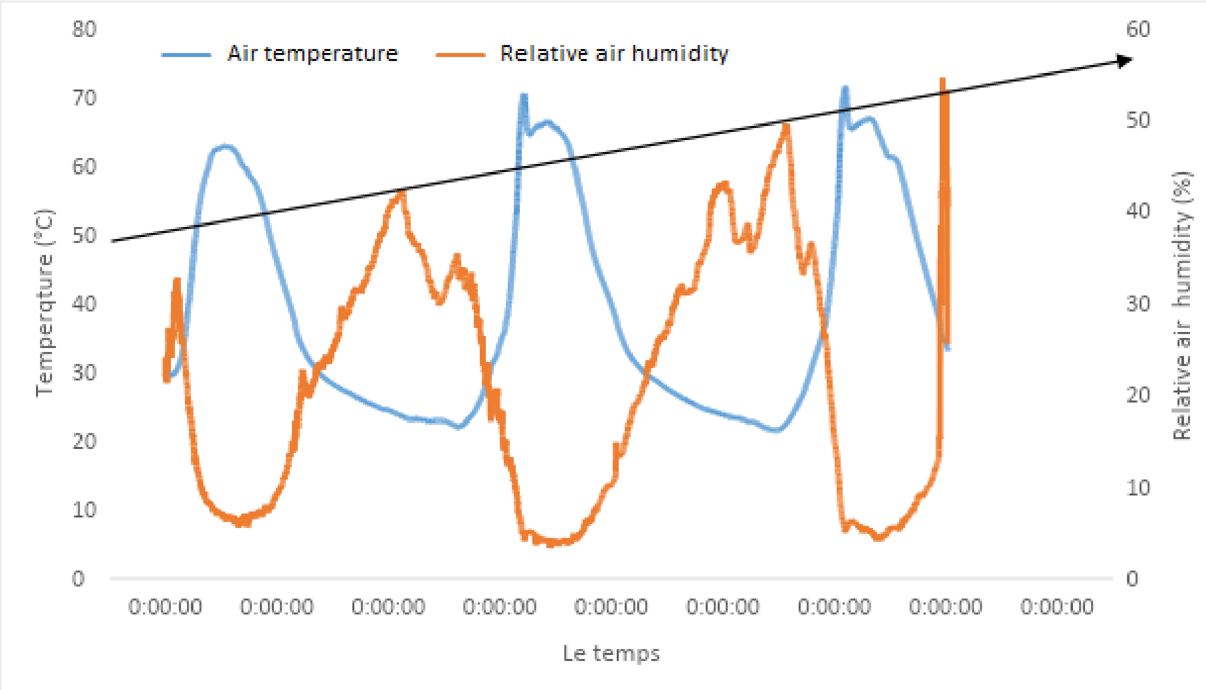

Figure 3: Changes in temperature and relative air humidity on the fourth rack

We find that these two parameters vary in opposite ways. Indeed, the increase in air temperature at the beginning of the day by greenhouse effect leads to a gradual decrease in its relative humidity which reaches its minimum in the middle of the day when the temperature inside the dryer is at its maximum. We have a relative humidity of 4% around 2 p.m. for a temperature of 72°C. At night we have humidity values above 48% with a temperature of 21°C. The maximum value of the relative humidity of the air increases from the first to the third day, this is due to the presence of part of the water vapor yielded by the product which remains in the drying chamber.

Figure 4 shows the air temperature variations along the drying cage. The temperatures are recorded on the racks and at the level of the chimney (outlet)

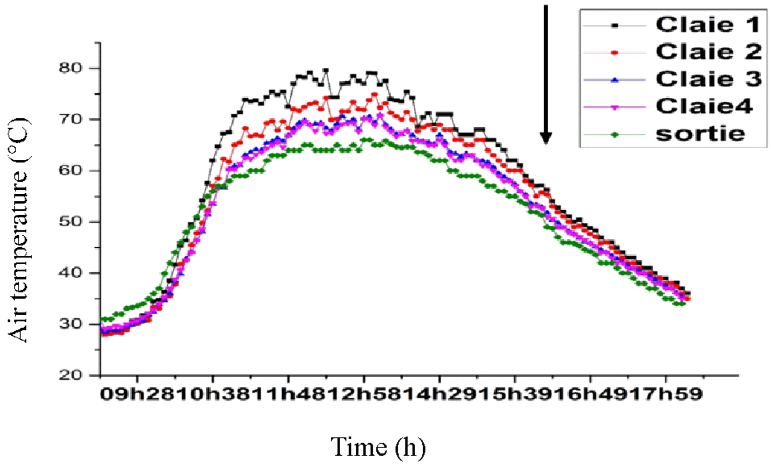

Figure 4: Evolution of temperatures between inlet and outlet at the level of the drying cage

In a multi-tiered dryer, during drying, the drying air circulating vertically from bottom to top, the temperatures on racks 1 and 2 are (slightly) higher than those of racks 3 and 4.

This difference can be explained by the humidity of the air which increases from bottom to top. The heat provided by the drying air causes the water in the product to evaporate. The air drying at the “n” rack is that coming from the “n-1” rack and so on. The air gives up part of its heat to the products on the previous rack and takes on moisture, so the temperature decreases along the dryer. Fidèle Anoumou ANANIVI [12] also obtained similar results during this work.

III.2. Kinetics of drying

Figure 5 shows the comparative drying kinetics of slices with thicknesses of 0.5cm and 1cm

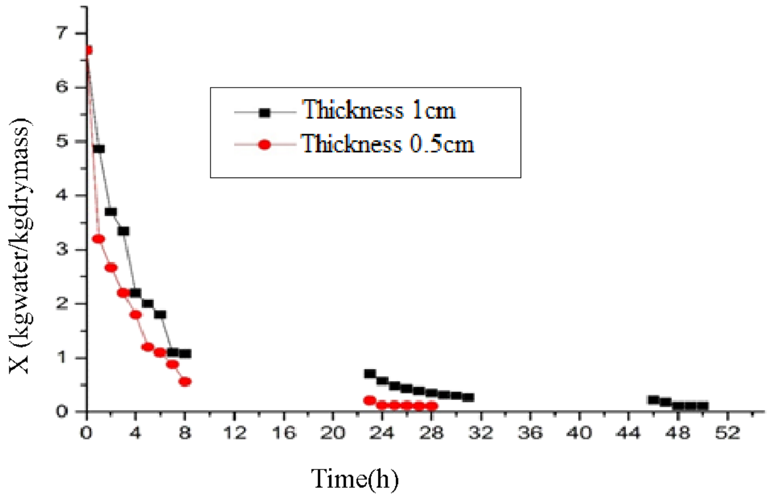

Figure 5: Variation of water content as a function of time and thickness

The pace of the drying kinetics of papaya slices shows that the water content of the product decreases rapidly at the start of drying, then more and more slowly.

The study of the solar drying kinetics of papaya shows the unique presence of the slowing down phase, and the absence of the warming up phase and the phase at constant speed, as is the case for the majority of agricultural products [13].

Papaya slices reach a water content of about 10% at the end of drying, this result is similar to that obtained by Donald G. Mercer et al [9]. This final water content is appropriate for the conservation of papaya.

As for the influence of thickness on the drying kinetics of papaya. We find that the higher the initial thickness (1cm), the slower the drying, so the slices whose the thickness is 0.5cm dries faster. In a thick slice, water vapor travels a longer path than in a thinner slice, which is why it dries less quickly. Similar results were found by DIANDA et al on tomato [4].

III.3. Effective diffusion coefficient

The diffusion coefficient is an important parameter for modeling drying.

For the determination of the diffusion coefficient, we consider the papaya slice as having a cylindrical shape. The solutions to Fick's second law depend on the shape of the sample. For this, the experimental results can be analyzed using the Fick diffusion equation, developed by Crank (1975)[14]. Assuming that the transfers are one-dimensional, the water content initially uniform in the product, without contraction of the solid matter and a long diffusion time, the analytical solution of the Fick equation, according to the geometric shape of the sample, is given by the equations:

$$X^* = \frac{X(t)-X_e}{X_0-X_e} = \frac{4}{\beta^2}\exp\left(-\frac{\beta^2.D_{eff}.t}{r_c^2}\right) \qquad (3)$$

with :

X^* : reduced water content (kgwater/kgdrymass)

D_{eff} : effective diffusion coefficient ($m^2.s^{-1}$)

$X(t)$: average water content at time t (kgwater/kgdrymass)

X_0 : initial water content (kgwater/kgdrymass)

X_e: equilibrium water content (kgwater/kgdrymass)

t : drying time in (s)

r_c : the radius of the cylinder (m)

The diffusion coefficient is generally determined by plotting the curve of the function

$\ln ln\, X^* = f(t)$

From (3) we have:

$$\ln ln\, X^* = \ln ln\, \frac{4}{\beta^2} - \left(\frac{\beta^2.D_{eff}.t}{r_c^2}\right) \qquad (4)$$

This equation can be written in the form : $\ln ln\, X^* = A + B.t$ $\quad A = \ln ln\, \frac{4}{\beta^2}$ et $B =-\frac{\beta^2.D_{eff}}{r_c^2}$

being constants to be determined graphically. From these constants we determine β and D_{eff}

Figure 6 below represents function $\ln ln\, X^* = f(t)$

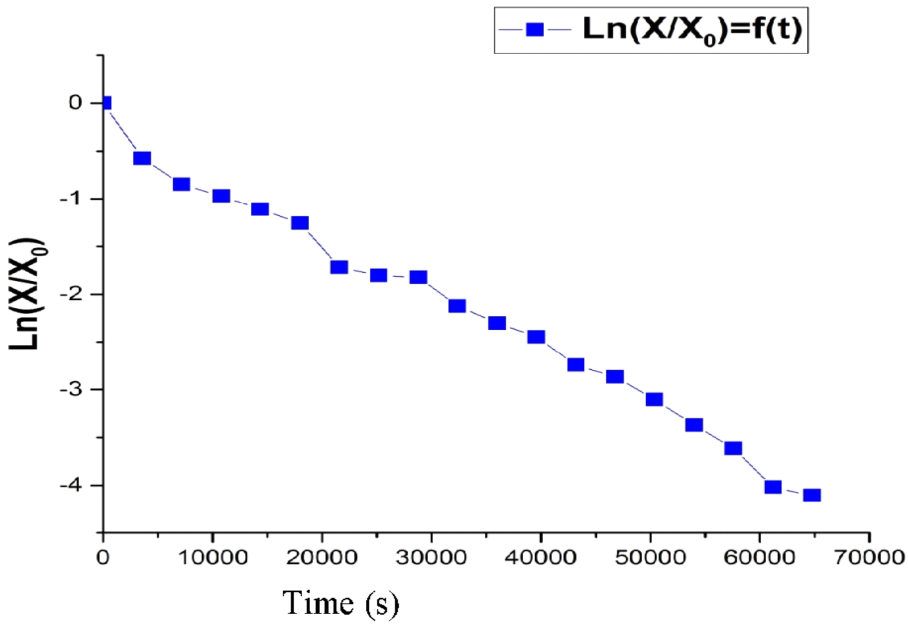

Figure 6: Variation of ln(X/Xo) as a function of time

We obtain $A =- 0,286$ and $B =- 5,8.10^{-6}$ with a confidence interval of 95%. We deduce β= 2,3074 and $D_{eff} = 6,80.\ 10^{-10} m/s^2$

This result is close to that obtained by Lemus-Mondaca et al. [15] who found a value of $6{,}25.10^{-10}$ m/s^2 at 40°C.

III.4. Adaptation of drying curves

Curve fitting is a technique that consists of reducing the irregularities and singularities of a curve and deducing an equation from the curve.

In this study, papaya experimental data were fitted to 10 commonly used models which are empirical and semi-empirical drying models. In addition to these known models we will use the Gaussian, a new method tested by DIANDA et al. [4]

Table 1 presents the drying models used

Table1: Table of some drying models

Nom du model	Expression de l'équation	Référence
Lewis	$X^*=\exp(-k^*t)$	Lewis (1921)
Page	$X^*=\exp(-k^*t^n)$	C. Page, 1949
Page modifié	$X^*=\exp(-k^*t)^n$	D. G. Overhults et al, 1973

Henderson et Padis	X*=a*exp(-k*t)	Tunde-Akintunde, 2011
Logarithmic	X*=a*exp(-k*t) + c	Yaldiz et al. (2001)
Two-term	X*=a*exp(-k_o*t) + b*exp(-k_1*t)	Henderson(1974)
Exponetiel two-terme	X*=a*exp(-k*t) + (1-a)*exp(-k*a*t)	Midilli and Kucuk (2003)
Wang and Singh	X*= 1 + a*t + b*t^2	Wang and Singh (1978)
Verma et al	X*=a*exp(-k*t + (1-a)exp(-k*b*t)	Verma et al. (1985)
Midilli et al	X*=k_o*exp(-k1*t^n) + b*t	Sacilik et al. (2006)
General model Gauss1	X*= a*exp(-((x-b)/c)^2)	DIANDA et al
General model Gauss2	X*=a_1*exp(-((t-b_1)/c_1)^2) + a_2*exp(-((t-b_2)/c_2)^2)	DIANDA et al

The drying curve is generally represented by the reduced water content as a function of time :

$X^* = \frac{X(t)-X_e}{X_0-X_e}$. This expression for reduced water content can be simplified to relative water content: $X^* = \frac{X(t)}{X_0}$ because the values of the equilibrium water content X_e are relatively low compared to those at a time t denoted X(t) and to the water content in the initial state X_0. The error made is therefore very low.

The approaches used for adaptation are summarized in Table III.1. The accuracy of each model is evaluated using the correlation coefficient R^2, the statistical parameter χ^2, and the root mean square error RMSE. These parameters are given by the following relations:

$$R^2 = 1 \frac{\sum_{i=1}^{N}\left(X^*_{pre,i} - X^*_{exp,i}\right)^2}{\sum_{i=1}^{N}\left(\overline{X^*_{pre}} - X^*_{exp,i}\right)^2} \quad \textbf{(6)}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(X^*_{pre,i} - X^*_{exp,i}\right)^2}{N-Z} \quad \textbf{(7)}$$

$$RESM = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(X^*_{pre,i} - X^*_{exp,i}\right)^2} \quad \textbf{(8)}$$

$X^*_{exp,i}$: designates the experimental reduced water content at point i

$X^*_{pre,i}$: designates the reduced water content predicted at point i

N denotes the number of points

Z denotes the number of constants in the model.

The best model is the one with the highest possible value of R2 (close to 1), χ^2 and RMSE should be as small as possible.

MATLAB calculation software was used to adapt empirical or semi-empirical expressions to the drying curve with those obtained experimentally.

The results of these adaptations are recorded in Table 2

Table 2: results of adaptations

Nom du model	Expression de l'équation	R^2	RESM	χ^2
Lewis	X*=exp(-k*t)	0,9708	$4,607.10^{-2}$	$1,911.10^{-2}$
Page	$X^*=exp(-k^*t^n)$	0,9944	$2,132.10^{-2}$	$3,636.10^{-3}$
Page modifier	$X^*=exp(-k^*t)^n$	0,9708	$4,887.10^{-2}$	$1,911.10^{-2}$
Henderson et Padis	X*=a*exp(-k*t)	0,979	$4,145.10^{-2}$	$1,374.10^{-2}$
Logarithmic	X*=a*exp(-k*t) + c	0,9886	$3,261.10^{-2}$	$7,443.10^{-2}$
Two-term	X*=a*exp(-k*t) + b*exp(-k*t)	0,995	$2,334.10^{-2}$	$3,267.10^{-3}$
Exponetiel two-terme	X*=a*exp(-k*t) + (1-a)*exp(-k*a*t)	0,7199	$1,514.10^{-1}$	$1,833.10^{-1}$
Wang and Singh	$X^*= 1 + a^*t + b^*t^2$	0.9603	$5,699.10^{-2}$	$2,598.10^{-2}$
Verma et al	X*=a*exp(-k*t + (1-a)exp(-k*b*t)	0.995	$2,16.10^{-2}$	$3,267.10^{-3}$
Midilli et al	$X^*=k^*exp(-k1^*t^n) + b^*t$	0.9949	$2,351.10^{-2}$	$3,315.10^{-3}$
General model Gauss2	X*=a*exp(-((t-b)/c)^2) + a*exp(-((t-b)/c)^2)	0,9997	$9,386.10^{-3}$	$1,762.10^{-4}$
General model Gauss1	X*= a*exp(-((x-b)/c)^2)	0,9932	$2,625. 10^{-2}$	$3,446.10^{-3}$

In view of these results, we can say that the Gaussian adapts the drying kinetics of the papaya slice samples used even better.

Figures 7 and 8 show the experimental curves and the curves obtained by adapting them to the Gaussian model

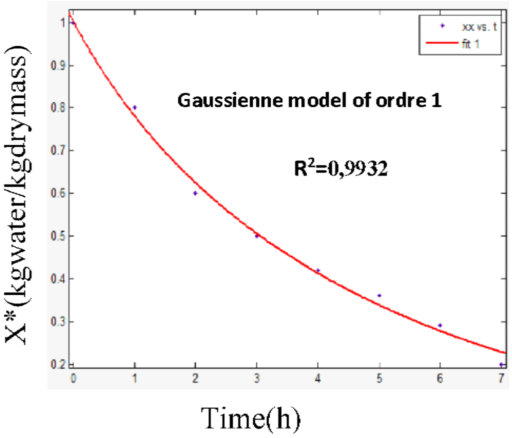

Figure 7 : fitting of the drying kinetics by the Gaussian of order 1

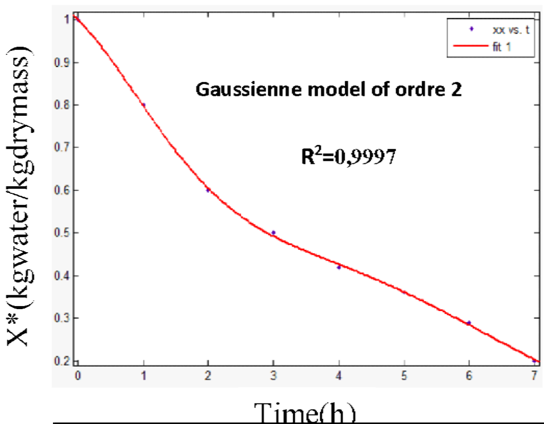

Figure 8 : fitting of the drying kinetics by the Gaussian of order 2

Through these curves we see that the Gaussian adapts better to the drying kinetics.

IV CONCLUSION

Papaya convective drying experiments have shown a single-phase drying kinetics: this is the decay phase. The drying of the slices at different thicknesses shows that the thin slices dry faster.

The smoothing of the kinetic curves of the convective drying process of papaya slices shows that the Gaussian adequately reproduces the evolution of the drying kinetics of papaya slices. The diffusion coefficient, factor responsible for the drying time is approximately $6.8.10^{-10} m/s^2$

REFERENCES

[1] Minh-Hue Nguyen, William E. Price. (2007). Air-drying of banana: Influence of experimental parameters, slab thickness, banana maturity and harvesting season. Journal of Food Engineering (79) 200–207

[2] W.J.N. Fernando, H.C. Low, A.L. Ahmad. (2011). Dependence of the effective diffusion coefficient of moisture with thickness and temperature in convective drying of sliced materials. A study on slices of banana, cassava and pumpkin. Journal of Food Engineering (102) 310–316

[3] Kondia Honoré OUOBA, Hélène DESMORIEUX, François ZOUGMORE et Bétaboalé NAON. (2010). Caractérisation du séchage convectif du gombo, influence de la découpe et de ses constituants. Afrique SCIENCE 06(2) 37 – 48

[4] Dianda B, Ousmane M, Kam S, Ky T. and Bathiébo D. J. Experimental study of the kinetics and shrinkage of tomato slices in convective drying. African Journal of Food Science. 9(5), pp. 262-271

[5] Lemuel M. Diamante, Reiner Ihns, Geoffrey P. Savage and Leo Vanhanen. (2010). A new mathematical model for thin layer drying of fruits. International Journal of Food Science and Technology, 45, 1956–1962

[6] Kamil Sacilik. Effect of drying methods on thin-layer drying characteristics of hull-less seed pumpkin (Cucurbita pepo L.) (2007). Journal of Food Engineering (79) 23–30

[7] A. Vega-Ga´lvez, R. Lemus-Mondaca, C. Bilbao-Sa´inz, P. Fito, A. Andre´s. (2008).
Effect of air drying temperature on the quality of rehydrated dried red bell pepper (var. Lamuyo). Journal of Food Engineering (85) 42–50

[8] A. Kaya; O. Aydın; C. Demirtas. (2007).Drying Kinetics of Red Delicious Apple. Biosystems Engineering 96 (4), 517–524

[9] Donald G. Mercer, An Introduction to the Dehydration and Drying of Fruits and Vegetable Department of Food Science University of Guelph Ontario, Canada

[10] Boukaré Ouedraogo, Boureima Dianda, Kalifa Palm and Dieudonné Joseph Bahiébo. (2015). Influence of Adding Rectangular Fins on the Performances of a Thermal Solar Air Plane Collector. British Journal of Applied Science & Technology
11(6): 1-11,

[11] Michel Daguenet. (1985). Les séchoirs solaires : théorie et pratique. Unesco

[12] Fidèle Anoumou ANANIVI. (2016). Modélisation phénoménologique d'un séchoir solaire. Mémoire de master, 2ie, Burkina Faso

[13] Youcef-Ali, A. (2001). Etude numérique et expérimentale des séchoirs solaires indirects à convection forcée : Application à la pomme de terre. Thèse de doctorat Université de Valenciennes.

[14] Crank, J. (1975). The mathematics of diffusion (2nd ed.). Great Britain, Oxford: Claredon Press.

[15] R. LEMUS –Mondaca, N.BETORET, A.VEGA-Galvez, E.LARA-Aravena.(2009). Dehydratation charactéristics of papaya (Carica pubenscens) : détermination of equilibrium moisture content and diffusion coefficent . Journal of food process engenering.32(5) 645-663.