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EFFECT OF SHRINKAGE ON PREDICTION ACCURACY OF THE WATER DIFFUSION MODEL FOR PINEAPPLE DRYING

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ABSTRACT

Drying kinetics of pineapple slabs was analyzed. Fruits were cut into 6-mm-thick slices and dried in a convective cross flow dryer at constant air velocity (1.5 m/s) and temperature (45, 60 or 75C). Two simple diffusional models were applied for modeling the mass transfer during pineapple drying. In the first model, fruit shrinkage was ignored and the analytical solution was applied. In the second model, the premise of variable shrinkage with moisture content was assumed, and the mass transfer equations were solved through a finite differences scheme. In addition, an empirical model of drying rate was found. The average error of moisture estimation was lower for the model with shrinkage. Moisture diffusivity values increased with temperature and decreased when shrinkage was taken into account. Results also showed that fruit shrinkage can be represented by a linear function of moisture content and that volume variation was independent of drying temperature.

PRACTICAL APPLICATIONS

Pineapple is one of the most popular tropical fruits and is consumed mainly as canned, juice or fresh fruit; a lesser proportion is consumed as dried fruit. However, the drying makes it possible to extend the shelf life of pineapple by reducing water content and improves efficiency in transportation and storage. In this study, characteristics of drying kinetics of pineapple slices at different air temperatures were studied. Also, a simple model for the simulation of drying process, taking into account the fruit shrinkage, was proposed. The results of this study will be helpful in the technological application of hot air drying for pineapple preservation.

INTRODUCTION

Pineapple (*Ananas comosus*), a fruit originally from South America, has sensorial (mechanical properties, flavor, acidity/sweetness ratio, color) and nutritional (ascorbic acid, minerals, fibers, antioxidants, etc.) characteristics, making it attractive for the consumption as fresh fruit and in processed form. Among processed products, the dehydrated fruits stand out because they are easy to manufacture and have a more prolonged shelf life than the fresh fruit, besides reducing the costs of transport with respect to the fresh material. In this aspect, it is important, from the theoretical and the practical points of view, to characterize the process of pineapple dehydration.

Drying process has been modeled in two general tendencies: detailed and simplified (Balaban and Pigott 1988; Wang and Brennan 1995; Li *et al.* 2010). Detailed models have great importance in the understanding of food drying phenomena; nevertheless, its application to design and simulation of dehydration process of different fruits and vegetables is practically nonviable, because of the amount of parameters involved, which is not always available in the literature.

Simplified theoretical models may be obtained from detailed models. The most common simplifications are (Hernández *et al.* 2000): that diffusion coefficient and temperature in the solid are constant; homogeneity; and no shrinkage of the material. Simplifications have been widely used by a great number of authors to predict or to describe the drying kinetics of fruits and vegetables (Hernández *et al.* 2000; Márquez *et al.* 2006; Singh and Gupta 2007; Vega *et al.* 2007). Generally these authors do not make reference to or evaluate the accuracy loss of their predictions owing to these simplifications.

In particular, Mulet (1994) evaluated detailed models with different levels of complexity and concluded that the main factor to be considered in the model of food drying is the shrinkage. In addition, shrinkage is macroscopically evident during drying of foods with high water content, mainly in fruits and vegetables, and numerous works about this subject were published (Talla *et al.* 2004; Hassini *et al.* 2007; Dissa *et al.* 2008). Prediction models of volume and superficial area variation during food drying usually are the result of the fitting of experimental data to empirical models (Lozano *et al.* 1983; Ratti 1994; Katekawa and Silva 2006).

Volume variation during the food drying affects the value of the calculated diffusion coefficient because a shortening in the length of the path followed by water molecules takes place, and it must be considered in mathematical equations for drying time prediction. Katekawa and Silva (2006) presented a review of the different strategies used to model drying processes in which material shrinkage occurs; in this paper, 143 articles were analyzed.

In recent years, some studies on the use of new methods for pineapple drying and optimizing existing ones have been published. The performance of the solar tunnel drier for drying of pineapple slices under Bangladeshi conditions was researched by Bala *et al.* (2003). The influence of modified atmosphere with ethanol on the water evaporation during pineapple drying was studied by Braga *et al.* (2009). However, the effect of different factors that could affect the accuracy of prediction models for pineapple drying has been little investigated. Rahman and Lamb (1991), working with an African variety of pineapple, *Gian kew*, studied the drying kinetics at 60C of fresh and osmotically dehydrated fruit, applying a model based on Fick's second law of diffusion, with constant volume. The drying kinetics of pineapple, fresh and osmotically dehydrated, at different conditions of temperature and air rate was analyzed by Nicoleti *et al.* (2001). In addition, they compared the drying curves at constant air temperature and constant temperature of solid. No comparison with variable volume models was done.

The main objective of the present study was to evaluate the drying kinetics of pineapple slices in hot air and the effect of neglecting or considering the shrinkage on the accuracy of a drying simulation model of pineapple slices through the testing of two diffusional models (with and without shrinkage). With the aim of reaching this objective, drying kinetics of pineapple slices and the shrinkage of material during the process at different air temperatures were also evaluated.

MATERIALS AND METHODS

Sample Preparation

A. comosus fruits of the Smooth Cayenne variety, of local production, with commercial ripeness degree, procured from a commercial shop, were used in this work. Fruits were washed and manually peeled, cored and cut into half rings of 0.6 ± 0.05-cm thickness and of 11.5 ± 0.5-cm diameter.

Drying Kinetics – Experimental Procedure

Drying experiments were performed in a convective cross flow pilot dryer at constant conditions. Air velocity was fixed at 1.5 m/s and its temperature was fixed at 45, 60 or 75C. The pineapple slices were put into two aluminum baskets, avoiding contact between the fruit pieces. Air passed through the slices. At pre-established times, a basket was removed from the dryer, and its weight was registered; from the other basket, four samples were extracted (at random) and their thickness was measured with a manual calliper in three points of each sample, and they were immediately returned to the dryer.

Drying tests were performed at 45, 60 and 75C in triplicate. The average moisture content of fresh and dehydrated pineapple was 750 and 23% in dry basis, respectively; and drying times varied between 150 and 430 min for different drying temperatures.

Volume Variation

Shrinkage coefficient is defined as the relation between the present volume and the initial volume (Lozano *et al.* 1983), but when the transversal area of the material remains constant during drying, it can be considered as the relation between the present thickness and the initial thickness of the slice (L/L_0).

During drying, shrinkage can be represented as a function of moisture content (Suzuki *et al.* 1976; Lozano *et al.* 1983; Hernández *et al.* 2000; Mayor and Sereno 2004). Hernández *et al.* (2000) proposed a linear function for relating shrinkage with the moisture content X (grams of water per grams of dry solid) (Eq. 1).

$$\frac{L}{L_0} = e^{-\eta L_0} + \left(1 - e^{-\eta L_0}\right)\frac{\bar{X}}{\bar{X}_0}, \tag{1}$$

where $L = L_0$ when $\bar{X} = \bar{X}_0$ and $L = e^{-\eta L_0} L_0$ when $\bar{X} = 0$.

The parameter η was quantified by regression analysis of Eq. (1) with experimental data, obtained during the drying of the pineapple slices.

To evaluate the influence of temperature on shrinkage, experimental results obtained at each drying temperature were analyzed separately.

The change in the cross-sectional area of pineapple half slices after 3.5 h of drying at 60C and 3 h of drying at 75C was registered. For this purpose, the area of each sample was measured drawing it on a paper (five samples every time), and then cutting and weighing the paper (Mantovani 1999). Then, this value was compared with the weight of a well-known area (100 cm^2) of the same paper, considering direct relation between the area and the mass of the paper. At the beginning and at the end of the drying period, this process was repeated.

Measurement of Moisture Content

Moisture content was determined gravimetrically by drying at 75C until constant weight, during approximately 48 h.

Theoretical Considerations

Drying Rate. The average drying rate (*DR*) can be calculated by the loss of water ΔX during a period Δt (Doymaz 2007):

$$DR = \frac{\Delta \bar{X}}{\Delta t} = \frac{\bar{X}_{t+\Delta t} - \bar{X}_t}{\Delta t}, \tag{2}$$

where $\bar{X}$ is the average moisture content and Δt is the time period.

During the drying of some high-humidity vegetables, an initial period of constant rate, followed by one or two of decreasing rate can be distinguished. During the constant rate period, free moisture of material evaporates, and the external conditions predominate. This period is rarely observed during drying of most biological materials (Nogueira 1991). Then, as drying proceeds, the moisture content falls, and the access of water from the interior of the food to the surface affects the rate and decreases it.

Fick's Second Law: Diffusion Through Porous Solids

In most studies carried out on drying kinetics, diffusion is usually accepted to be the main mechanism of moisture transport to the solid surface (Hassini *et al.* 2007; Aghbashlo *et al.* 2009).

To consider drying as a mechanism of one-dimensional diffusion is a frequent assumption in dehydration studies of sliced fruits and vegetables such as bananas (Karim and Hawlader 2005), pumpkins (Arévalo-Pinedo and Murr 2006) and pineapples (Kosegarten-Conde *et al.* 1999; Nicoleti *et al.* 2001), among others.

Previously, a theoretical (and approximate) evaluation based on the size and shape of our samples, the experimental values of water's D_{eff} during the pineapple drying and the considerations of Turhan and Erdoğdu (2003) was carried out to clarify if the assumption of infinite slab was valid. These calculations demonstrated that this assumption introduces a relative error in predicted moisture values below 1% during the first 10 h of the process at 75C, and it is extended to 20 h at 45C.

The Lewis number, $Le = \alpha/D$, represents the ratio between the heat diffusion and the mass diffusion (Gekas 2000). If $Le > 60$, the profile of temperature can be considered negligible compared with the moisture gradient, thus the mass transfer would be the predominant mechanism of process (Demirel and Turham 2003). From the Choi and Okos model (Gekas 2000) and the pineapple composition, the value of thermal diffusivity could be calculated (approximately 10^{-7} m^2/s), whereas the coefficient of water diffusivity, by applying the analytical solution of the Fick's second law to our experimental data, is in the order of 10^{-10} m^2/s. These values justify the supposition of constant temperature during the process.

When the sample is considered a homogeneous solid with constant properties of material and the water movement is one-dimensional, the variation of the moisture content within the pineapple slice during the drying can be considered to be adequately described by the Fick's second law of diffusion:

$$\frac{\partial X}{\partial t} = D_{\text{eff}} \frac{\partial^2 X}{\partial x^2}, \tag{3}$$

where X is the moisture content (on a dry basis), x is the position inside the slice, t is the time and D_{eff} is the effective moisture diffusivity.

To solve this differential equation, the following assumptions were made:

1. Solid temperature remained constant and equal to air temperature during the drying process;
2. Uniform initial moisture distribution;
3. Pineapple slice was considered as a thin slab of thickness $L_0 = 2l$. Both sides of the slice are exposed to uniform airflow at constant temperature throughout the process;
4. External resistance to the mass transfer was negligible. Moisture content in the surface of the pineapple slices was in equilibrium with the surrounding atmosphere at any time. This assumption is based on the fact that the water vapor diffusion coefficient in air is several orders higher than that in the solid food.

Approximations to the analytical solution of Eq. (3) can be arbitrarily classified into constant volume and variable volume models. In these models, some fissuring phenomenon that could occur during drying, or other changes in structure, are always neglected.

Approximate Model 1: Constant Thickness

The solution to Eq. (3) for slab geometry, considering previous assumptions and constant thickness of the sample, was developed by Crank (1975):

$$\frac{\bar{X}-\bar{X}_e}{\bar{X}_0-\bar{X}_e}=\frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left\{-D_{\text{eff}}(2n+1)^2\frac{\pi^2}{4l^2}t\right\}, \quad (4)$$

where $\bar{X}$ is the average moisture content (on a dry basis), $\bar{X}_e$ is the equilibrium moisture content (on a dry basis) at the air temperature and $\bar{X}_0$ is the initial moisture content (on a dry basis).

Usually, approximate versions of this solution are used in studies of dehydration processes (Feng *et al.* 2000; Karatas and Pinarh 2001). An important and widely known characteristic of this series (Eq. 4) is that exponential terms tend quickly to zero as time advances. In the present work, the first five terms of Eq. (4) were used for quantification of diffusion coefficient. By nonlinear regression of experimental results D_{eff} values were calculated.

The needed values of X_e were measured, drying the samples by approximately 48 h at the corresponding temperature (45, 60 or 75C). These experimental data were satisfactorily compared with those published by Hossain *et al.* (2001).

Approximate Model 2: Thickness Variable with Moisture Content

This model incorporates the thickness variation during dehydration as a function of average moisture content.

To include the shrinkage observed during fruit drying, the differential equation (Eq. 3) was solved applying a numerical approach of explicit finite differences (Burden and Faires 1985; Chapra and Canale 1998). In this model, the shrinkage was taken into consideration in the value of the time-variable space increments Δx_i^t, so as to maintain a constant number of increments.

The explicit finite differences method is used to numerically solve the resulting equations. For mathematical purposes, the solid was divided into twenty slices of variable thickness as a function of moisture content ($\Delta x_i = 0.03$ cm), called subvolumes. The thickness of each subvolume was reduced because of water losses.

In one point (nodal point), placed at the center of the subvolume, mass balance was performed through the finite differences scheme. The nodal equations were solved in iterative form at each time step, considering $\Delta t = 0.5$ min, values for which the numerical scheme had a stable behavior.

Equation (3) was numerically solved with the following initial and boundary conditions:

$$X = X_i^0 = X_0 \quad -1 \le x \le 1 t = 0$$

$$X = X_1^t = X_e \quad x = \pm 1 \quad t > 0$$

Second derivatives were written by using central differences, for internal grid points, and the first derivatives by forward differences. By replacing these numerical expressions in Eq. (3) (Fick's second law), Eq. (5) was obtained:

$$D_{\text{eff}}\frac{X_{i+1}^t - 2X_i^t + X_{i-1}^t}{\left(\Delta x_i^t\right)^2} = \frac{X_i^{t+\Delta t} - X_i^t}{\Delta t}. \quad (5)$$

It can be written as

$$X_i^{t+\Delta t} = X_i^t + \lambda\left(X_{i+1}^t - 2X_i^t + X_{i-1}^t\right), \quad (6)$$

where $\lambda = D_{\text{eff}}\dfrac{\Delta t}{\left(\Delta x_i^t\right)^2}$.

These equations provide an explicit way to calculate values of moisture content in each node for a later time, if present values of moisture are known.

The subscript *i* and superscript *t* represent the space and time step, respectively. The thickness of each subvolume (Δx_i^t) was calculated by Eq. (1), with moisture content of the respective node at time *t*, assuming that remains unchanged during the very short time step Δt.

This equations system was used to evaluate the D_{eff}. The smallest *Epp* value, calculated by means of Eq. (7), was the fitting criterion used.

$$Epp = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{\bar{X}_{\text{exp}}^t - \bar{X}_{\text{estimated}}^t}{\bar{X}_{\text{exp}}^t}\right| * 100 \quad (7)$$

The methodology allowed, including the shrinkage in the mathematical model, to obtain an approximated profile of moisture content at every time step during the drying process.

RESULTS AND DISCUSSION

Shrinkage

To apply the model proposed by Hernández *et al.* (2000), the η parameter was estimated through adjustment of Eq. (1) to experimental data of pineapple slices thickness during drying (Fig. 1). Values of η at different temperatures and percentage average relative error of the thickness estimation (*Epp*) are shown in Table 1. On the basis of these results, the Eq. (1) is considered appropriate to describe the thickness changes of pineapple slices during the drying with hot air.

The main superficial area of samples at the end of drying was 75–80% of the initial area (in fresh fruit), whereas the thickness was approximately 30% of the initial thickness, in the same experiences. This fact shows that the shrinkage in radial direction is three times smaller than the loss of thickness.

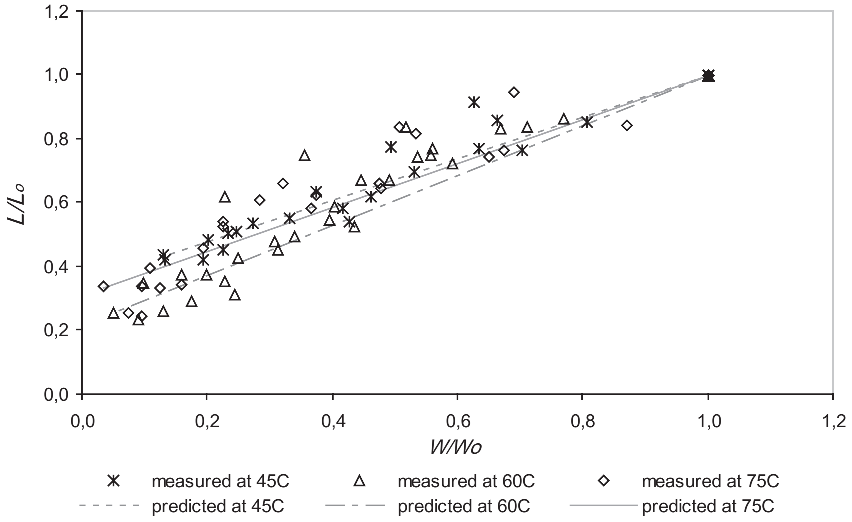

FIG. 1. VARIATION OF DIMENSIONLESS THICKNESS FOR PINEAPPLE SLICES DURING DRYING AT DIFFERENT TEMPERATURES
Predicted values by Eq. (1) are shown through individual lines, as specified.

Moisture Diffusivity

Diffusion coefficients (D_{eff}) were estimated from experimental data of drying tests (Table 2). The fitting criterion used was the minimum value of *Epp*. According to these results, considerations carried out in the application of Fick's model can generate important discrepancies among the calculated diffusion coefficients. Diffusion coefficients obtained with model 1 and model 2 can be considered statistically different.

Values of D_{eff} were somewhat greater when shrinkage is not considered. This difference increased with drying temperature, from 20% higher at 45C until 35% at 75C. These results are in agreement with those published by Dissa *et al.* (2008) in a study of convective drying of mango. *Epp* values in Table 2 show that the proposed model with shrinkage is, as was expected, more accurate than the model without shrinkage. In other words, average moisture content values simulated through diffusion model with shrinkage were in close agreement with experimental moisture content values, as can be seen from the Table 2. This favorable effect is more important for high temperature of drying.

TABLE 1. VALUES OF EMPIRICAL PARAMETER η AND *Epp* OF THICKNESS ESTIMATION BY LINEAR MODEL

Temperature, °C	η	*Epp* (Eq. 1), %
45	1.76	5.025
60	2.56	11.362
75	1.95	11.501

Moisture diffusivity values during the drying of pineapple slices with the assumption of constant slab thickness were published. Nicoleti *et al.* (2001) obtained values of effective diffusion coefficients at different temperatures and air velocities, which varied between 2.05×10^{-10} and 9.17×10^{-10} m^2/s; Rahman and Lamb (1991) published values of D_{eff} during pineapple drying at 60C (9×10^{-10} to 12×10^{-10} m^2/s). These values are in agreement with those of Table 2, when the shrinkage was not considered.

In coincidence with the expressed above, the shape of pineapple drying curves (Fig. 2) show that when shrinkage is considered in the mass transfer model, predicted moisture values are closer to the experimental ones than when the model with constant thickness is applied.

The mathematical model developed in finite differences was able to predict the moisture distribution in pineapple slab, with and without considering shrinkage, during drying. Given that it is very difficult to experimentally determine the moisture distribution in a slab of 0.4- to 0.6-cm thickness, predictions of the moisture distribution by the numerical model could not be verified in the present study. Only average moisture content was determined experimentally.

TABLE 2. COMPARISON OF RESULTS OBTAINED BY FITTING OF TWO PINEAPPLE DRYING MODELS

	Without shrinkage		With shrinkage	
Drying temperature (C)	$D_{eff} \times 10^{10}$ (m^2/s)	*Epp* (%)	$D_{eff} \times 10^{10}$ (m^2/s)	*Epp* (%)
45	2.667 ± 0.254	5.07 ± 1.87	2.117 ± 0.142	6.55 ± 1.82
60	4.722 ± 0.256	11.07 ± 3.62	3.183 ± 0.161	4.47 ± 1.04
75	7.920 ± 0.838	14.51 ± 6.69	5.038 ± 0.172	1.95 ± 1.13

Mean of three tests ± standard deviation.

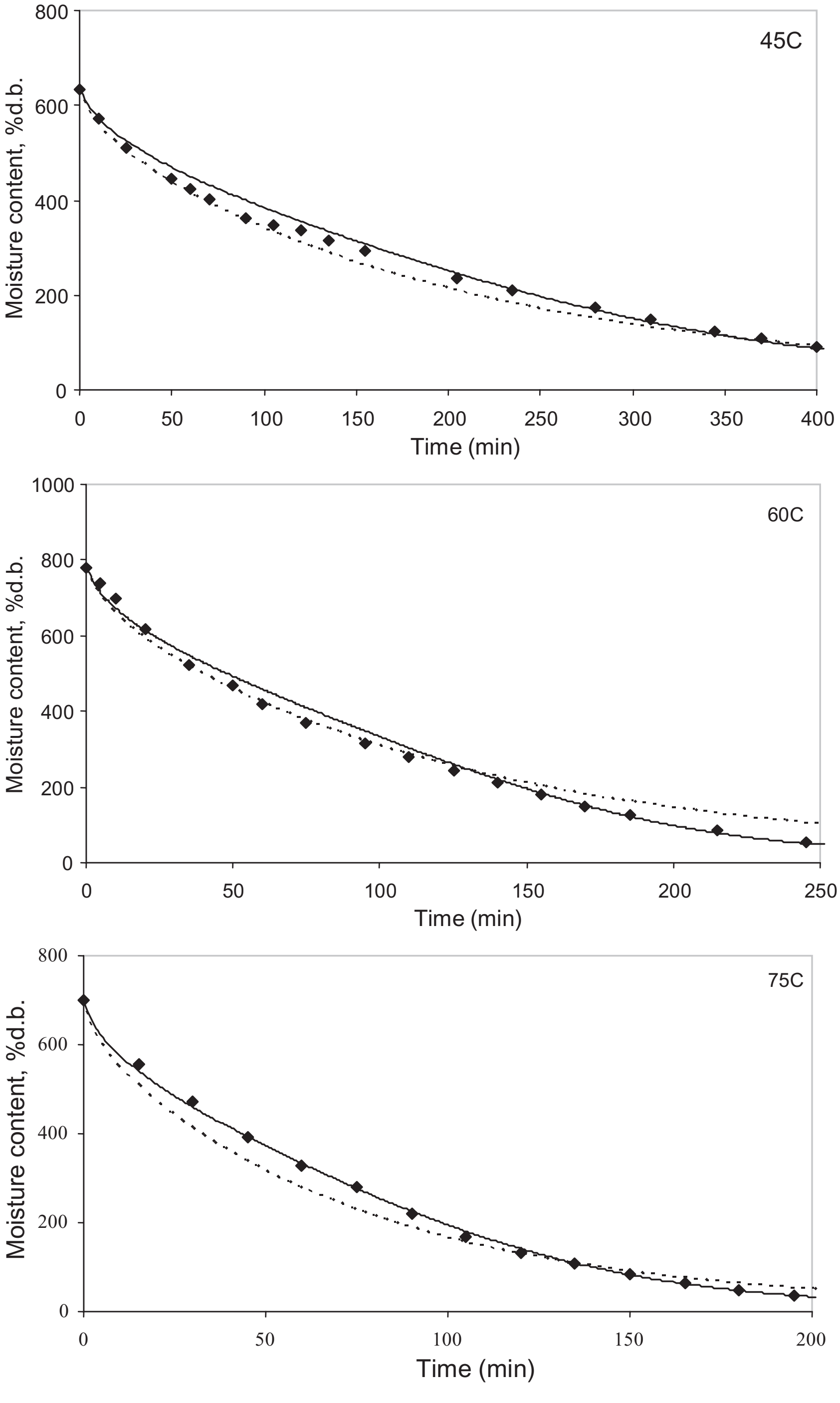

FIG. 2. EXPERIMENTAL (◆) AND PREDICTED AVERAGE MOISTURE CONTENT DURING DRYING OF PINEAPPLE SLICES
Continuous line (—) represents the model with shrinkage. Discontinuous lines (– – –) represent the model without shrinkage.

Experimental and predicted average moisture content of pineapple slab, at each time, were compared during the simulation to determine the best water diffusion coefficient.

The influence of the shrinking on predicted values through the numerical simulation is more important in the inner layers of material, distant to the surface directly exposed to the drying air, as is shown in Fig. 3. Here, values of predicted moisture from the model with constant thickness are represented by discontinuous lines and continuous lines represent predicted moisture values by model with shrinkage. It can be seen that the moisture content in the solid surface decreases quickly and there are no differences of predicted values by the two mathematical models. This is predictable because both models apply, for their numerical integration, the boundary

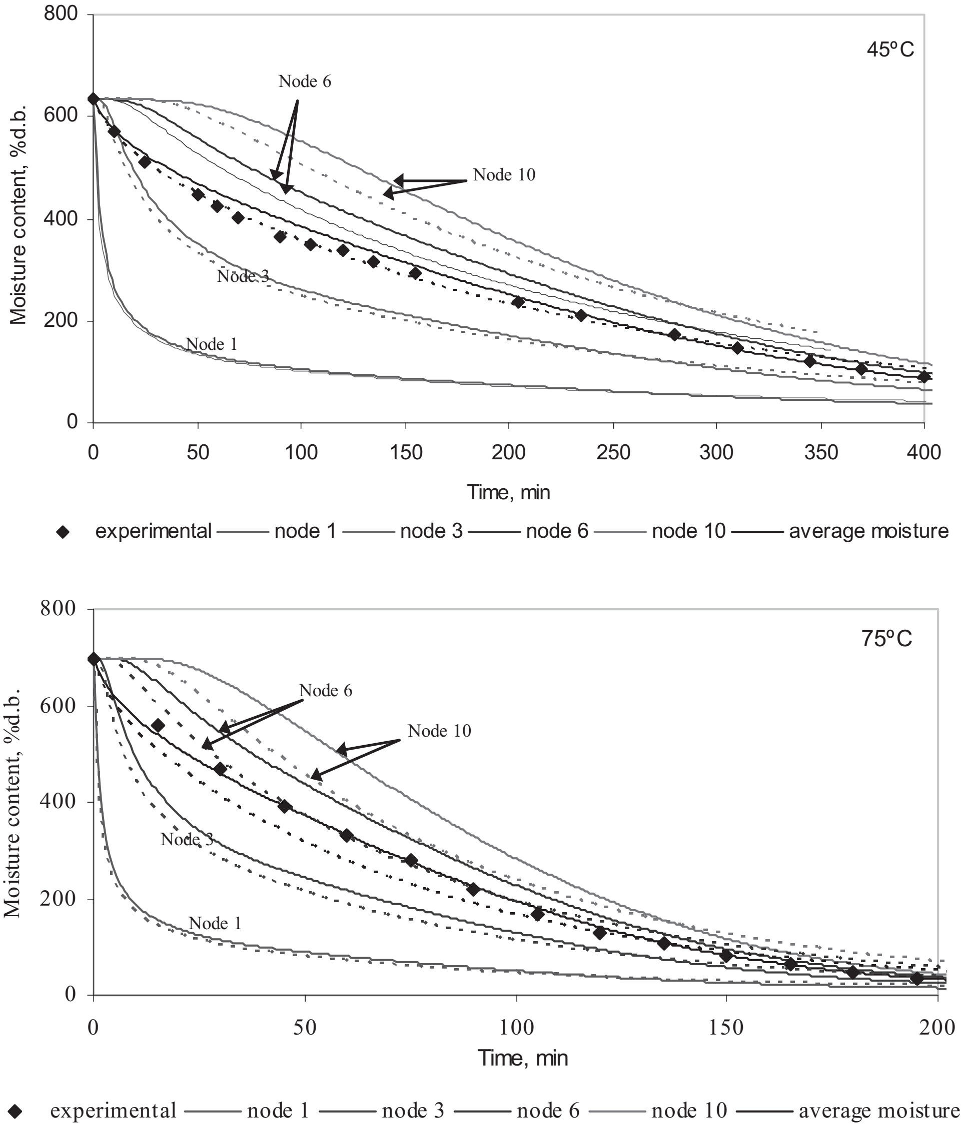

FIG. 3. MOISTURE PROFILE IN PINEAPPLE SLICES DURING DRYING
◆: Experimental average moisture, full lines: simulated moisture with shrinkage, dotted lines: simulated moisture without shrinkage. Node 1 is surface and node 10 is the center of the body.

condition that establishes that the moisture in the surface is equal to the equilibrium water at that temperature. Thus, in the proximity to the surface of the solid the differences of results predicted by both techniques would have to be practically null.

Drying Rate

The moisture content during pineapple drying at different temperatures and constant air velocity is shown in Fig. 2. As expected, the increase in the drying temperature diminishes the required time to obtain a specific moisture value in the solid.

To study the temperature effect on the behavior of dehydration rate, experimental results of DR (water extracted in a time interval, grams of water per 100 g dry matter/min) as a function of moisture content were analyzed. As can be observed in Fig. 4, the constant rate drying period is absent in the drying of pineapple slices under the employed experimental conditions. To this respect, a period of constant *DR* was observed, although not clearly defined, during the drying of green peas at 55C, but it disappears at 60C (Pardeshi *et al.*

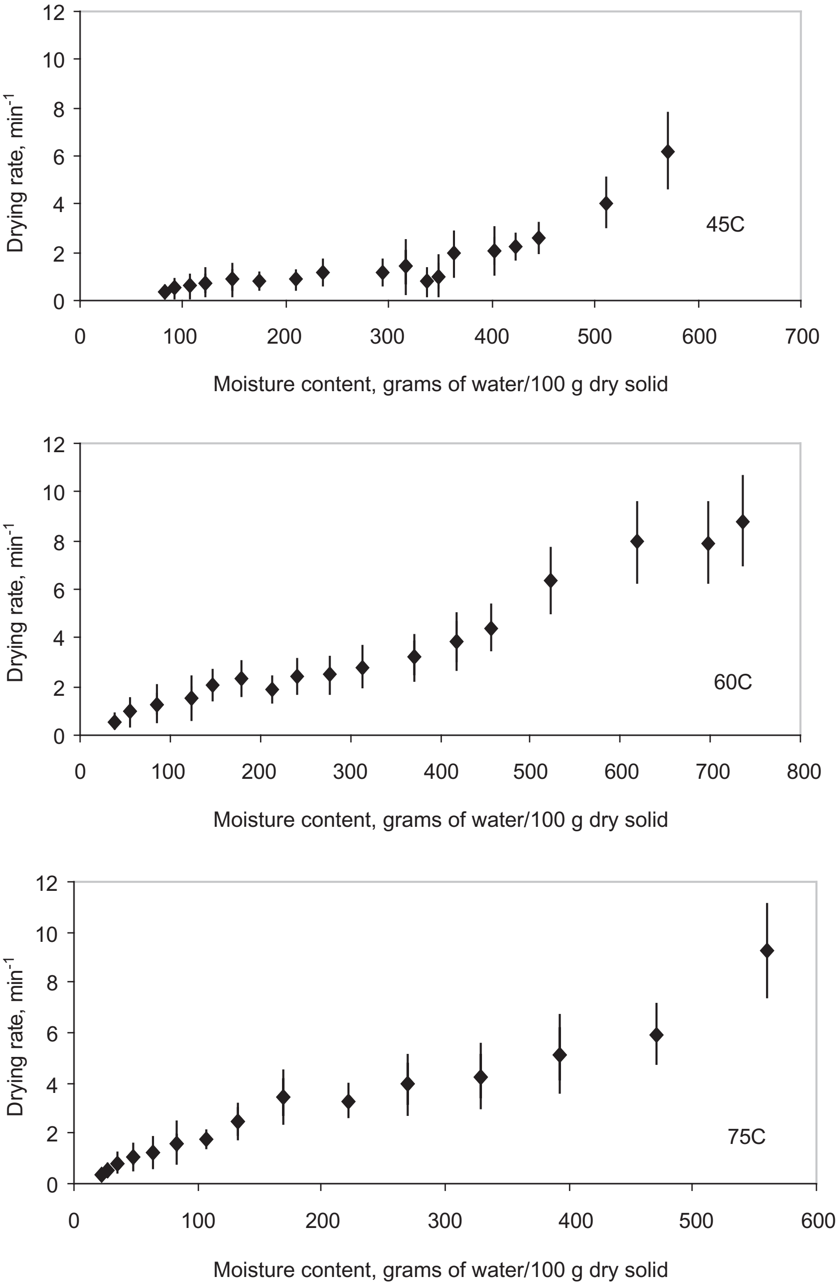

FIG. 4. RELATIONSHIP BETWEEN THE DRYING RATE (*DR*) AND THE MOISTURE CONTENT DURING DRYING OF PINEAPPLE SLICES AT DIFFERENT AIR TEMPERATURES
◆ Represent drying rate values calculated with experimental moisture content and Eq. (3), and vertical lines correspond to respective standard deviation.

2009); this period was not present during the drying of bananas at 60C and 3.3 m/s air velocity (Demirel and Turham 2003). Experimental data obtained during solar drying of prickly pear cladode showed only a falling rate period (Lahsasni *et al.* 2004)

At 45C, two falling rate periods can be observed: the first period or (with surface dry spots) is extended approximately until a moisture value of 400% d.b.; from this point, the water movement in the solid is the dominant physical mechanism of drying and the second – slowest – period of falling rate, occurs.

During pineapple drying at 60C, drastic differences between the two stages of falling rate were not observed, although there is a slight change in the curve slope of *DR* at a moisture content of 400% d.b. During pineapple drying at 75C, the *DR* gradually decreased as the moisture content lowers, showing a falling rate period of strict internal control. The shape of *DR* curves is similar to those published by Demirel and Turham (2003) for hot air drying of bananas.

Even if an equation to describe the *DR* may be regarded as an oversimplification of the mass transfer mechanism,

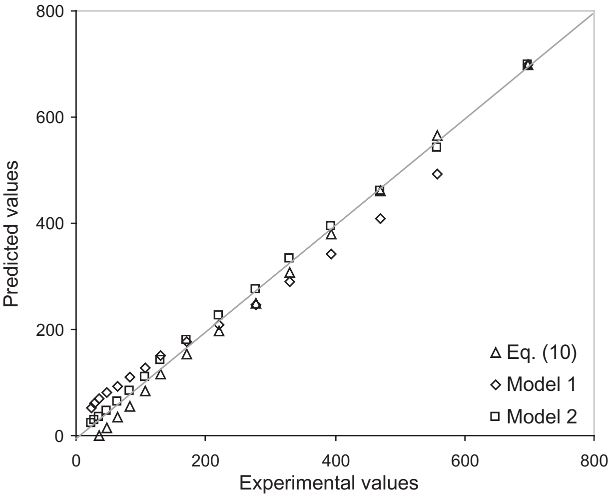

FIG. 5. EXPERIMENTAL AND PREDICTED VALUES OF MOISTURE CONTENT DURING PINEAPPLE DRYING IN AIR AT 75C

resulting parameters can be useful to predict the behavior of the system. Experimental data have a good agreement with an empirical equation of the type $DR = a \ln(t) + b$, where values of a and b parameters change systematically with the temperature.

Based on this observation, parameters a and b were assumed to vary according to a linear relationship with the drying temperature. In this way, Eqs. (8) and (9) were obtained by regression analysis, where T is the temperature (C).

$$b = 0.3012\,T - 5.2133 \; R^2 = 0.995 \tag{8}$$

$$a = 0.05883\,T + 1.3057 \; R^2 = 1 \tag{9}$$

A generalized equation for the prediction of DR is obtained as:

$$DR = (-0.05883\,T + 1.3057)\ln(t) + 0.3012\,T - 5.2133 \tag{10}$$

The linear model described properly the variation of parameters a and b, because R^2 values were equal or higher than 99.5%. Therefore, the DR can be easily predicted at any temperature in the range 45–75C by using Eq. (10).

Comparison Between Prediction Models

Evaluation of diffusional and empirical (Eq. 10) models for moisture prediction can be made by comparing the experimental moisture values with the respective predicted values. The experimental and predicted moisture values at 75C lay around the straight line (Fig. 5). Similar plots were obtained from predicted and observed values at 45 and 60C. Moisture content values predicted by all models gave a random error distribution, but the best agreement between experimental and predicted moisture values was obtained by the model 2.

TABLE 3. AVERAGE RELATIVE ERRORS FROM THE ESTIMATION OF DRYING RATE CALCULATED THROUGH EQ. (10) AND EQ. (2). IN EQ. (2) THE WATER CONTENT WAS OBTAINED BY MODEL 1 AND MODEL 2

	Epp (%)		
Temperature (C)	Eq. (10)	Eq. (2), model 1	Eq. (2), model 2
45	29.1 ± 5.6	22.6 ± 9.6	23.5 ± 2.5
60	20.5 ± 6.8	22.7 ± 1.4	17.9 ± 3.2
75	22.8 ± 1.8	21.8 ± 0.6	10.4 ± 1.0

Mean of three tests ± standard deviation.

In addition, to analyze the analogies between the proposed empirical model, Eq. (10) and the theoretical model of the Fick's law, the *DR* was also calculated with Eq. (2) using the simulated moisture content from model 1 (constant thickness) and model 2 (with shrinkage). Afterward, these results were compared with those obtained from Eq. (2) and experimental moisture content. The comparison was made by the average error *Epp* of *DR* estimation, as is shown in Table 3. Values after ± symbol correspond to the standard deviation of three independent tests. It is possible to see in Table 3 that minor errors were obtained with the simulated moisture considering the shrinkage of the slab (model 2), during pineapple drying at 75C. Estimation of *DR* with the simulated moisture by model 1 is next to the values of *DR* through Eq. (10), as can be seen from *Epp* values (Table 3).

CONCLUSIONS

A linear relationship between shrinkage and moisture content of pineapple slices during drying was found. Air temperature had a very small influence on the shrinkage attributes. Shrinkage in radial direction three times lower than the loss of thickness was measured.

Two diffusional models to simulate pineapple drying curves were compared. As expected, the inclusion of the slice thickness variation during drying as a function of average moisture content (model 2) allowed a significant increase of the accuracy of simulation, with values of the mean percentage error of the estimation in a range of 1.95–6.55%, whereas error values of the moisture estimation by application of the model 1 varied between 5.07 and 14.5%. The proposed model provides a simple mathematical calculation tool for taking into account the shrinkage during drying of fruits with high moisture content, like pineapples.

In addition, an empirical model of *DR* was developed. By a simple linear equation, the pineapple *DR* could be predicted at any temperature in the range 45–75C, with estimation error or *Epp* less than 29%. However, the most accurate values of *DR* were obtained with moisture content estimated by Fick's second law of diffusion with shrinkage (Model 2).

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