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Modeling of Banana Convective Drying by the Drying Characteristic Curve (DCC) Method

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ABSTRACT

Experimental convective drying tests of banana have been carried out for different air conditions to show the influence of air temperature, absolute humidity and speed on the drying rate. The analysis of the drying rate evolution as a function of product water content enables the identification of fourth drying phases: temperature rising (phase 1), exponentially decreasing drying rate (phase 2), linearly decreasing drying rate (phase 3) and very low drying rate (phase 4). The temperature rising phase 1 being very short and the last phase 4 being not reached during typical drying, the drying characteristic curve (DCC) has been represented by two different mathematical functions fitting phases 2 and 3. Their parameters have been

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determined by minimization of the quadratic errors between experimental and theoretical curves. It leads to a unique curve (the DCC) representing all air drying conditions the integration of which enables the calculation of the product water content with a maximum error of 0.09 between experimental and simulated values.

Key Words: Convective drying; Fruit; Banana; Characteristic curve; Drying rate; Reduced parameter.

INTRODUCTION

Drying of foodstuffs, particularly of fruits and vegetables, produces important variations in their volume and exchange area because of their high initial water contents value. During drying, their exchange area decreases due to the effect of the tissues contraction which partially occurs with water migration. As a result, all the parameters depending on internal and external dimensions change, so that the use of a complete model to simulate the drying of these products is quite complicated. The small amount of reliable data on this contraction phenomenon for high water content products, such as foodstuffs has led the Drying Characteristic Curve (DCC) method to be the most commonly used one to describe foodstuff behavior during drying (Fornell,[1] Desmorieux and Moyne,[2] Belhamidi et al.,[3] Ahouannou et al.,[4] Talla et al.[5]).

Several theoretical and experimental studies have been carried out to analyse and predict mass transfer in foodstuffs. Banana drying is a rather good example of these studies (Bowkey et al.,[6] Mauro and Menegalli,[7] Drouzas and Schubert,[8] Schirmer et al.,[9] Kiranouidis et al.,[10] Rastogi et al.,[11] Krokida et al.,[12] Prasertsan et al.,[13] Queiroz and Nebra,[14] Talla et al.[5]). According to Queiroz,[14] the simulation of banana drying with the diffusion model without taking into account product contraction and superficial convection leads to systematic differences between theoretical and experimental drying curves. By using a power function to represent the DCC, Talla et al.[5] succeed in simulating banana drying with acceptable differences between simulation and experimental results. Nevertheless, the number of experimental points in the beginning of the drying were not sufficient to clearly show the temperature rising period and a possible constant drying rate period. Furthermore, the fitting between experimental and simulated curves was evaluated with a small number of experimental points.

The aim of the present study is to analyse complete banana drying curves (for which the final desired water content is approximately equal to 0.2 kg w kg dm^{-1} according to Gret-Geres[15]) with a large number of experimental points. This analysis will be based on drying rates at constant drying air temperature and it is expected to lead to an improved drying model which will be evaluated on a large number of experimental points.

EXPERIMENTAL DEVICE AND METHOD

Experimental Device

The experimental device consists of a drying apparatus in which a sample of the product to be studied is presented to an airflow which temperature, humidity and speed are controlled by a regulated system. This device is represented in Fig. 1. Masses are measured with a precision of 0.001 g, air temperature, humidity, and speed are measured with respective precisions of 0.5°C, 2% RH and 0.1 m s^{-1}. The dimensions of

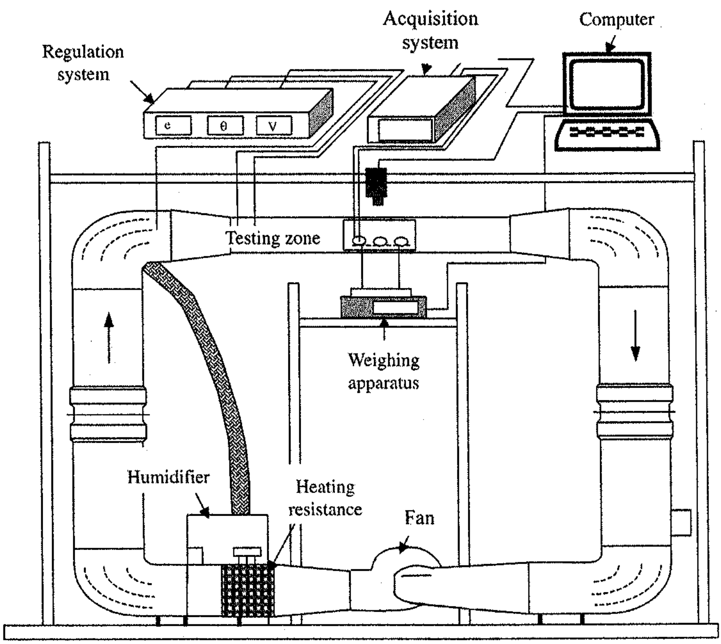


Figure 1. Experimental device.

the test cross section are $150 \times 150\,mm^2$. Product samples are set on a perforated tray the dimensions of which are $250 \times 110\,mm^2$.

Procedures

Measurements and especially mass product are recorded every 10 s during the first hour, then every minute during the following 5 h and finally every 10 min until the drying ends. The drying was stopped after a duration of 72 h that ensured complete drying (final water content less than 0.2) of the product whatever the drying conditions are.

The products are first washed with water before being peeled and cut Bananas used in these tests have a mean diameter of 30 mm. A banana was cut in two cylinders with 50 mm height and 30 mm diameter then each cylinder is cut longitudinally to obtain four quarters of cylinder.

When airflow thermal conditions have reached the required values, the products to be dried are set on a tray in a single layer and then introduced in the testing zone parallel to the air flow. As the mass of the product is quite low (approximately 30 g) and the testing zone quite short (250 mm) the air temperature and relative humidity are assumed to be constant all along the support. The mass product evolution is deduced from the recorded measurements.

A set of seven tests has been carried out with different air conditions as described in Table 1.

Mass measurement of a product set on a tray placed in a parallel airflow must take into account the force exerted by the airflow on the tray. This force may vary with the geometry of the support and with the projected area of the product on its support. In case of a highly

Table 1. Air conditions for the different tests.

Test	T (°C)	RH (%)	x (kgw kgda^{-1})	u (m s^{-1})	$\overline{X}_0$ (kgw kgdm^{-1})	$\overline{X}_f$ (kgw kgdm^{-1})	$\overline{X}_{eq}$ (kgw kgdm^{-1})
1	60	16.3	0.02	2.0	3.29	0.103	0.09
2	50	26.3	0.02	2.0	3.79	0.141	0.12
3	40	44.0	0.02	2.0	3.28	0.162	0.15
4	50	26.3	0.02	0.5	3.65	0.131	0.12
5	50	26.3	0.02	1.0	3.50	0.125	0.12
6	50	16.0	0.01	1.0	3.64	0.160	0.14
7	50	38.0	0.03	1.0	2.96	0.152	0.14

shrinkable product as banana, this force may vary along the drying time but in our case, it was verified that it was constant and lead to a mean mass correction of 0.2 g throughout the drying time. A more precise value was evaluated for each drying test.

RESULTS AND DISCUSSION

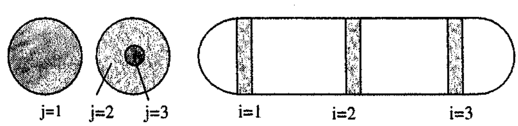
Results

Banana is quite a complex product with an heterogeneous water content. Several tests have been carried out that show that, on the same banana, the water content varies from the middle to the extremity as well as from the centre to the periphery as shown in Table 2. This result proves that a drying test on banana must be done on a sufficiently large product piece to be representative.

Moreover, Fig. 2 shows the initial water content of a banana piece as a function of the drying time of the piece in an oven which temperature is maintained at 102°C to obtain the bone-dry mass. This figure shows that the mass goes on decreasing even after seven days, leading to an increasing estimated value of the initial water content. Some physico-chemical phenomena different from water extraction of the product may occur at high temperature (102°C). For bone mass determination, a dessication duration of 48 h in an oven at 102°C for the entire tests presented here has been chosen.

Since moisture content calculation is strongly dependent on bone mass and that the experimental estimated value of the bone mass varies with dessication time, it would be better to know the dessication times

Table 2. Initial water content distribution in a banana (kgw kg dm^{-1}).



	Extremity ($i=1$)	Middle ($i=2$)	2 cm from extemity ($i=3$)
Periphery ($j=2$)	3.16	3.92	3.78
Centre ($j=3$)	3.90	4.80	4.63
Cross section mean ($j=1$)	3.27	3.90	3.92

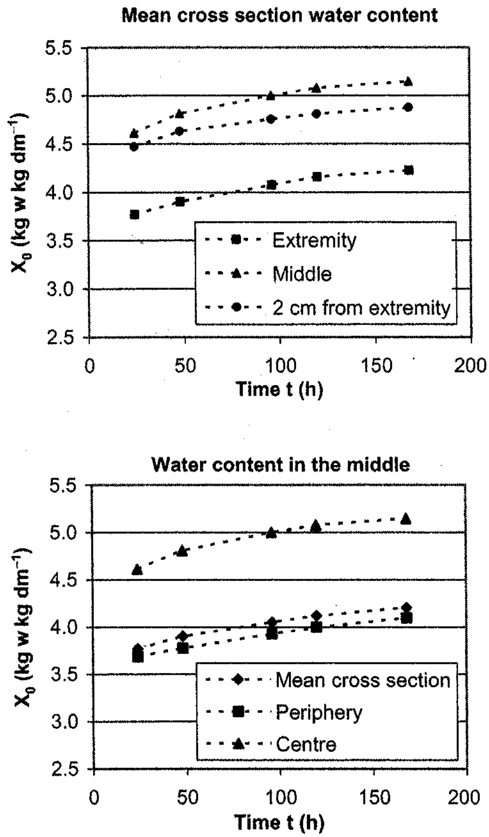


Figure 2. Variation of the estimation of initial moisture content of banana according to the heating time of the product and of the position in the product.

(and temperature) used by different authors to compare their banana drying curves.

The curves representing the variations of the mean water $\overline{X}$ content as a function of time t, or representing the drying rate $-d\overline{X}/dt$ as a function of $\overline{X}$ are commonly called drying curves. The mass product m_t evolution with time is deduced from total mass measurement and mass support measurement. Mean product water content is then deduced by applying relation (1).

$$\overline{X} = \frac{m_t}{m_f}(\overline{X}_f + 1) - 1 \qquad (1)$$

with: m_f Product mass at the end of the drying (kg)

m_t Product mass at time t (kg)

$\overline{X}_f$ Mean product water content (dry basis) at the end of the drying (kgwkgdm^{-1})

$\overline{X}$ Mean product water content (dry basis) at time t (kg w kg dm^{-1})

A reduced water content X_r is commonly used for the exploitation of drying kinetics. It is defined as follows:

$$X_r = \frac{\overline{X} - \overline{X}_{eq}}{\overline{X}_{cr} - \overline{X}_{eq}} \tag{2}$$

where $\overline{X}_{cr}$ represents the critical water content (water content at the transition between the constant drying rate phase and the decreasing drying rate phase) and $\overline{X}_{eq}$ represents the equilibrium product water content given by the sorption isotherms and depending on drying air conditions.

The values of $\overline{X}_{eq}$ used in this article have been obtained by extrapolation of the experimental curves representing $-d\overline{X}/dt$ as a function of $\overline{X}$: $\overline{X}_{eq}$ is considered to be the value of $\overline{X}$ corresponding to $-d\overline{X}/dt = 0$. For products with no clear first drying phase, the critical water content is usually taken equal to the initial water content. Banana is one of them since Talla et al.[5] found a very short first drying phase corresponding to $\overline{X}_{cr} \approx 0.95\ \overline{X}_0$ but with an insufficient number of points that could lead to a confusion between temperature rising phase and constant drying phase. Consequently, in this paper the critical water content $\overline{X}_{cr}$ has been taken equal to the initial water content. Table 1 indicates the estimated values of $\overline{X}_0$, $\overline{X}_f$ and $\overline{X}_{eq}$ during the different tests.

The curves representing $-d\overline{X}/dt$ as a function of $\overline{X}$ are calculated by a numerical estimation of the derivative of $\overline{X}$ at each measurement time t. In this study, the drying rate at a given time is calculated by application of formula (3) to (5) below. Equations (3) and (4) represents the slopes respectively on the right side and on the left side of the considered point since Eq. (5) calculates the mean value of the left and of the right slopes. At initial time, the drying rate is calculated as:

$$V_0 = \left(-\frac{d\overline{X}}{dt}\right)_0 = \frac{\overline{X}_0 - \overline{X}_1}{t_1 - t_0} \tag{3}$$

- At the final time t_n, V_n is calculated as:

$$V_n = \left(-\frac{d\overline{X}}{dt}\right)_n = \frac{\overline{X}_{n-1} - \overline{X}_n}{t_n - t_{n-1}} \tag{4}$$

- At each time t_i, i varying from 1 to $n-1$, the drying rate is first calculated as:

$$V_i = \left(-\frac{d\overline{X}}{dt}\right)_i = \frac{1}{2}\left(\frac{\overline{X}_{i-1} - \overline{X}_i}{t_i - t_{i-1}} + \frac{\overline{X}_i - \overline{X}_{i+1}}{t_{i+1} - t_i}\right) \tag{5}$$

Given the high number of experimental points (with low time interval between two mass measurements) which generates important estimation noise on calculated drying rate, a mobile centred mean calculated on nine points has been applied to the raw drying rate values calculated by formula (5). The number of calculation points (nine) was the higher that has no significant influence on the drying rate curves that would have been affected (translated and reduced values) by the choice of a higher number of points.

Figure 6 represents the drying rates of banana obtained by use of this calculation method for three different air temperatures, all other parameters being the same.

The DCC method consists in representing, for the whole experimental points obtained under various air conditions kept constant along all the test, the drying curves under the following reduced form:

$$V_r = \left(-\frac{d\overline{X}}{dt}\right)_r = \frac{V}{V_I} = f(X_r) \tag{6}$$

where V_I represents the first phase drying rate when this phase (with constant drying rate) is identifiable.

Discussion

An arbitrary mathematical expression is imposed to the function $f(X_r)$; this function must verify the following equations:

$$\left.\begin{array}{ll} f(X_r) = 0 & \text{for } X_r = 0 \\ 0 < f(X_r) < 1 & \text{for } 0 < X_r < 1 \\ f(X_r) = 1 & \text{for } X_r = 1 \end{array}\right\} \tag{7}$$

It can be noticed that the drying rate rising phase is not taken into account in conditions (7) since it is a very short phase compared to the drying duration as will be further verified. The curves on Figs. 3–5 representing product water content as a function of time show the very low influence of air absolute humidity and speed compared with the influence of air temperature. This leads to study first the experimental

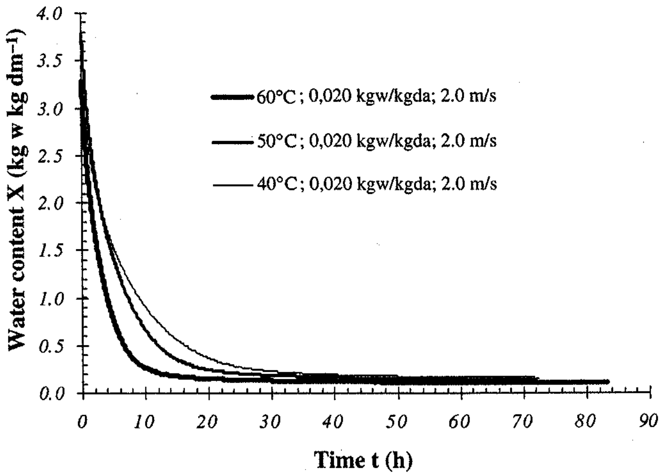


Figure 3. Drying curves for three different temperatures.

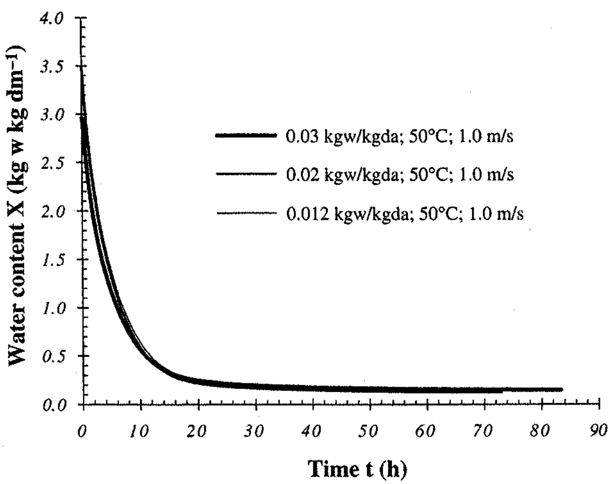


Figure 4. Drying curves for three different air absolute humidities.

curves obtained with variable temperature, all the other parameters being constant.

Three different drying phases appear clearly on Fig. 6 representing the drying rate as a function of the product reduced water content on a semi-logarithmic scale. The drying rate rising phase 1 is quite short

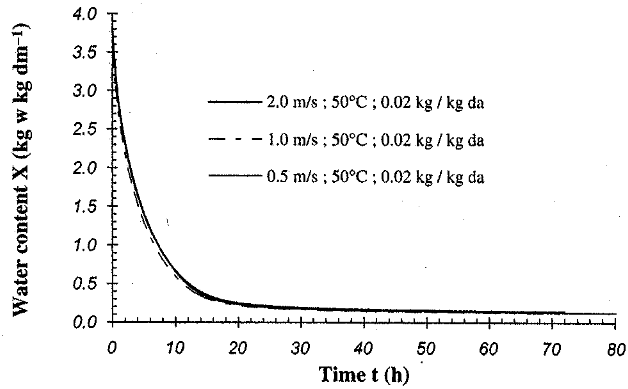


Figure 5. Drying curves for three different air velocities.

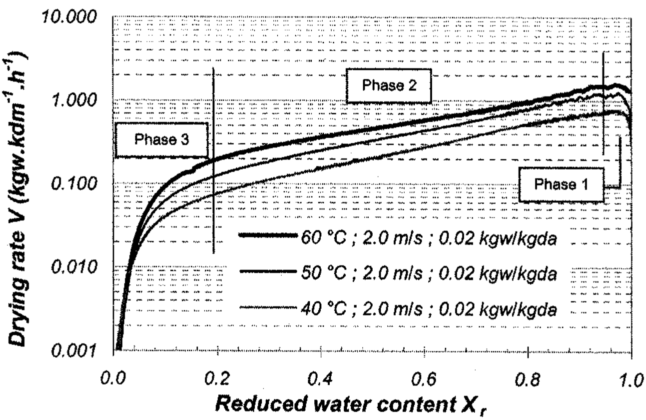


Figure 6. Drying rate as a function of reduced water at three different temperatures.

(reduced water content comprised between 1 and 0.95 for a drying time of 10 min and is followed by a long phase 2 where the drying rate decreases exponentially until the reduced water content reaches a transition value X_{r2}. Then a phase 3 occurs where the drying rate decreases linearly and more slowly.

Furthermore, the representation of the drying rate for reduced water content lower than 0.2 (Fig. 7) shows a phase 4 characterised by the convexity of the drying rate curve. This phase 4 occurs for reduced product water contents between 0 and X_{r1}.

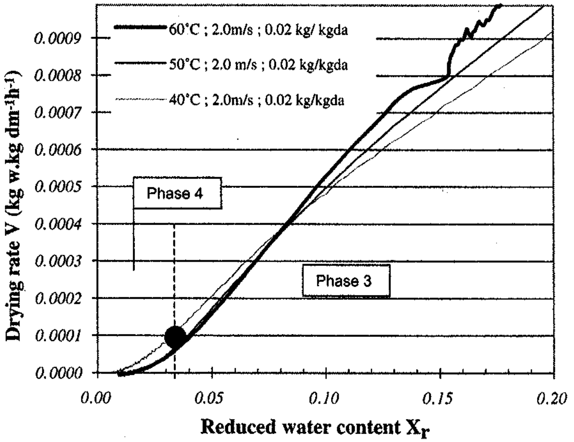


Figure 7. Drying rate at low reduced water content.

These graphical observations of the experimental results leads to define a function $f(X_r)$ representing this DCC for the two phases 2 and 3. The form of this function is defined by the following relations:

$$\text{If } X_{r1} \leq X_r \leq X_{r2} \qquad f(X_r) = cX_r + d \tag{8}$$

$$\text{If } X_{r2} \leq X_r \leq 1 \quad f(X_r) = a\exp(bX_r) \tag{9}$$

The third conditions of the system (7) and Eq. (9) lead to the following expression of the coefficient "a" as a function of the coefficient "b":

$$a = \frac{1}{\exp(b)} \tag{10}$$

The values of the product reduced water contents X_{r1} and X_{r2} corresponding to phase transitions have been determined graphically and the following values have been considered: $X_{r1} = 0.04$ and $X_{r2} = 0.2$. It can be noticed that the value $X_{r1} = 0.04$ corresponds to a product water content of approximately 0.12 that is never reached in a drying operation since the final water content to reach is around 0.2 as pointed out previously.

Taking into account all these constatations and hypotheses, the drying rate will be calculated by:

$$V = V_I \quad f(X_r) \tag{11}$$

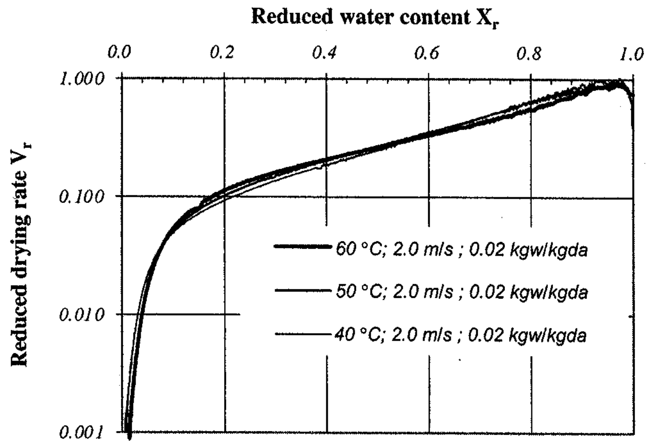


Figure 8. Drying rate in reduced coordinates for three different temperatures.

Contrarily to the rising drying rate phase, no constant drying rate phase can be evidenced on the experimental curves as shown in Fig. 6. Figure 8 represents the temperature T of the drying air, the temperature T_c in the heart of the product and temperature T_s of the product near its surface. These temperatures were recorded during a drying test with an air temperature of 50°C and a wet bulb temperature of 25.3°C. It can be observed a continuous rising of the temperatures inside the product with no constant temperature period confirming that no constant drying phase occurs. A delay between the temperatures of the surface and of the heart of the product can also be observed, it is due to internal diffusion processes. Consequently in relation (11) the first phase drying rate V_I will be replaced by a reference drying rate V_{ref} that will be considered as a parameter of the model.

By considering functions (8) and (9), the integration of Eq. (11) gives the theoretical expressions of the product water content as a function of the drying time:

$$\overline{X}(t) = \overline{X}_{eq} + (\overline{X}_0 - \overline{X}_{eq}) \left[\left(X_{r2} + \frac{d}{c}\right)\exp\left(-\frac{cV_{ref}}{\overline{X}_0 - \overline{X}_{eq}}(t - t_2)\right) - \frac{d}{c}\right] \quad (12)$$

$$\overline{X}(t) = \overline{X}_{eq} - \frac{1}{b}(\overline{X}_0 - \overline{X}_{eq}) \ln\left[\exp(-bX_{r0}) + \frac{abV_{ref}}{\overline{X}_0 - \overline{X}_{eq}} t\right] \quad (13)$$

- t_2 corresponds to the time at which the first transition ($X_r = X_{r2}$) is reached. It depends on the drying conditions.
- X_{r0} is the reduced initial water content ($X_{r0} = 1$ if $\overline{X}_{cr} = \overline{X}_0$ as considered for banana).

Figures 3–5 represent the drying curves for various air temperature, velocity and absolute humidity values. These figures show the significant influence of air temperature compared with air absolute humidity. It could also be remarked that drying curves are quite insensitive to air velocity except at the beginning of the drying.

The exponentially decreasing drying rate phase 2 following the temperature rising phase corresponds to the free water evacuation from the product (Fig. 9). It can be seen on the same figure a linear slowly decreasing drying rate phase 3 corresponding to the evacuation of linked water. The last phase 4 shown on Fig. 7 should correspond to the evacuation of water molecules highly linked to the monolayer.

The parameters V_{ref}, b, c, d of the proposed model are identified from experimental results by minimisation of the sum S_j of quadratic relative errors calculated by relation (14) for the first three tests at different temperatures, all the other parameters being the same. The couples (V_{ref}, b) are determined for the X_r values greater than 0.2 since the couples (c, d) are determined for the X_r values lower than 0.2. Table 3 summarises all the results of this identification. The equation of the DCC is then

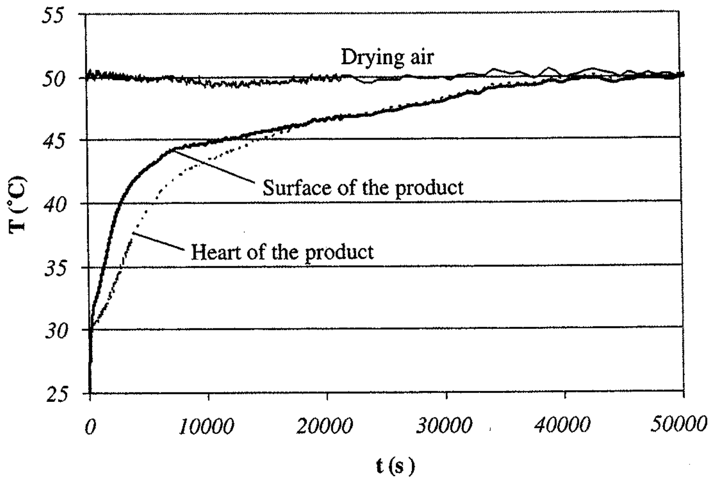


Figure 9. Experimental curves of temperatures during a banana drying test at 50°C.

Table 3. Identified parameters of the DCC model.

	X_r 0.20				$X_r < 0.20$			
T	b	V_{ref}	b_{op}	V_{ref_op}	c	d	c_{op}	d_{op}
40	2.861	0.863		0.807	0.420	−0.002		
50	2.798	1.344	2.648	1.281	0.431	−0.005	0.447	−0.004
60	2.541	1.631		1.716	0.478	−0.004		

shown by representing on Figure 8 the drying rate in reduced coordinate for the first three tests. This figure shows a very low dispersion around a mean curve defined by Eqs. (6), (8) and (9) in which the parameters a, b, c, and d (very close for each test) are replaced by unique and optimal values a_{op} , b_{op} , c_{op}, and d_{op}, obtained by minimisation of the sum S of the quadratic mean errors of each test calculated by (14):

$$S_j = \left[\sum_{i=1}^{n}\left(\frac{\overline{X}_{exp} - \overline{X}_{mod}}{\overline{X}_{exp}}\right)^2\right]_i \tag{14}$$

$$S = \sum_{j=1}^{p} \min\left[\sum_{i=1}^{n}\left(\frac{\overline{X}_{exp} - \overline{X}_{mod}}{\overline{X}_{exp}}\right)^2\right]_i \tag{15}$$

where n is the number of measurements for a test and p is the number of tests.

Using these optimal values a_{op}, b_{op}, c_{op}, and d_{op}, the reference drying rates V_{ref} are then recalculated for the entire tests realised at various air temperature, absolute humidity and speed, the obtained values of V_{ref} for each test are presented in Table 4.

This reference drying rate depends on drying air conditions, so that a correlation between V_{ref}, the air temperature θ, absolute humidity x and speed u has been sought in the basic form:

$$V_{ref} = A\,\theta^{\alpha}\,u^{\beta}\,x^{\gamma} \tag{16}$$

The values α, β, and γ have been obtained by minimisation of the sum S' of the quadratic relative errors of the different tests by relation (15):

$$S' = \sum_{i=1}^{n}\left(\frac{V_{ref\,exp} - V_{ref\,mod}}{V_{ref\,exp}}\right)^2 \tag{17}$$

Table 4. Identified parameters of reference drying rate model.

Model parameters			$A=0.0766$	$\alpha=1.866$	$\beta=0.0753$	$\gamma=-0.0091$
Test	T (°C)	RH (%)	x ($kgw\,kgda^{-1}$)	u ($m\,s^{-1}$)	V_{ref_exp} ($kgw\,kgdm^{-1}\,h^{-1}$)	V_{ref_mod} ($kgw\,kgdm^{-1}\,h^{-1}$)
1	60	16.3	0.02	2.0	1.72	1.749
2	50	26.3	0.02	2.0	1.28	1.24
3	40	44.0	0.02	2.0	0.807	0.816
4	50	26.3	0.02	0.5	1.12	1.12
5	50	26.3	0.02	1.0	1.15	1.17
6	50	16.0	0.01	1.0	1.18	1.18
7	50	38.0	0.03	1.0	0.92	1.01

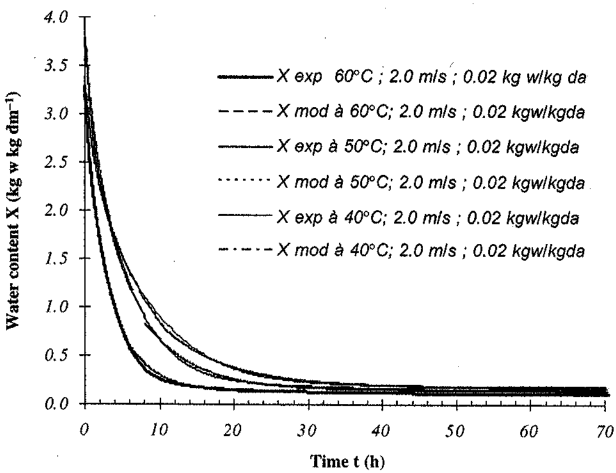


Figure 10. Experimental and simulated drying curves for three different temperatures.

Table 4 presents the calculated values of σ, β, and γ and the values of the experimental reference value calculated by relation (16). The maximal relative error between the experimental and calculated values is less than 9%.

Figure 10 represents experimental and simulated drying curves obtained using the same values a_{op}, b_{op}, c_{op}, and d_{op} for all the curves and a reference drying rate V_{ref} calculated by (16). For the entire set of tests, the proposed model describe quite satisfactorily the experimental curves with a maximum error of $0.09\,kgw\,kgdm^{-1}$.

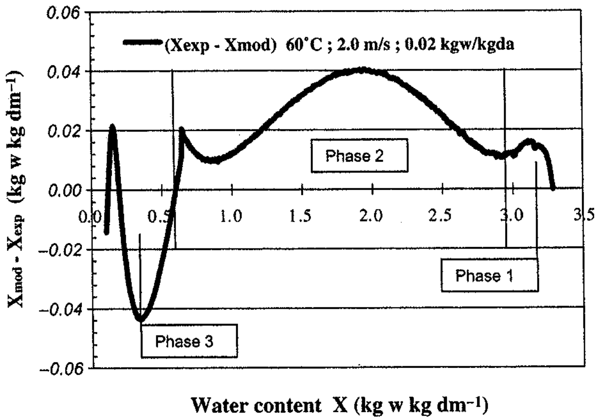


Figure 11. Residues between an experimental and its modeled drying curve.

Figure 11 represents the residues on the product water content X (difference between the experimental and simulated values) as a function of X for a drying test. This figure shows that the error induced by neglecting the temperature rising phase is quite low, it is less than 0.05 for all the curves. The residues analysis of phase 2 shows that this is not a random function so that the drying curve is not a perfect exponential. The analysis of the form of the representative curve of the residues in phase 2 could lead to find a better mathematical form if necessary. The end of phase 2 shows an increasing error until the point where a discontinuity of the slope is visible corresponding to the change of model at $X_r = 0.2$. This change of model enables a quite satisfactorily fitting in phase 3 at the end of the drying. As for phase 2, the analysis of the residues (not a random function) may lead to an improved mathematical representation of the DCC in this phase.

Comparison with Other Models

According to Dandamrongrak et al.[16] who have tested several models: the one-term exponential model, the two-term exponential model, and the Page model, the best model for describing the drying curves of banana is the two-term exponential model:

$$\overline{X}(t) = A_1 + A_2 \exp(-kt) + A_3 \exp(lt) \tag{18}$$

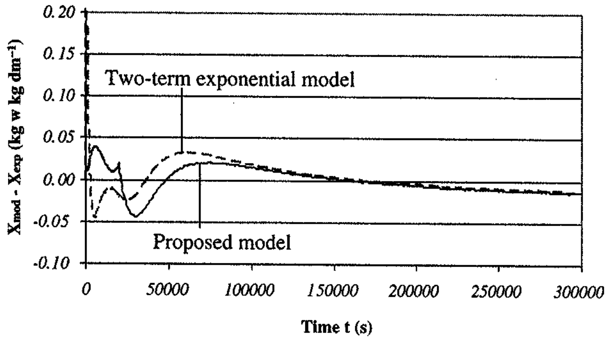


Figure 12. Residues between an experimental and two modeled drying curves.

This model with five parameters leads to a quite good representation of the drying curves as shown in Fig. 12 representing for a drying test at 60°C the residues on the product water content X (difference between the experimental and simulated values) as a function of the drying time t for the proposed model and for the two-term exponential model. The two models have rather the same precision so that the essential difference between the two models is the way their coefficients could be estimated . In the proposed complete model the coefficients a, b, c, and d are independent of the drying air conditions and the expression of the parameter V_{ref} as a function of air conditions (T, RH, u) has been established with a four-coefficients model given by formula (16). In the two-term exponential model, the five coefficients A_1, A_2, A_3, k, and l must be estimated for each new drying air conditions and a general expression of these coefficients as a function of drying air conditions (T, RH, u) has not yet been given for banana. The proposed model is so more convenient for use in a simulation programme of a drier in which the drying air temperature and relative humidity may be time-dependent and have not the same values in each point of the drier.

CONCLUSION

This study has shown the respective influence of the different air parameters on the convective drying of banana. Moreover, different drying phases corresponding to different physical mass transfer phenomena have been identified on the experimental drying curves.

Then an equation of the DCC has been established considering two different forms: one for the drying phase 2 with slowly decreasing drying rate and another for the drying phase 3 with fast decreasing drying rate, after having identified the transition point at a reduced water content of 0.2. The integration of these two forms has leads to a modeling of the drying curve $X=f(t)$ that fits the experimental curves with a maximum error of 0.09 kgwkgdm^{-1} for the drying tests carried out in this study.

NOMENCLATURE

a, b, c, d	Parameters of the DCC model
DCC	Drying characteristic curve
m	Product mass (kg)
n	Number of experimental points
p	Number of tests (–)
RH	Air relative humidity (%)
t	Time (s)
T	Air temperature (°C)
u	Air flow speed (m s^{-1})
V	Drying rate (kgw kgdm h^{-1})
x	Air absolute humidity (kgw kgda^{-1})
$\overline{X}$	Mean product water content (dry basis) (kgw kgdm^{-1})
A, α, β, γ	Parameters of reference drying rate model

Subscripts

0	Initial
1	First drying phase
cr	Critical
da	Dry air
dm	Dry matter
eq	Equilibrium (relative to product sorption isotherm)
exp	Experimental
f	Final (end of drying)
i	Experimental point number
j	Test number
mod	Model
op	Optimal
r	Reduced

ref	Reference
s	Surface of the product
w	Water

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