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RESEARCH ARTICLE

MODELING OF THE DRYING KINETICS SOLAR OF GOMBO SECTION

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ABSTRACT

The objective of this work is the modeling of the drying kinetics of the gombo sections by using a solar drier. The objective of this work is to model the drying kinetics of okra slices using a hybrid solar dryer. The work focused on the kinetics of okra slices at different thicknesses (1cm, 1.5cm and 2cm), temperatures (40°C, 50°C and 60°C) and different air speeds (1m/s, 1 .5m/s and 2m/s). The methodology consisted in following water content okra section of time function. The driying curves obtained were modeled with six semi-empirical models by the nonlinear regression method with the validation criterion following : coefficient of determination (R^2), chi-square (χ^2)andMean Square Error (RMES).The diffusion coefficient was estimated from the simplified solutions of Fick's second law Two parameters were given: the energy of activation and the coefficient of diffusion. The results obtained show that mass diffusivity increases with the temperature and the thickness of the product. The coefficient of diffusion varies from $3.5.10^{-8}$ to $5.88.10^{-7}$ m^2/s, and the activation energy of 12.50kJ/mol with 54.82KJ/mol. The time of drying decreases with the increase in the temperature, and the speed of air and increases with the increase thickness of produit. The models of Demir et al., and Wang and Singh are most reliable to represent the water content reduced of the gombo according to time, therefore as well as possible simulate the kinetics of the gombo drying with for coefficients of correlation respective :$R^2=0.99708$,$\mathcal{X}^2=0.000467$,RMES=0.0215 for Demir et al., and $R^2=0.99527$,$\mathcal{X}^2=0.00734$,RMES=0.02289 for Wang and Singh.

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INTRODUCTION

Drying is an operation which consists in eliminating water in the product.It is a conservation method of the agroalimentary products by reduction of the water activity within the product. The principle of the operation based on a simultaneous transfer of heat and matter within the product to be dried and the interface between the product to be dried and the draining air (Kouhila,2001). However, the complex character of its physical mechanism and nonthe maitrise of this process lead to the deterioration of the nutritional quality of the product, to the prolongation of the drying time and energy overconsumption (Daguenet,1985). Public works by studied by (Khemiri.J *et a*l., 1993; Rios *et al*., 1987), showed that the representation of the systems of equations mathematical models was difficult because of complexities of these equations and require the recourse to experimental measurements often delicate.

A study made by(Youssouf Kone, 2011)made it possible to work out a mathematical model making it possible to optimize the operation of tomato drying by rationalizing the power consumption, the water content of conservation and the drying time, also to account for the drying kinetics and to apprehend the physical laws which control the various transfers.Among these theories, one can quote the modeling of the kinetics by empirical models.The kinetics of drying consists in following the water loss of the product according to time and contributes to the analysis and the comprehension of the phenomena of transfer which influence the operation of drying and makes it possible to have the idea over the time of drying and the water conservation content of the dried product (Elongo,2018).

The objective of this work is to model the drying kinetics of the gombo sections by using a hybrid indirect solar drier.

MATERIAL AND METHOD

Material

Experimental material: The experimental material used in this work is a hybrid solar drier designed at the laboratory of genius process.The experimental drier is a hybrid standard convectif drier, coupled to a solar collector functioning in forced convection (figure 1). It is about a drying system of the agroalimentary products, of which the components are:

A solar collector with circulation simple and simple glazing, of 1.70 m^2 surface, tilted of 19° compared to the horizontal one and directed full south. The room of drying from dimensions 0.8m of depth, 0.7 m of width and 0.9m height. It counts six aluminium trays, each tray with a surface of 0.55 m^2.The distance between the trays is 10 cm. The walls external of the room are out of iron with a polystyrene insulation thickness 5 cm. A vacuum cleaner, supporting the aspiration of outgoing air of the sensor towards the room. A thermoregulator of range 0-400°C and precision 0.01°C connected to a probe of the type K acting on the electric auxiliary heating makes it possible to fix the temperature. Two electric resistances of 1kW of power playing the auxiliary role of energy source.

Figure 1. Hybrid solar Sechoir

Figure 2. balance with precision of 0.001g

Vegetable Material The vegetable material used was fresh gombo *(Abelmoscus Esculentus*) bought at the total market in the town of Brazzaville.

METHODS

Experimental study: This study initially consists in following the water reduction of the product during drying. For that, the samples are cleaned, dimensioned and weighed (to determine the initial mass).In order to ensure a better stability of the conditions of drying and a good homogeneity of the temperature interior the hybrid drier must function at least 30 minutes before introducing the trays charged.Measurement at the moment gives us the wet mass of the Mh product.The process is repeated until stabilization of the mass after three weighed successive.During this process, several samples are dried for various temperatures (40°C,50°Cand 60°C) and thicknesses (1cm,1.5cm and 2cm).

Analyze data: For the treatment of the results, two softwarewere used: Excel and Origin Pro8. The Excel software for the determination of the kinetic parameters (water content, Dmass and Ea) and to plot the various curves and Orgin Pro8 for the kinetics modeling of the gombo sections.

Determination of the kinetic: sizes

Method of determination of the water content: Measurements of the masses are taken by means of an electronic balance with a precision of 0.001g. This method of measurement makes it possible to follow the reduction in the mass of the product during drying. This size is determined by the formula hereafter:

$M_p = \frac{(M_{h-}M_s)}{M_s} \times 100$ (1) with

M_h:mass humic product (kg)
Ms:mass dry product (kg)
M_p :water content of the product(g water/g mass sc)
$M_R = M_t/M_0$
M_R: definit like the water content reduced of the product
M_t:mass product in at the moment of drying (kg)
M_0: mass product in at the initial moment (kg)

Estimate of mass diffusivity: The transfer of matter during drying is controlled by internal diffusivity. The second law of Fick indicated in the equation (2) was largely used to describe the process of drying for the majority of the biological products (Crank.J,1975).

$\frac{\delta M}{\delta t} = D\frac{\delta^2 M}{\delta Z^2}$(2) binder the water content of the produit(M), diffusivity mass(D_{mass}), time (t) and the direction(Z).In supposing the distribution is uniform,negligible external resistances and an isothermal process, the solution of équation(2) is (3).

$$\frac{M-M_e}{M_0-M_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{n} \times \frac{1}{(2n+1)^2} \times exp[-\frac{(2n-1)^2}{4} \times \pi^2 \times D_{mass} \times \frac{t}{L^2}] \quad (3)$$

By taking the first term of the solution of series and while supposing $M_0 M_e$ equal to 0.

$$M_R = \frac{M}{M_0} = \frac{8}{\pi^2} \times \exp\left[-\frac{\pi^2 \times D \times t}{4L^2}\right] \qquad (4)$$

The coefficient of diffusion is given by plotting the curve $\mathrm{Ln}(M_R) = Ln\frac{8}{\pi^2} - \pi^2 \frac{Deff}{L^2} t$

i.e. $\mathrm{Ln}(M_R)$ according to the time which is a linear line whose slope corresponds to $-\pi^2 \frac{D}{4L^2}$ for the form plates infinite.

Estimate of the energy activation: The activationenergy it is energy necessary to the vaporization of water quantity during drying.According to(Srikiatden .J and Robert .J.S. 2008), this size is related to the temperature and diffusivity by the law of Arrhenius hereafter:

$$D_{massique} = D_0 \exp\left(\frac{-Ea}{RT}\right) \qquad (5)$$

and starting from the linearization of the equation (5) pennies the form can be calculated:

$\mathrm{Ln}D_{mass} = \ln D_0 - \frac{Ea}{RT}$ with E_a = slope× R.

MODELISATION OF THE DRYING KINETIC: The modeling of the curves of drying consists in defining a function checking the equation M_R= f(time) known as equation characteristic of drying.This modeling must be done by using Orginpro8.Six(06) empirical semi models in table I were used to follow the curves of drying kinetics .

Table I. Semi-empirical models of drying used

Numbers of model		models Equations
1	*Page*	*MR= exp (- K xt^n)*
2	*Wang and Singh*	*MR=1+at+bt^2*
3	*Midili et al.*	*MR=a ×exp (- K ×t^n) +bt*
4	*Demir et al.*	*MR=a ×exp(-k ×t) ^{n}+b*
5	*Newton*	*MR=exp(-k ×t)*
6	*Henderson et al.*	*MR=a ×exp(-k ×t)*

RESULTS

The adjustment enters the experimental data and the data envisaged was given by using the coefficient of determination (R^2), le Chi-public garden réduit (χ^2) and (RMSE) the average error of the square root.

The model will be considered to be better when R^2 is more raised and tends towards 1 and that RMSE tends towards 0 (Elongo et *al*., 2018).

$$R^2 = \frac{\sum_{=1}^{N}(M_{RP,re,i} - M_{R,Pre,i}\,bar)^2}{\sum_{=1}^{N}(M_{R,exp,i} - M_{R,exp,i}\,bar)^2}$$

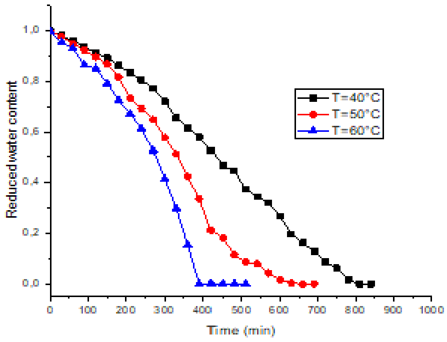
$$\chi^2 = \frac{\sum_{i=1}^{N}(M_{R,Pexp,i} - M_{R,pre,i})^2}{N-n}$$

RMES=$\sqrt{\frac{1}{N}\sum_{i=1}^{N}(M_{R,Pre,i} - M_{P,exp,i})^2}$

$M_{R,exp,i}$:ième water content reduite experimental,
$M_{R,Pre,i}$: ième water content reduce predictible ,
$M_{R,Pre,i}bar$:averages of the water contents reduce,
N : a number of the observations,
n :the number constants in the studied model.

RESULTS AND DISCUSSION

EFFECT OF THE PARAMETTRES ON THE CINETIQUE OF DRYING



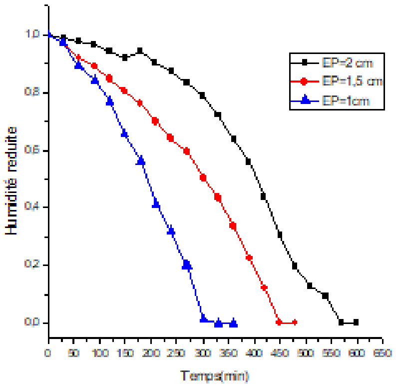


Figure 4. Effect the thickness the product ¶

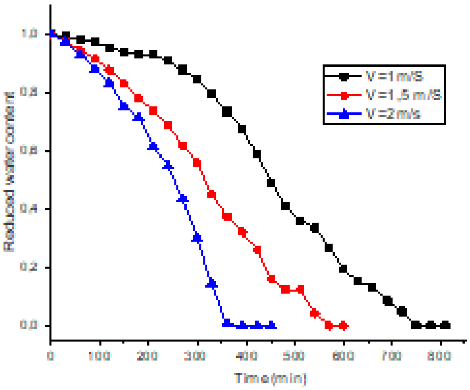


Figure 05. Effet air speed

$$R^2 = \frac{\sum_{=1}^{N}(M_{RP,re,i} - M_{R,Pre,i}\,bar)^2}{\sum_{=1}^{N}(M_{R,exp,i} - M_{R,exp,i}\,bar)^2}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(M_{R,Pexp,i} - M_{R,pre,i})^2}{N-n}$$

RMES=$\sqrt{\frac{1}{N}\sum_{i=1}^{N}(M_{R,Pre,i} - M_{P,exp,i})^2}$

Table II. Average values of the diffusion coefficients and activations Energies

Samples	Thickness (Cm)	Température (°C)	Speed (m/s)	$D_{mass(m^2/s)}$	E_a(Kj/mol)	R^2
		40		$3.45.10^{-8}$		
Sections of gombo	1 cm	50	1	$5.41.10^{-8}$	14.519	0.9863
		60		$1.024.10^{-7}$		
Sections of gombo		40		$1.301.10^{-7}$		
	2 cm	5		$1.501.10^{-7}$	47.04	0.9894
		60	1	$1.82.10^{-7}$		
Sections of gombo		40		$6.49.10^{-8}$		
	1 cm	50	2	$7.606.10^{-8}$	12.507	0.79
		60		$8.66.10^{-8}$		
Sections of gombo		40		$1.64.10^{-7}$		
	1.5 cm	50	2	$1.8.10^{-7}$	54.82	0.9167
		60		$5.88.10^{-7}$		
Sections of gombo		40		$1.12.10^{-7}$		
	1.5 cm	50	1.5	$1.436.10^{-7}$	41.88	0.9167
		60		$2.96.10^{-7}$		
Sections of gombo		40		$1.257.10^{-7}$		
	2 cm	50	1.5	$2.07.10^{-7}$	37.15	0.9985
		60		2.96.10-7		
Sections of gombo		40		$1.99.10^{-7}$		
	2 cm	50	2	$2.76.10^{-7}$	25.8	0.9941
		60		$3.61.10^{-7}$		

Table III: Statistical parameters of the various models for the drying of the samples thicknesses

models	thickness (Cm)	Temperature (°C)	Speed (m/s)	Constant of the models	R^2	X^2	RMES
Newton	1 cm	40°C	1 m/s	K=0.00458	0.83	0.024	0.1547
		50°C		K=0.00274	0.81577	0.02042	0.14289
		60°C		K=0,00201	0.7344	0.03039	0.17433
Henderson	1 cm	40°C	1 m/s	a=1.16806, k=0.00539	0.868	0.02043	0.14292
		50°C		a=1.1476 ;k=0.00326	0.85236	0.01745	0.13211
		60°C		a=1.17057 ;k=0.00249	0.7831	0.0262	0.16186
Démir et al	1 cm	40°C	1 m/s	a=-0.20806 ; k=4.413 ; n=-0.00147 b=1.2121	0.633	0.0696	0.2638
		50°C		a=-0.21203 ;k=1.70515 ;n=-6.06296E-9 ;b=0.78797	0.49737	0.06856	0.26185
		60°C		b=-0.12953 ; k=1.38542 ; n=-0.00292 ;b=1.1305	0.99584	0.00113	0.03358
Page	1 cm	40°C	1 m/s	k=3.81816E-6 ; n=2.3236	0.9833	0.0024	0.024
		50°C		k=2.33966E-6 ;n=2.23482	0.96905	0.00366	0.06049
		60°C		k=8.01212E-8 ;n=2.7056	0.95914	0,00494	0.07025
Midilli	1 cm	40°C	1 m/s	a=1.08487 ; k=1.39715E-7 ;b=-0.00319	0.9778	0.00379	0.0616
		50°C		a=1.09423 ;k=1.37576 E-8 ;b=-0.00216	0.96652	0.00424	0.06512
		60°C		a=1.13918 ;k=2.5601E-9 ;b=-0.00182	0.91383	0.01102	0.10498
Wang and sigh	1 cm	40°C	1 m/s	b1=1.04834 ;b2=-1.84501E-6	0.98103	0.03242	0.05694
		50°C		b1=-7.78602E-4 ;b2=-2.87885 E-6	0,99527	0.00734	0.02289
		60°C		b1=9.22927E-5 ;b2=-3.3584E-6	0.9876	0.02697	0.03983
Newton	2 cm	40°C	1 m/s	k=0.0019	0.69495	0.04058	0.20143
		50°C		k=0.00251	0.79321	0.02797	0.16725
		60°C		k=0.00226	0.80577	0.02306	0.15186
Henderson	2 cm	40°C	1 m/s	b=1,21653 ;k=0,00245	0.76241	0.03327	0.18239
		50°C		a=1.19612 ;k=0.00306	0.84139	0.02259	0.15028
		60°C		a=1.18036 ;k=0.00276	0.85396	0.01825	0.1351
Démir et al	2 cm	40°C	1 m/s	a=-0.21394 ;k=0.52995 ;k=-0.00589 ;b=1.26653	0.97209	0.00437	0.06608
		50°C		a=-0.23183 ;k=1.25242 ;n=-0.00265 ;b=1.24026	0.99708	4.6507E-4	0.02157
		60°C		a=-0.61959 ;k=-8.23977 E-4 ;n=2.07869 ;b=1.6564	0.99163	0.00117	0.0419
Page	2 cm	40°C	1 m/s	k=4.66381E-9 ;n=3.15913	0.98271	0.00242	0.0492
		50°C		k=5.08072 E-7 ;n=2.44231	0.97647	0.0335	0.05788
		60°C		k=5.37836E-7 ; n=2.40764	0.98951	0.0169	0.04106
Midilli	2 cm	40°C	1 m/s	a=1.18754,k=-8.81808 ;b=-0.00186	0.9047	0.01408	0.11868
		50°C		a=1.1197 ;k=3.50442E-8 ;b=-0.00194	0.96417	0.00539	0.07339
		60°C		a=1.11706 ;k=1.63481 E-8 ;b=-0.00182	0.97111	0.00381	0.06174
Wang and sigh	2 cm	40°C	1 m/s	b1=1.50099E-4 ;b2=-3.35614E-6 ;c=-3.35614 E-6	0.98164	0.04886	0.0521
		50°C		b1=1.03768 ;b2=-0.00108 ;C=-1.43897E-7	0.97807	0.05933	0.05741
		60°C		b1=1.01937 ;b2=-7.95761 E-4 ;C=-1.71401E-6	0.99287	0.01523	0.02909

$M_{R,exp,i}$:ième water content reduite experimental,

$M_{R,Pre,i}$: ième water content reduce predictible ,

$M_{R,Pre,i}bar$:averages of the water contents reduce,

N : a number of the observations,

n :the number constants in the studied model.

Figure 03 presents the effect of the air temperature on the drying kinetics of the gombo.The results obtained show that an increase in the drying temperature of entraineda reduction of the drying time thus an increase the speed of drying.These results are similar to those found by(Elongo et *al*.,(2018)).This influence is due to the increase in the osmotic pressure of water inside the product which accelerates the migration of the water of the product towards outside. Figure 04 presents to us the effect the thickness of the product section of the drying kinetics .One raises a reduction of the time drying when the thickness of the product passes from 1 cm to 2 cm.By comparing the drying time compared to the thicknesses, one notices an increase in the drying time when the thickness increases.In the same way, it is noted that it y' has a significant variation in drying kinetics when the thickness takes values 1 cm and 2 cm and that are due probably to traverses longer which moisture must cross to reach surface and with more significant resistances internal to the transfers of the matter for the 2 cm thickness compared to that of 1 cm, which has as a consequence a reduction the speed of drying. Figure 05 translated the effect the speed of air on the drying kinetics. We note a reduction in the time of drying when the speed of air increases. This result can be due to the increase in the convectif effect between the hot air and the product which increases with the speed of air.

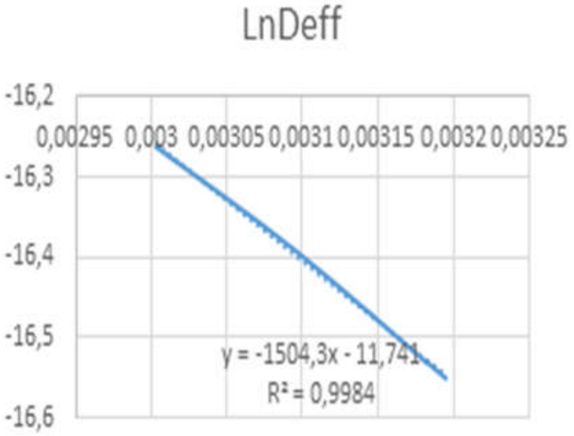


Figure 6. Mass diffusivity D_{mass}

The values of mass diffusivities and activation energy are presented in table II.The values of the coefficients of mass diffusion of the gombo samples dried with 40°C, 50°C and 60°C vary from $3.45.10^{-8}$ to $5.88.10^{-7} m^2/s$.These results show that mass diffusivity increases with the temperature, the thickness of the product as well as the speed of air drying.One notes an increase in D_{mass} with the temperature of the air drying.Indeed, the increase in the temperature of the air drying accelerates the transfer and the elimination of water within the gombo.The results found are close with those found ($2.15.10^{-8}$ -$1.71.10^{-7} m^2/s$) by (Aghfir *et al*., 2008).

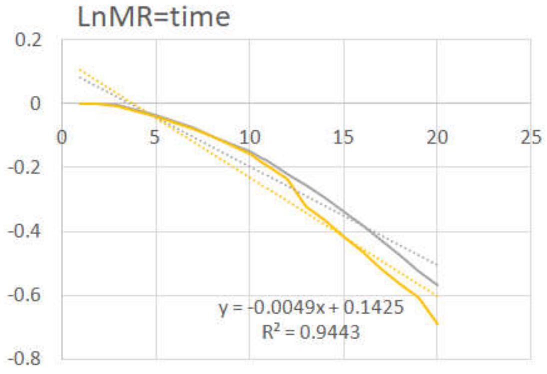


Figure 7. Energy of activation

We also note the influence thickness of the product on the mass coefficient of diffusivity.An increase thickness of the product entraine an increase in the diffusion coefficient .This increase can be explained by the fact why the effect edge (side diffusion) is taken into account in the thick samples with the result that the mass coefficient of diffusion increases.The selected model of diffusion supposes that the diffusion is unidimensional interior towards surface of the sections.This assumption is valid for the thin sections, in which the effect edge is negligible.These results are identical with those found by (Boughali S, 2010). The results of table III show that the energy of activation varies 12.50 kJ/mol with 54.82 kJ/mol. We note that the energy of activation varies with the thickness of the product and the air speed.The more the thickness of the sample increases, the more energy of activation increases.These values close with some others are reported in the literature:drying of *Dioscorea alata. L* (20.47 kJ/mol-28.03 kJ/mol)by (Nkeletela, 2019). Table III represents the parameters and adjustment criteria of modeling while using six (06) model the semi-empirical.According to the results, the Demir model et *al*. and Wang and singh are the best models which make it possible to describe in a satisfactory way the characteristics of drying of the sections gombo with respectively for $R^2=0.99708$,$\chi^2=0.0004657$ and RMES= 0.00 2157 for Demir et *al.,* and $R^2=0.99527$,$\chi^2=0.00734$ and RMES=0.02289 for Wangand Sigh. These two models could proposed like the most reliable models to describe the evolution of the water content reduced according to time.

Conclusion

The objective of this work is the modeling of the drying kinetics the gombo by using a hybrid solar drier designed at the Polytechnic Higher National School. The experimental study makes it possible to follow the water loss of the product according to the time of the gombo sections. The experimental results are treated by using two software: Excel 2010 and Origin pro8. The Parameters such as the energy of activation and the coefficient of diffusion were given. The analysis of the curves shows the effect of the temperature, the speed of air drying and the thickness of the product on the drying kinetics. This influence results in the reduction of the drying tim when the temperature and the speed of air increase. Moreover, one observes a reduction of the time drying with the reduction thickness the product. The results of modeling revealed that the model of Demir et al and Wang and Singh are the most reliable models to describe the evolution of the water content reduced according to time with respectively the statistical parameters like:

$R^2 = 0.99708$,$\chi^2 = 0.99708$ and RMES=0.0004657 for Demir et*al*., and

R^2= 0.99527, χ^2=0.00734 $RMES$ = 0.02289for Wang and Sigh.

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