International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 – 5161

Available at http://inpressco.com/category/ijcet

Research Article

Experimental characterization of convective drying of papaya (*Carica papaya L.)* to licking airflow

Fouakeu-nanfack Gildas Armel[1*], Gnepie Takam Nicolas Wilfred[1], Matuam Balbine[1], Edoun Marcel[1], Zeghmati Belkacem[2]

[1]Applied Energy and Thermal Laboratory, ENSAI-University of Ngaoundere, Cameroon,
[2]Laboratory of Mathematics and Physics (LA.M.P.S), University of Perpignan via Domitia, 66860, Perpignan, France

Received 20 Nov 2022, Accepted 26 Dec 2022, Available online 03 Jan 2023, **Vol.13, No.1 (Jan/Feb 2023)**

Abstract

The thermo-physical properties of papaya (Carica papaya L.) were determined experimentally using a licking flow drying air stream operating in forced convection. The drying experiments were carried out at 40, 50 and 60°C with a constant rate air flow of 0.0848 kg/s and an initial mass of $800^{\pm 0.01}$g. Seven semi-empirical models were used to approximate the experimental drying kinetics. The diffusion coefficient was estimated from simplified solutions of Fick's second law. The Arrhenius model was used to estimate the activation energy. The analysis of the curves shows the influence of the temperature on the drying curves. Two term is the model that can best describe the drying kinetics of papaya in a licking flow dryer with R^2, RMSE, and SSE varying respectively from 0.9722 to 0.9999; 4.187×10^{-3} - 5.039×10^{-2} and 1.448×10^{-4} - 2.694×10^{-2} for a temperature ranging from 40 to 60°C. The values of the mass diffusivity coefficient vary between 1.5645×10^{-10} and 2.2729×10^{-10} m²/s. The activation energy E_a is equal to 16.262 kJ/mol for an Arrhenius factor D_0 equal to 8.171 m²/s.

Keywords: *Experimental characterization, Drying kinetics, Activation energy, Convective drying*

1. Introduction

Many agricultural products such as fruits and vegetables, consumed in large quantities, are not always available during the seasons. These fruits and vegetables are very rich in various vitamins and minerals and are an important source of nutrients for the human diet [1]. Most of these products are harvested with a very high water content and especially during seasons of high rainfall with a high thermal amplitude. Under these conditions, these products do not last long after harvesting, which leads to post-harvest losses that can reach 40% in sub-Saharan regions. Among the solutions proposed to alleviate this problem, the drying of agri-food products occupies a place of choice to reduce these post-harvest losses. Drying is an operation that aims to partially or totally remove water from a wet body by evaporation to a water content that ensures its preservation [2]. An analysis of previous works shows that convective drying is the most widespread drying method and applied regardless of the scale of production. During this physical phenomenon, heat and material transfer phenomena occur simultaneously within the product to be dried, and between this product and the drying medium [3].

For a good understanding of the behavior of this complex process, drying modeling is a very important step. The principle of modeling is to replace a complex system with a simple system that reproduces the main behavior of the original phenomenon . Modeling in mathematics is the representation of a physical reality by a set of physical or mathematical laws. Very often, the complexity of the systems to be studied means that we limit ourselves to a few aspects of the system by making simplifying assumptions. The cancellation of heat transfer before material transfer or vice versa [5]–[7]. The reduction of drying equations to be studied to 1D by Takamte *et al.* [8] and Tzempelikos *et al.* [9]; to 2D by Kaya *et al.* [10], Da-silva *et al.* [11] and Esfahani *et al.* [12]. These approaches, although robust, do not always lead to an exact approximation of the phenomenon studied.

Another approach is to use a series of experiments to analyse the parameters and graders of the system: experimental drying characterization. Lozano *et al.* [13]; Laohasongkram *et al.* [14]; Telis-Romero *et al.* [15]; Lisowa *et al.* [16]; Phomkong *et al.* [17] and Bon *et al.* [18] adopt this approach to determine the thermo-physical properties of some food products. Similarly, the work of Ratti and Crapiste [19]; Villa-Corrales *et al.* [20] and Chandramohan [21] believe that the knowledge of thermo-physical properties allows a better

*Corresponding author's ORCID ID: 0000-0000-0000-0000
DOI: https://doi.org/10.14741/ijcet/v.13.1.1

approximation of reality when modeling fruit and vegetable drying. These authors showed that there is a good agreement between experimental drying data and simulated data (average relative error ranging from 4 to 11%). However, considering that this error should be less than or equal to 3%, it is clear that there is still a need to improve the heat and mass transfer prediction models during convective drying.

A deep analysis of previous works shows that in many cases, the boundary layer (the air-product interface) is always neglected to simplify the drying equations. However, this boundary layer is the seat of heat and material exchanges, and contributes effectively to the conduct of a drying operation. The works of Amir *et al.* [22], Helel *et al.* [23] Kahlerras and Belhamri [24] and Tcheukam-Toko *et al*. [25] have shown that the velocity, temperature and moisture profiles vary in the boundary layer thus constituting a resistance to transfers. To the limit of our knowledge, there is no relationship between the boundary layer and the thermo-physical properties of food products.

This is why the present work focuses on the experimental characterization of the drying of papaya (*Carica papaya L.)* in a drying air stream with licking flow. The objective is to highlight the thermo-physical properties that will be used later in the modeling of heat and material transfers during the convective drying of papaya taking into account the parietal boundary layer.

2. Materials and methods

2.1. Plant material

The samples used in this work are the 'Solo 8' papayas of the Caricaceae family, a local variety from the Littoral Region of Cameroon (Latitude: 4.16821 and Longitude: 10.08073). These papayas were washed, peeled and cut along the longitudinal and perpendicular fibers. The product was sliced to a length (L) of 9 cm and thickness (2e) = 5 mm using the vernier caliper. The initial weight of the samples was measured with the electronic balance, with an uncertainty of ±0.01 g.

2.2. Experimental device

The experiments were carried out in an electric drying air stream (fig. 1) with a dimension of 1.2 x 0.2 x 0.2 (m^3). It is equipped with 3 identical racks, each of which has a dimension of 0.3 x 0.19 (m^2). Inside this equipment, the racks are arranged horizontally and exposed to a flow of licking air. This experimental device is an equipment designed and realized within the Laboratory of Energetics and Applied Thermal (LETA) of the Department of Electrical, Energetic and Automatic Engineering (GEEA) of the National School of Agro-Industrial Sciences (ENSAI) of the University of Ngaoundere. The energization of the electric drying air stream absorbs an electric current through the heating resistors which dissipates heat by Joule effect. This device is regulated in temperature by means of an electric controller XSTC-200t equipped with a Pt100 probe. The drying air stream is also regulated in air flow by a rheostat connected in series with the fan. During the tests, the weight of the product was measured with an Adam Nimbus NBL 2602 digital scale (reading accuracy ±0.01 g), the temperature of the ambient air, drying air and product were measured with type K thermocouples (reading accuracy ±0, 5 °C), the relative humidity by means of a hygrometer of mark 'Almemo FHAD 46-Cx' (accuracy of reading of ±0,2%) and the speed of the drying air by means of an anemometer with propellers of mark 'Almemo FVAD15S120R1E4' (accuracy of reading of ±0,01 m/s).

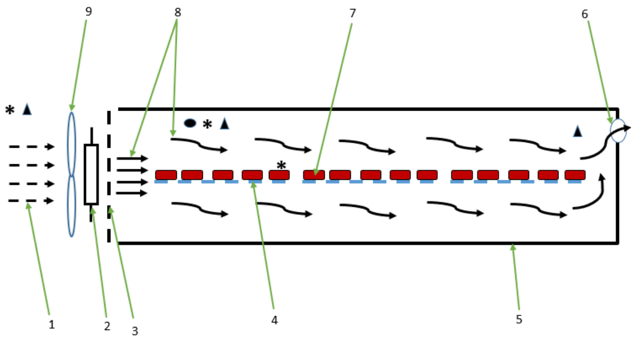

Figure 1: Experimental device of the licking airflow vein

1- Ambient air; 2-Heating resistance; 3-Air diffuser; 4-Shelf support; 5-Plywood box; 6-Moist air outlet Product to be dried; 7-Product to be dried; 8-Hot air drying; 9-Fan

Anemometer; * Thermocouple; Hygrometer

2-3. Methods

The drying experiments took place in an electric air stream during the months of January and March 2021, the papaya harvest period, under the following atmospheric conditions (Atmosphere of the room housing the test device installed in Ngaoundéré): average temperature of $26.8^{\pm 1.25}$°C, average relative humidity of $35^{\pm 1.85}$%. Twenty-one tests were carried out, seven for each air temperature. Thus, three temperature values were used: 40°C, 50°C and 60°C, for a constant rate air flow. The initial weight of the slices spread on each rack was on average $800^{\pm 0.01}$g. For each test, the weight loss of the products is recorded.

2-3-1. Experimental protocol

The papayas are washed and rinsed with drinking water to remove any impurities on their surface. They are peeled, cleaned and cut lengthwise into slices of 5 mm thickness and 9 cm length with a small knife and measured with a caliper. We will weigh them with a digital scale. The racks are weighed every 30 minutes outside the drying chamber. The duration of each weighing varies from 70 to 75 seconds and is deduced from the total drying time of the product. The measurements of temperature, relative air humidity and flow velocity were taken automatically by a data acquisition system 'Almemo 2590'.

2- 3-2. Determination of drying parameters

Samples taken and placed in an oven at 105°C for 24 hours were used to determine the initial moisture content in wet basis of the papaya using the following expression [26]:

$$.x_0 = \frac{m_e}{m} \quad (1)$$

Knowing the dry mass (m_s) of the samples, and using the masses obtained by weighing, the water content in dry basis(X_s) can be obtained from the following expression [27]:

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

The dimensionless form or moisture ratio is obtained from the following expression [28]:

$$MR = \frac{m(t)}{m_0} \quad (3)$$

The drying rate can be determined by the following expression [29]:

$$V_s = \frac{dX}{dt} = \frac{X_t - X_{t+dt}}{dt} \quad (4)$$

2-3-3. Modeling of drying kinetics

In the literature, the curves of drying kinetics are described by many mathematical models in the form of empirical or semi-empirical relations. These relations, which express the evolution of the moisture ratio of the product over time, contain constants that are adjusted so that this evolution corresponds to the experimental curve [30]. We have selected seven semi-empirical (Table 1) of thin film drying commonly used to describe the kinetics of thin film drying of a food product.

Table 1: Semi-empirical thin layer drying models

Models	Equations	References
Newton	$MR = exp\,(-kt)$	[31]
Page	$MR = exp\,(-kt^n)$	[32]
Henderson and Pabis	$MR = a \cdot exp\,(-kt)$	[33]
Logarithmic	$MR = a \cdot exp(-kt) + c$	[34]
Two term	$MR = a \cdot exp(-k_0 t) + b \cdot exp\,(-k_1 t)$	[35]
Diffusion approximative	$MR = a \cdot exp(-kt) + (1-a) \cdot exp\,(-kbt)$	[36]
Midilli *et al.*	$MR = a \cdot exp(-kt^n) + b \cdot t$	[37]

The analysis of the accuracy of the equation that describes the drying curves is generally based on the correlation coefficient (R^2), the root mean square error (RMSE) and the sum of the squared errors (SSE) [30], [36], [38]. The best model describing the drying characteristics of the product was chosen as the one with the highest value of R^2, and the lowest values of RMSE and SSE.

$$R^2 = \frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2}{\sum_{i=1}^{N}(\overline{MR_{exp,i}} - MR_{exp,i})^2} \quad (5)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2} \quad (6)$$

$$SSE = \sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2 \quad (7)$$

2-3-4. Mass diffusivity coefficient

The experimental data for the determination of the effective diffusivity are calculated using the second Fick diffusive model, which is widely used to describe the drying process of most biological products [39].

$$\frac{\partial X}{\partial t} = D_{eff} \nabla^2 X \quad (8)$$

For an effective diffusion coefficient assumed constant and a negligible shrinkage of the product during drying whose duration is assumed to be very long, this equation admits the following expression for solution in the case of samples of products in a thin layer of parallelepiped shape [30] :

$$MR = \frac{X - X_{eq}}{X_0 - X_{eq}} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2} exp\left(-\frac{(2n-1)^2\pi^2 D_{eff} t}{4l^2}\right) \quad (9)$$

In general, only the first term of the expression is retained to evaluate the effective diffusion coefficient of a product .

$$MR = \frac{8}{\pi^2} exp\left(-\frac{\pi^2 D_{eff} t}{4l^2}\right) \quad (10)$$

Thus plotting it using the experimental data of the equation curve leads to a straight line whose slope ko is the effective diffusivity [37]:

$$ln(MR) = ln\left(\frac{8}{\pi^2}\right) - \pi^2 \frac{D_{eff} t}{4l^2} \quad (11)$$

$$\text{With } k_0 = \pi^2 \frac{D_{eff}}{4l^2} \quad (12)$$

2-3-5. Calculation of activation energy

The effective diffusion coefficient (D_{eff}) can be related to the temperature of the drying air by the Arrhenius expression [38]:

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

This expression (13) can be written in the following form:

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

The activation energy (E_a) is deduced from the Ln(D_{eff}) curve as a function of 1/ T (K).

3. Results and discussion

3-1. Kinetics of drying

Figure 2 shows the evolution of the moisture ratio as a function of time for a drying rate air flow equal to 0.0848 kg/s.

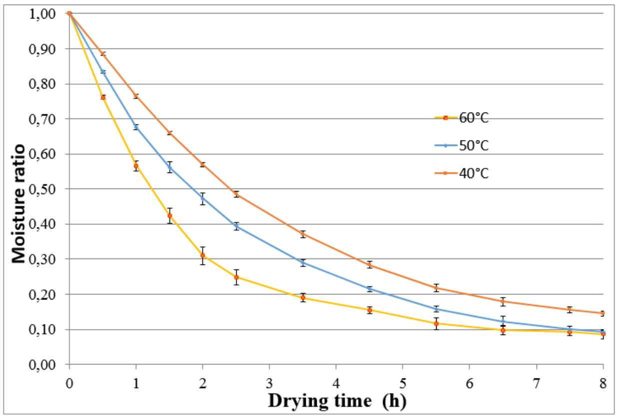

Figure 2: Evolution over time of the moisture ratio of papaya. Drying rate air flow equal to 0.0848 kg/s, average relative humidity equal to 35±1.85%.

It is observed that the moisture ratio is inversely proportional to the drying time whatever the temperature. During the first two hours of drying, we note a linear decrease of the curves with a slope of -0.35; -0.225; -0.14 respectively for 60; 50 and 40°C. For the kinetics at 60°C, we observe a change of concavity after 2h of drying which is manifested by the reduction of the quantity of water to be removed per unit of time: drying phase decrease. Indeed, the departure of water leads to the collapse of the cell structure and causes the shrinkage that opposes the departure of water from the product. The variation of the moisture ratio at the end of drying is almost zero for temperatures of 60 and 50 °C. Two phenomena can explain this reduction: the unavailability of water and the phenomenon of crusting on the surface of the product. Similar paces have been observed in the drying of food products by Dissa *et al.* [42] in licking air flow, by Edoun *et al.* [37] in through air flow and by Ekani *et al.* [27] in counter-current licking air flow.

Figure 3 shows the evolution of the drying rate as a function of time for drying air temperatures equal to 40°C, 50°C and 60°C, for a drying rate air flow equal to 0.0848 kg/s and an average relative humidity of the drying air equal to $35^{\pm1.85}$%.

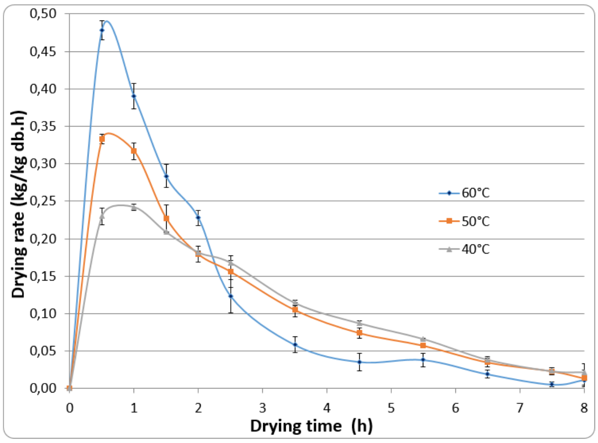

Figure 3: Evolution of the drying rate as a function of time. Drying rate air flow equal to 0.0848 kg/s, average relative humidity equal to 35±1.85%.

The curves in Figure 4 show two phases: an increasing phase and a decreasing phase. The increasing phase is a period of heating of the product. It is characterized by the departure of the liquid water available on the surface of the product. For temperatures of 60°C and 50°C, the drying rate reaches its maximum of $0.48^{\pm0.012}$ kg/kg db.h and $0.33^{\pm0.006}$ kg/kg db.h respectively after 30 minutes of drying. On the other hand, at 40°C, it takes 1 hour of drying to reach the maximum at $0.24^{\pm0.01}$ kg/kg db.h. Also we note a phase of drying where the speed of drying is almost observed (between 30 min and 1h). After 2 h15 min of drying, we observe that the drying speed at 40°C is higher than at 50 and 60°C. Indeed, the evaporative power of the air being proportional to the temperature, the departure of water is more important at high temperature at the beginning of drying and almost null at the end of drying.

Figure 4 shows the evolution of the surface temperature of papaya slices as a function of time for drying air temperatures equal to 40°C, 50°C and 60°C, for an equal drying rate air flow at 0.0848 kg/s and an average relative humidity of the drying air equal to $35^{\pm1.85}$%.

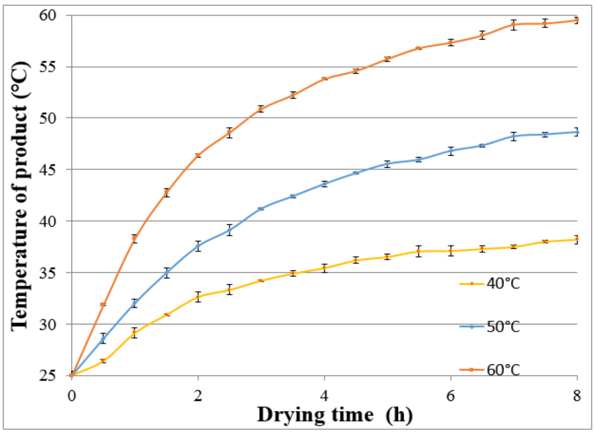

Figure 4: Evolution of product temperature as a function of time. Drying rate air flow equal to 0.0848 kg/s, average relative humidity equal to 35±1.85%.

The results show that the temperature of the product grows from its initial value of $25^{\pm0.3}$°C and tends towards an asymptotic limit, which is the temperature of the drying air. It is also observed during the first two hours and thirty minutes of drying a linear growth of the curves with a slope of 3.324; 5.648; and 9.436 for 40; 50 and 60°C, respectively. This behavior is due solely to the strong dependence of the thickness and thermal conductivity of the product on temperature. Sabarez [43] presents similar evolutions of product temperature on food products at different conditions.

3-2. Modeling of drying kinetics

In this work, we used 7 mathematical models to model the drying kinetics of papaya slices. To determine the best model, we calculated and compared the statistical parameters for each model. The principle of the least squares method is applied to each model with respect to the parameters to be identified. We considered the correlation coefficient as the first adjustment parameter. Table 2 presents the static parameters of the fit of the models selected in this work.

Table 2: Statistical parameters of the models

Temperatures	Models	Statistical parameters		
		R^2	RMSE (10^{-3})	SSE (10^{-4})
40°C	Newton	0.9967	17.17	32.41
	Page	0.9972	16.52	27.28
	Henderson and Pabis	0.9967	13.70	32.38
	Logarithmic	0.999	10.37	9.672
	Two term	**0.9997**	**5.85**	**2.742**
	Diffusion approximative	0.9991	10.07	9.128
	Midilli et al,	0.9993	9.021	6.510
50°C	Newton	0.9953	20.97	48.37
	Page	0.9988	10.92	11.93
	Henderson and Pabis	0.996	20.11	40.46
	Logarithmic	0.9998	4.999	2.249
	Two term	**0.9999**	**4.187**	**1.448**
	Diffusion approximative	0.9998	4.271	1.578
	Midilli et al.	0.9998	5.578	2.489
60°C	Newton	0.9722	49.49	269.4
	Page	0.9877	34.55	119.4
	Henderson and Pabis	0.9738	50.39	253.9
	Logarithmic	0.9985	12.52	14.10
	Two term	**0.9986**	**12.98**	**13.49**
	Diffusion approximative	0.9985	12.80	14.74
	Midilli et al.	0.9976	16.96	23.02

Comparing the average values of the above criteria, it is evident from Table 3 that the Two term model has the highest value of (R^2) and the lowest values of RMSE and SSE to describe the drying behavior of papaya slices, regardless of the drying air temperature used in this study. The Two term model best optimizes the smoothing of the experimental points (Fig. 5). The values obtained from the model are marked in yellow in the table with R^2 = 0.9994, RMSE = 0.007674 and SSE= 0.000589.

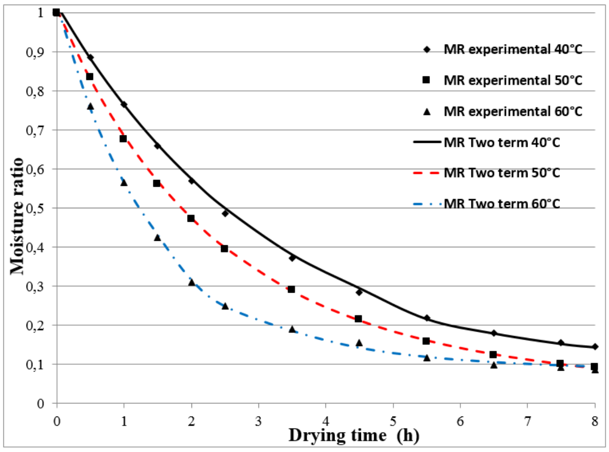

Figure 5: Variation of the experimental and predicted water content at the temperature 40°C, 50°C, 60°C and at a rate air flow of 0.0848 kg/s.

As observed in this figure, a good fit between numerical and experimental variables is appreciated. The Two term model has been demonstrated by Yaldiz *et al.* [44] for grape drying placed perpendicular to a drying air flow, by Midilli and Kucuk [45] for pistachio drying in licking air flow, by Dissa *et al.* [42] for mango drying in single licking air flow, and by Edoun et al. [37] for mango drying in through air flow.

3-3. Calculation of effective diffusivity

The effective diffusivity coefficients of the papaya slices of the three different temperatures were evaluated by plotting the graph ln(MR)=f(t) of the slope K. The effective diffusivities of the papaya slices are: 1.5645×10^{-10}; 2.0031×10^{-10} and 2.2729×10^{-10} m^2/s at 40°C, 50°C and 60°C, respectively.

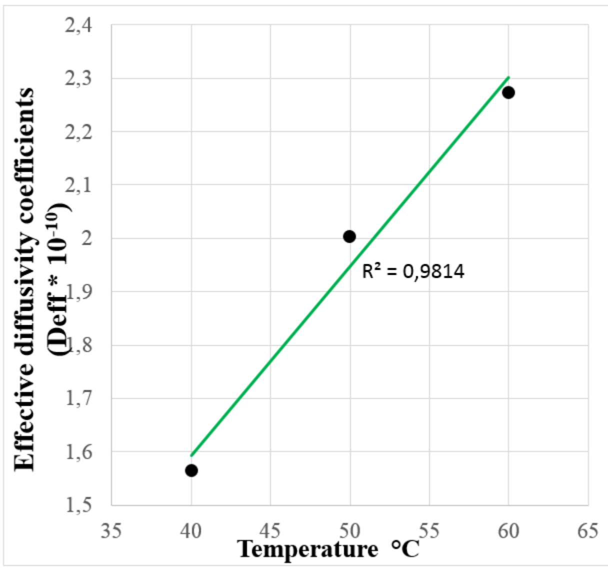

Figure 6: Effect of drying air temperature on effective diffusivity.

This result shows that the effective diffusivity coefficients increases with the drying temperature. The diffusion coefficients obtained in the literature during the drying of food products with temperature ranges from 40 to 70°C vary between (2.941 - 4.462)10^{-9} m^2/s [36] in flux crossing, between (5.018 – 7.395)10^{-10} m^2/s [37] in crossing airflow, between (1.2501 - 11.857)10^{-8} m^2/s [30] in cross-flow air and between (1.83 - 2.25) 10^{-7} m^2/s [39] in counter-current air flow.

3-4. Calculation of activation energy

The activation energy (E_a) is calculated from the curve Ln(D_{eff}) as a function of 1/T (K), as shown in the preceding paragraphs. Thus we obtain an activation energy E_a equal to 16.2622 kJ/mol for an Arrhenius factor D_0 equal to 8.1717x10^{-8} m^2/s. This value is in the range of 12 to 110 kJ/mol [46]. The activation energies obtained in the literature during the drying of food products, with temperature ranges between 40 and 60°C are grouped in Table 3. We note that the value of activation energy obtained for papaya slices placed perpendicularly to drying air is very close to that obtained from drying by a drying air flow parallel to mango slices.

Table 3: Activation energy for drying various products

Authors	Activation energy E_a (kJ/mol)	Products	Air flow
[37]	16.86 and 31.51	Mango	Crossing
[30]	32.466; 44.288 and 42.027	Okra	
[39]	30.58	Mango	Licking CC
present work	**16.2622**	**Papaya**	**Licking**

Conclusion

This work aimed to study the drying kinetics behavior of papaya (*Carica papaya L.*) using a licking flow drying air stream operating in forced convection. The drying experiments were performed in the laboratory under different drying air temperature conditions (40, 50 and 60°C) and for a constant rate air flow of 0.0848 kg/s. The obtained drying kinetics were modeled using seven semi-empirical models, by the non-linear regression method with as validation criteria, the coefficient of determination (R^2), the mean of squared errors (RMSE) and the sum of squared errors (SSE). The diffusion coefficient was estimated from simplified solutions of Fick's second law. The activation energy was determined from the diffusion coefficient versus temperature equation using the Arrhenius model. The results showed that the Two term model is the semi-empirical model that can best predict the drying kinetics of papaya with licking air flow. The values of mass diffusivity coefficient varied between 1.5645x10^{-10} and 2.2729x10^{-10} m^2/s, activation energy E_a =16.262 kJ/mol and the Arrhenius factor D_0 = 8.171 m^2/s. These results will be useful later in the modeling of heat and matter transfers during the convective drying of papaya by considering the parietal boundary layer.

References

[1] M. Kouhila, A. Belghit, M. Kaoua, et M. Daguenet, « Etude expérimentale du séchage convectif de la menthe dans un séchoir modulaire polyvalent à chauffage partiellement solaire », *Revue des Énergies Renouvelables, numéro spécial, Alger*, vol. 1, nº 6, 1998.

[2] A. O. Omolola, A. I. Jideani, et P. F. Kapila, « Quality properties of fruits as affected by drying operation », *Critical reviews in food science and nutrition*, vol. 57, nº 1, p. 95-108, 2017.

[3] J.-P. Nadeau et J.-R. Puiggali, « Sechage: des processus physiques aux procedes industriels », 1995.

[4] A. M. Castro, E. Y. Mayorga, et F. L. Moreno, « Mathematical modelling of convective drying of fruits: A review », *Journal of Food Engineering*, vol. 223, p. 152-167, 2018.

[5] S. J. Babalis, E. Papanicolaou, N. Kyriakis, et V. G. Belessiotis, « Evaluation of thin-layer drying models for describing drying kinetics of figs (Ficus carica) », *Journal of food engineering*, vol. 75, nº 2, p. 205-214, 2006.

[6] S. Janjai *et al.*, « Finite element simulation of drying of mango », *Biosystems Engineering*, vol. 99, nº 4, p. 523-531, 2008.

[7] M. Torki-Harchegani, D. Ghanbarian, et M. Sadeghi, « Estimation of whole lemon mass transfer parameters during hot air drying using different modelling methods », *Heat and mass transfer*, vol. 51, nº 8, p. 1121-1129, 2015.

[8] G. Takamte, M. Edoun, L. Monkam, A. Kuitche, et R. Kamga, « Numerical Simulation of Convective Drying of Mangoes (mangifera Indica L.) Under Variable Thermal Conditions », *International Journal of Thermal Technologies*, vol. 3, nº 2, p. 48-52, 2013.

[9] D. A. Tzempelikos, D. Mitrakos, A. P. Vouros, A. V. Bardakas, A. E. Filios, et D. P. Margaris, « Numerical modeling of heat and mass transfer during convective drying of cylindrical quince slices », *Journal of Food Engineering*, vol. 156, p. 10-21, 2015.

[10] A. Kaya, O. Aydin, et I. Dincer, « Numerical modeling of forced-convection drying of cylindrical moist objects », *Numerical Heat Transfer, Part A: Applications*, vol. 51, nº 9, p. 843-854, 2007.

[11] W. P. da Silva, C. M. e Silva, et J. P. Gomes, « Drying description of cylindrical pieces of bananas in different temperatures using diffusion models », *Journal of Food Engineering*, vol. 117, nº 3, p. 417-424, 2013.

[12] J. A. Esfahani, H. Majdi, et E. Barati, « Analytical two-dimensional analysis of the transport phenomena occurring during convective drying: apple slices », *Journal of Food Engineering*, vol. 123, p. 87-93, 2014.

[13] J. E. Lozano, M. J. Urbicain, et E. Rotstein, « Thermal conductivity of apples as a function of moisture content », *Journal of food science*, vol. 44, nº 1, p. 198-199, 1979.

[14] K. Laohasongkram, S. Chaiwanichsiri, C. Thunpithayakul, et W. Ruedeesarnt, « Thermal properties of mangoes », *J. Sci. Soc. Thailand*, vol. 21, nº 199, p. 63-74, 1995.

[15] J. Telis-Romero, V. R. N. Telis, A. L. Gabas, et F. Yamashita, « Thermophysical properties of Brazilian orange juice as affected by temperature and water content », *Journal of Food Engineering*, vol. 38, nº 1, p. 27-40, 1998.

[16] H. Lisowa, M. Wujec, et T. Lis, « Influence of temperature and variety on the thermal properties of apples », *International agrophysics*, vol. 16, nº 1, 2002.
[17] W. Phomkong, G. Srzednicki, et R. H. Driscoll, « Thermophysical properties of stone fruit », *Drying Technology*, vol. 24, nº 2, p. 195-200, 2006.
[18] J. Bon, H. Váquiro, J. Benedito, et J. Telis-Romero, « Thermophysical properties of mango pulp (Mangifera indica L. cv. Tommy Atkins) », *Journal of Food Engineering*, vol. 97, nº 4, p. 563-568, avr. 2010.
[19] C. Ratti et G. H. Crapiste, « Modeling of batch dryers for shrinkable biological materials », *Food and bioprocess technology*, vol. 2, nº 3, p. 248-256, 2009.
[20] L. Villa-Corrales, J. J. Flores-Prieto, J. P. Xamán-Villaseñor, et E. García-Hernández, « Numerical and experimental analysis of heat and moisture transfer during drying of Ataulfo mango », *Journal of food engineering*, vol. 98, nº 2, p. 198-206, 2010.
[21] V. P. Chandramohan, « Numerical prediction and analysis of surface transfer coefficients on moist object during heat and mass transfer application », *Heat Transfer Engineering*, vol. 37, nº 1, p. 53-63, 2016.
[22] H. Amir, G. Le Palec, et M. Daguenet, « Séchage superficiel d'un matériau poreux humide par convection forcée d'air chaud: couplage entre les équations de transfert dans le matériau et celles de la couche limite », *International Journal of Heat and Mass Transfer*, vol. 30, nº 6, p. 1149-1158, juin 1987.
[23] D. Helel, N. Boukadida, et E. Dorignac, « Effet des couches limites dynamique thermique et massique sur les mécanismes des transferts de chaleur et de masse au sein d'un milieu poreux soumis à une convection », *Interface*, vol. 50, p. 1m, 2005.
[24] L. Kahlerras et A. Belhamri, « Etude de l'évolution des coefficients de transfert de surface lors du séchage d'un milieu poreux humide », *Proceedings du 1er Séminaire International sur le Génie Climatique et l'Energétique, SIGCLE'2010*, 2010.
[25] D. Tcheukam-Toko, L. Kongue, C. Koueni-Toko, R. Mouangue, et M. Bélorgey, « Numerical Simulation and Experimental Validation of Boundary Layer Generated by a Turbulent Flow on a hydraulically Smooth Bed », *Res. J. of Applied Sci*, vol. 7, nº 2, p. 108-112, 2012.
[26] O. Prakash et A. Kumar, *Solar drying technology: concept, design, testing, modeling, economics, and environment*. Springer, 2017.
[27] Y. R. Ekani, T. F. Abraham, E. Marcel, et K. Alexis, « Experimental Study of the Drying Kinetics of Mango (mangifera indica L.) during Airflow Drying Licking Countercurrent », *American Journal of Food Science and Technology*, vol. 7, nº 4, p. 127-132, 2019.
[28] B. Matuam, M. Edoun, A. Kuitche, et B. Zeghmati, « Experimental evaluation of the thermal performance of dryer airflow configuration », p. 80-86. 2015.
[29] F. A. Tetang, E. Marcel, et K. Alexis, « Intermittent Drying of Mango Slices (Mangifera indica L.)" Amelie": A New Model », *American Journal of Food Science and Technology*, vol. 8, nº 3, p. 81-86, 2020.
[30] N. Y. Jiokap, N. Telewo, N. L. Nanko, et C. Kapseu, « Etude des cinétiques de séchage du gombo (Abelmoschus esculentus L.): Influence de la taille des rondelles, de la température de séchage, du prétraitement et de la variété », *Séminaire International sur les chaines de valeurs et transformations intégrales des résources locales, Lorexp « 2021 »*, p. 426-446, 2021.
[31] W. K. Lewis, « The rate of drying of solid materials. », *Industrial & Engineering Chemistry*, vol. 13, nº 5, p. 427-432, 1921.
[32] Q. Zhang et J. B. Litchfield, « An optimization of intermittent corn drying in a laboratory scale thin layer dryer », *Drying Technology*, vol. 9, nº 2, p. 383-395, 1991.
[33] P. W. Westerman, G. M. White, et I. J. Ross, « Relative humidity effect on the high-temperature drying of shelled corn », *Transactions of the ASAE*, vol. 16, nº 6, p. 1136-1139, 1973.
[34] A. Fofana, Y. D. N'guessan, et N. E. Assidjo, « Modélisation mathématique du séchage dans un four (air chaud) de tranches de mangue (Mangiféra indica L.) », *International Journal of Biological and Chemical Sciences*, vol. 14, nº 7, p. 2476-2490, 2020.
[35] T. Gunhan, V. Demir, E. Hancioglu, et A. Hepbasli, « Mathematical modelling of drying of bay leaves », *Energy Conversion and Management*, vol. 46, nº 11-12, p. 1667-1679, 2005.
[36] A. Kuitche, M. Edoun, et G. Takamte, « Influence of pre-treatment on drying on the drying kinetic of a local Okro (Hibiscus ersculentus) variety », *World J. Dairy Food Sci*, vol. 2, nº 2, p. 83-88, 2007.
[37] M. Edoun, B. Matuam, et A. Kuitche, « Mathematical modelling of thin layer mangoes (Mangifera indica L.) drying process », *International Journal of Current Engineering and Technology*, vol. 4, nº 5, p. 3672-3676, 2014.
[38] M. W. Ahmed, « Kinetics and mathematical modeling of thin layer drying of mango leather », 2019.
[39] R. Y. Ekani, F. A. Tetang, M. Edoun, et A. Kuitche, « Airflow Drying Licking Countercurrent of Mango (Mangifera Indica L): Experimental Determination of Drying Parameters », *International Journal for Research in Applied Science & Engineering Technology Technology (IJRA)*, p. 441-445, 2022.
[40] A. Stegou-Sagia et D. Fragkou, « Influence of drying conditions and mathematical models on the drying curves and the moisture diffusivity of mushrooms », *Journal of Thermal Engineering*, vol. 1, nº 4, p. 235-244, 2015.
[41] A. S.-S. Stegou–Sagia et A. Fragkou, « Thin layer drying modeling of apples and apricots in a solar-assisted drying system », *Journal of Thermal Engineering*, vol. 4, nº 1, p. 1680-1691, 2018.
[42] A. O. Dissa, D. J. Bathiebo, H. Desmorieux, O. Coulibaly, et J. Koulidiati, « Experimental characterisation and modelling of thin layer direct solar drying of Amelie and Brooks mangoes », *Energy*, vol. 36, nº 5, p. 2517-2527, 2011.
[43] H. T. Sabarez, « Computational modelling of the transport phenomena occurring during convective drying of prunes », *Journal of Food Engineering*, vol. 111, nº 2, p. 279-288, juill. 2012.
[44] O. Yaldiz, C. Ertekin, et H. I. Uzun, « Mathematical modeling of thin layer solar drying of sultana grapes », *Energy*, vol. 26, nº 5, p. 457-465, 2001.
[45] A. Midilli et H. Kucuk, « Mathematical modeling of thin layer drying of pistachio by using solar energy », *Energy Conversion and Management*, vol. 44, nº 7, p. 1111-1122, mai 2003.
[46] Z. Erbay et F. Icier, « A review of thin layer drying of foods: theory, modeling, and experimental results », *Critical reviews in food science and nutrition*, vol. 50, nº 5, p. 441-464, 2010.