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Intermittent Drying of Mango Slices (*Mangifera indica L.*) "*Amelie*": A New Model

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Abstract The present work has focused on the determination of a new model of intermittent thin film drying of mango. During the experiments, the samples spread on three trays, were placed in a through-flow modular electric dryer. The masses of the fresh products studied were 500 and 800g having an initial moisture content of 80%. Drying was carried out using three inlet air temperatures 40; 50 and 60°C for four cycles of 120 minutes and for each intermittency value α = ¼, α = ½ and α = ¾. The experimental values obtained have permitted to draw the profiles of moisture ratio for each temperature. Theses profiles have conducted for a test of twelve different thin film models encountered in the literature. For each given cycle and value of the selected intermittency, the results showed that all the curves were described by the same model. Taking into account the intermittency and the number of cycles, a new thin layer drying model has been developed. The simulation of this new drying model showed a good agreement with the experimental curves obtained under the same drying conditions with R^2 = 0.996, independently of the drying air temperature and the value of intermittency α.

Keywords: *intermittency, intermittent drying, mango, modeling, validation*

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1. Introduction

Drying, although it is the oldest means of preserving products, is still a major concern for researchers. Indeed, after many already achieved [1-7], there are always various points of dissatisfaction.

Regarding energy consumption, drying is still recognized as an energy-intensive operation, which slows down the use of electric dryers. To solve this problem, researchers have resorted to auxiliary energy sources such as the solar energy. However, the variability of this heat source in the tropical zones, forces drying over several days, which leads to the loss of the texture of the product; biochemical degradations [8,9].

Also, in terms of the final quality of the dried product, the work of [1,3] have shown that the exposure of products to a continuously elevated temperature leads either to the phenomenon of crusting, when it comes to food products in general, and fruits and vegetables in particular, either deformation, crackling or deterioration of the product [10].

So, in order to provide solutions to these problems of energy consumption and degradation of the final quality of dried products, researchers have developed a new drying technique related to the temperature variability of the heat source. One of the derivatives of this technique is to stop the source of heat from time to time during the drying operation, at a time interval that may be regular or irregular: it is the intermittent drying [11,12,13]. Many studies have shown that this technique leads to a reduction in the drying time, and improves the quality of the final product.

For example, in the case of drying low moisture products such as rice, the work of [13,14,15,16] showed that the breaking rate during shelling of intermittently dried rice was low compared to the continuous drying rate. As well, during the drying maize, the work of [17] showed that intermittent drying improves maize starch quality, while also saving time and lower final moisture content than drying continued. In the case of products with high water content, such as fruits and vegetables in general, several studies were conducted with satisfaction. This is the case of the squash drying [18] in intermittent mode, which has led to a reduction of the drying time compared to continuous drying. These same results have been obtained when carrots, peppers and apples were dried [19-22], bananas [23], olives [24], mangoes [25,26], cocoa [27] and cherries [28].

From these experimental results of intermittent drying, researchers have developed models to represent the phenomenon of intermittency. Thus, the work of [19] focused on the experimental modeling of intermittent drying of fresh carrots; [21] model convective and intermittent drying of carrots, apples and peppers; and [29] simulated the intermittent drying of fungi by a simplified model. However, these researchers did not take into account the period of intermittency in the writing of their different models of heat and mass transfer. It will therefore be a question in the present work to write a new model of intermittent drying, which takes into account the period of intermittency, this period being the seat of several phenomena of heat and mass transfer.

2. Materials and Methods

2.1. Experimental Device

It is an electric laboratory modular dryer (Figure 1), which can operate in two configurations: through flow and licking flow. Dimensions 0.52 x 0.72 x 1.80 (m^3), this dryer was designed and set up in the Laboratory of Energetic and Applied Thermal Engineering of the National School of Agro-Industrial Sciences of the University of Ngaoundere. It is divided into four main parts; the drying chamber, the heating compartment, the blowing system and an air diffuser. It has been amply described by Tetang (2018).

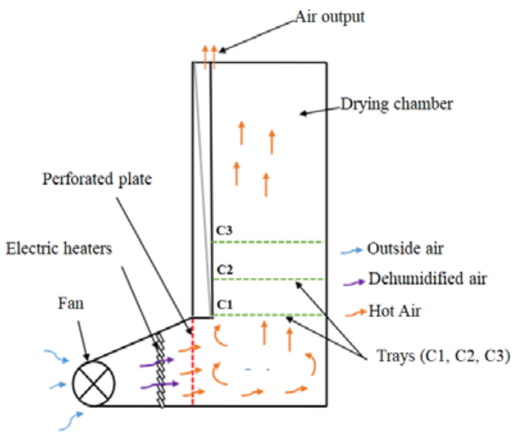

Figure 1. The electrical laboratory modular dryer

A caliper of brand Junior Roch-France in aluminum, having a total length of 25 cm, has been used to measure the dimensions of mango slices and a digital scales of brand Adam Nimbus NBL 2602, load between 5 and 2600 g with reading precision on measurements of ± 0.01 g, for the weighing of the samples at the beginning, during and at the end of the drying operation.

2.2. Plant Material

The samples used in this work are slices of mango "Amelie" family Anacardiaceae local variety of Adamawa Region in Cameroon. The harvest period extends from March to July of each year. These mangoes were collected in March of green color, spotted with yellow at maturity. They have a weight ranging from 150 g to 300 g [12].

2.3. Methods

2.3.1. Operating Conditions

As part of this work, two drying operations for respective initial masses of 500 and 800 g were carried out, with the three trays placed as shown in Figure 1.

The mangos were washed and rinsed with water to eliminate all impurities present at their surfaces. They are peeled, stoned and cut out in sections of average size of 80 x 20 x 8 (mm^3). Indeed, the slices have a thickness ranging between 6 and 8 mm, a length ranging between 80 and 82 mm, and a width between 18 and 20 mm. The measurements of size were carried out by means of a vernier caliper of brand Junior Roch-France Rule in aluminum, 250 mm. The remaining samples are spread over the three trays, and each tray is weighed before being inserted inside the drying chamber at 40; 50 and 60°C.

For drying operation, intermittency was defined as the relationship between the duration of drying and the total duration of the cycle [12,22,30]. In this case, intermittency can be express by equation (1) as follow:

$$\alpha = \frac{\tau_{on}}{\tau_{on} + \tau_{off}} = \frac{\tau_{on}}{\tau} \quad (1)$$

where τ_{on}: "on" period (minutes), τ_{off}: "off" period (minutes) τ: cycle period (minutes).

Thus, three values of intermittency α = ¼, α = ½ and α = ¾ are studying during four cycles of 120 minutes for an air flow of 0.266 kg/s. Each experiment was replicated three times for each value of intermittency, each temperature and mass.

The work done by Tetang et al. (2016) showed that in a humid tropical environment, the proper technique is to keep the products in the drying chamber. They also present the experimental protocol followed in this study.

In dry base, the moisture content can be calculated by using the different masses obtained by weighing (equation 2) [31].

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

where m(t) is the mass of fruit on a tray at instant t, m_s the corresponding dry mass, and X, slice's moisture content ($kg_{water}.kg_{dm}^{-1}$ d.b).

The moisture ratio which is a dimensionless form can be obtained by equation (3) [32,33].

$$MR = \frac{X - X_{eq}}{X_0 - X_{eq}} \quad (3)$$

X is the average moisture content of the product, X_0 the initial moisture content, X_{eq} the equilibrium moisture content.

The equilibrium moisture content, being negligible in front of average moisture content of the product and the initial moisture content, the equation (3) becomes [33]:

$$MR = \frac{X}{X_0} \quad (4)$$

The developing of equation (4) has conducted to following relation:

$$MR = \frac{m(t)}{m_i} \quad (5)$$

with m(t) and m_i mass of fruit respectively at instant *t* and initial instant (kg)

It is equation (5) which was used to determinate the moisture ratio during this study. Each experiment was stopped after four cycles (i.e. 480 minutes), and the moisture content used for drawing kinetics were the mean values of moisture content of three replications.

The kinetics obtained will be adjusted using the twelve (12) thin-film models encountered in the literature and listed by [1,11].

2.3.2. Statistical Analysis

The nonlinear regression analysis was done using the TableCurve 2D v5.01 software of the Laboratory of Mathematics and Physics (LAMPS) of the University of Perpignan via Domitia - France. The coefficient of determination (R^2) is the first selection criterion for the best model describing thin film drying kinetics. The various statistical methods such as the Khi-square (χ^2) and the root mean square error (RMSE) described by the equations (6) and (7) respectively, were where used to evaluate the goodness of the fit of the models. The model adopted is that for which χ^2 and the RMSE will have the smallest values, with the higher R^2.

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(Xr_{\exp,i} - Xr_{pre,i}\right)^2}{N - z} \quad (6)$$

$$MSE = \frac{1}{N}\sum_{i=1}^{N}\left(Xr_{pre,i} - Xr_{\exp,i}\right)^2 \quad (7)$$

3. Results and Discussion

3.1. Moisture content profiles

Figure 2 shows the profiles of the moisture ratio of the intermittent drying of 500g of fresh mango samples at 50 and 60°C.

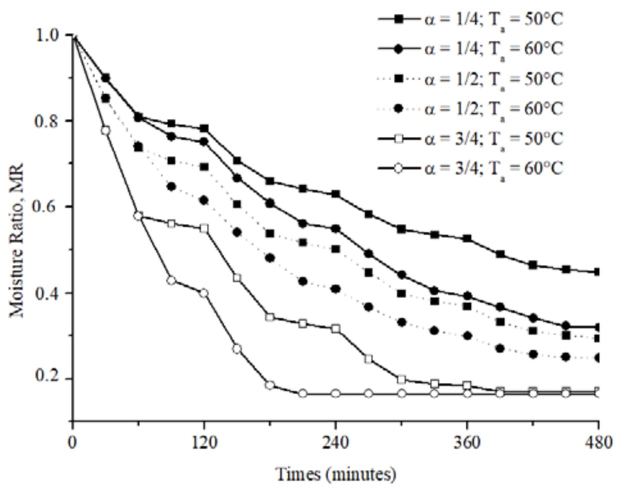

Figure 2. Influence of intermittency on the moisture ratio of mango samples at 50 and 60°C

In this figure, it is noted that the increase in the value of the intermittency leads to a lower final moisture ratio.

During each shutdown period of the four cycles, there is a low decrease in the moisture ratio due to the heat present in the drying chamber. This phenomenon is repeated as long as the moisture ratio of the product is greater than the relative humidity of the drying air. This variation in has also been illustrated by [12,22,25,26,34]. The off period is therefore the seat of the phenomena of heat transfer and diffusion of water from inside of the product to its surface, and its evaporation.

The figure shows that for α = ¼, the final moisture ratio is the highest, and for α = ¾, it is the lowest. But in the 4th cycle at 50°C, the moisture ratio tends to stabilize during the off period. This results from the fact that the moisture ratio is also substantially equal to the relative humidity of the drying air.

At 60°C, for α =¾, the moisture ratio of the product begins to stabilize after 180 minutes. The off period observed during the first cycle thus greatly contributed to the migration of water from the inside of the product to its surface, thus accelerating the drying operation in the second cycle.

The same observations were made at 40°C. It can then be said that increasing the value of the intermittency has a significant influence on the duration of the drying.

3.2. Model Writing

Statistical analysis shows that the model of Midilli et al. has the highest R^2 for each cycle at temperatures 40; 50 and 60°C in the three intermittency cases tested.

The parameters of the selected model are given in Table 1, for each value of intermittency, cycle and temperature.

For the three inlet air drying temperatures (40, 50 and 60°C) retained during the tests, among the twelve (12) different models tested, the one with the R^2 the highest in all cycles is the model Midilli et al. whose expression is:

$$MR = a \bullet \exp\left(-kt^n\right) + b \bullet t \quad (3)$$

a and b model's parameters; k and n model's coefficients.

The different tests took place in 480 minutes, ie 4 cycles of 2 hours. Since the kinetics was the same at each cycle, the final model can be expressed in the form of a numerical sequence of expression:

$$MR = \sum_{N=1}^{N}\left[a_N \exp\left(-k_N t^{n_N}\right) + b_N t\right] \quad (4)$$

where a_N, b_N, k_N and n_N, the main parameters of the new model function of the intermittency α and the number of cycles N, at each temperature of the drying air tested, can be put in the form:

$$y_N = y_1 + y_0\left(N - 1\right) \quad (5)$$

Where y_1 and y_0 are the secondary parameters for each main parameter of the new model.

Table 2 presents the expressions of all parameters of the model for the different experimental conditions of this work.

Table 1. Synthesis of the values of the parameters of Midilli *et al.*, for the different values of intermittency α

Value of intermittency	Cycle	T (°C)	a	B*10^{-3}	k	n	R^2	RMSE x 10^{-3}	χ2
α = ¼	1st cycle	40	1.000	0.270	0.031	0.380	1.000	0.943	1.000
		50	1.000	0.170	0.062	0.289	1.000	0.546	1.000
		60	1.000	1.790	0.046	0.575	1.000	2.711	1.000
	2nd Cycle	40	0.857	0.670	0.016	0.574	1.000	1.305	0.999
		50	0.800	0.310	0.068	0.315	1.000	2.255	0.999
		60	0.702	0.200	0.122	0.199	1.000	0.191	1.000
	3th Cycle	40	0.751	0.350	0.015	0.546	1.000	0.182	1.000
		50	0.626	0.200	0.055	0.314	1.000	0.363	1.000
		60	0.535	0.380	0.090	0.348	1.000	1.112	1.000
	4th Cycle	40	0.658	0.300	0.012	0.581	1.000	0.643	1.000
		50	0.514	0.470	0.046	0.433	1.000	0.382	1.000
		60	0.380	0.030	0.244	0.066	1.000	0.699	1.000
α = ½	1st cycle	40	1.001	3.980	0.006	1.113	0.994	14.606	0.975
		50	1.000	3.650	0.008	1.078	0.998	12.667	0.990
		60	1.001	3.870	0.006	1.243	0.993	31.589	0.974
	2nd Cycle	40	0.782	1.990	0.008	0.926	0.998	5.152	0.993
		50	0.693	2.220	0.008	1.037	0.998	7.781	0.990
		60	0.549	1.950	0.009	1.121	0.995	13.478	0.981
	3th Cycle	40	0.629	1.870	0.006	1.010	0.998	3.834	0.992
		50	0.501	1.640	0.006	1.088	0.998	4.871	0.992
		60	0.317	1.100	0.011	1.064	0.997	6.153	0.988
	4th Cycle	40	0.526	1.300	0.006	0.942	0.999	2.230	0.995
		50	0.368	0.790	0.009	0.886	1.000	0.754	0.999
		60	0.184	0.010	0.062	0.064	1.000	0.008	1.000
α = ¾	1st cycle	40	1.000	3.730	0.005	1.153	1.000	3.407	0.999
		50	0.999	2.600	0.005	1.132	0.999	11.215	0.995
		60	0.999	2.290	0.004	1.333	0.999	18.396	0.995
	2nd Cycle	40	0.751	2.240	0.006	1.078	0.998	6.780	0.993
		50	0.615	1.630	0.005	1.143	0.998	7.998	0.991
		60	0.399	1.180	0.010	1.187	0.999	5.031	0.997
	3th Cycle	40	0.549	1.740	0.004	1.154	0.999	2.980	0.998
		50	0.407	1.120	0.005	1.078	1.000	1.432	0.999
		60	-	-	-	-	-	-	-
	4th Cycle	40	0.392	1.460	0.004	1.177	0.999	1.769	0.997
		50	0.299	0.830	0.009	0.914	1.000	0.085	1.000
		60	-	-	-	-	-	-	-

Table 2. Expressions of parameters of the new model

Parameter	Ta (°C)	Expressions
Mains parameters		
a_1	40	$a_1 = 0.592\alpha^2 - 0.652\alpha + 1.08$
	50	$a_1 = -0.352\alpha + 1.021$
	60	$a_1 = 3.432\alpha^2 - 3.154\alpha + 1.435$
b_1	40	$b_1 = -0.0112\alpha^2 + 0.0148\alpha - 0.0022$
	50	$b_1 = -0.0304\alpha^2 + 0.034\alpha - 0.0064$
	60	$b_1 = -0.02272\alpha^2 + 0.02572\alpha - 0.00422$
k_1	40	$k_1 = 0.0576\alpha^2 - 0.0796\alpha - 0.034$
	50	$k_1 = 0.54\alpha^2 - 0.694\alpha + 0.219$
	60	$k_1 = 0.704\alpha^2 - 0.758\alpha + 0.1764$
n_1	40	$n_1 = -2.308\alpha^2 + 3.263\alpha - 0.112$
	50	$n_1 = -6.384\alpha^2 + 8.46\alpha - 1.48$
	60	$n_1 = -15.552\alpha^2 + 17.544\alpha - 3.077$
Secondary parameters		
a_0	40	$a_0 = -0.192\alpha^2 + 0.032\alpha - 0.095$
	50	$a_0 = 0.184\alpha^2 - 0.214\alpha - 0.101$
	60	$a_0 = -3.184\alpha^2 + 2.304\alpha - 0.538$
b_0	40	$b_0 = -0.0004\alpha - 0.0001$
	50	$b_0 = 0.009\alpha^2 - 0.0099\alpha + 0.002$
	60	$b_0 = 0.006\alpha^2 - 0.00806\alpha + 0.00156$
k_0	40	$k_0 = -0.0096\alpha^2 + 0.0112\alpha - 0.0041$
	50	$k_0 = -0.0792\alpha^2 + 0.1054\alpha - 0.0324$
	60	$k_0 = 0.103\alpha^2 - 0.213\alpha + 0.108$
n_0	40	$n_0 = 0.295\alpha^2 - 0.203\alpha + 0.036$
	50	$n_0 = 0.752\alpha^2 - 1.1\alpha + 0.287$
	60	$n_0 = 6.768\alpha^2 - 6.928\alpha + 1.243$

The works of [22,25,26,34] present only the kinetics as experimental model, which make appear the off period. The results of [19] have not shown the behavior of product during the off period, and [21] present only the kinetics as experimental model.

3.3. Validation of Model

Figure 3 and Figure 4 show the set of different simulated and experimental profiles of the moisture ratio of the mango samples, in the drying chamber, respectively for the air inlet temperatures drying at 50 and 60°C.

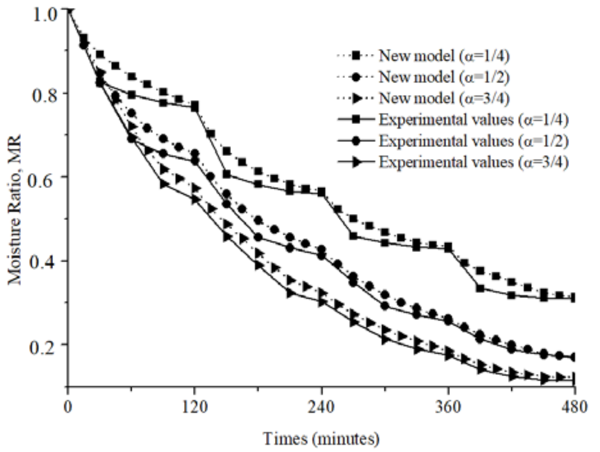

Figure 3. Comparison of the experimental profiles and the simulated model of the moisture ratio of mango during intermittent drying at 50°C

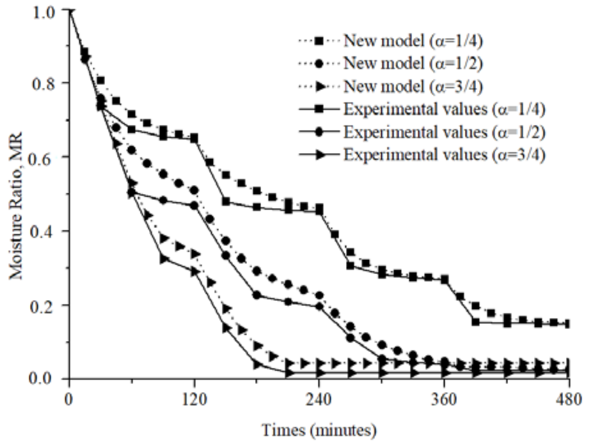

Figure 4. Comparison of the experimental profiles and the simulated model of the moisture ratio of mango during intermittent drying at 60°C

For the different values of intermittency, there is good agreement between the experimental and simulated results, at each cycle. It can see that the higher value of α conduct to the lower final moisture ratio.

From these different simulated and experimental curves, it is noted that with a drying inlet air temperature Ta = 60°C, the mango samples have a final moisture ratio less than 0.1. This value is lower than that of drying at 50°C.

4. Conclusion

The purpose of this work was to determine a new model for thin-layer fruit drying in intermittent mode. The mango samples obtained were dried in a through-flow modular electric dryer. The data collected during the various tests have permitted to test twelve different thin film models encountered in the literature. The principal results obtained at the end of this work are:

- The kinetics that describe the product behavior during each cycle on drying, with particular attention of product behavior at the off period.
- A new thin film drying model whose all different parameters depending of intermittency.
- The validation of the new model by simulation that shows a good agreement with the experimental values with R^2 = 0.996.

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