Comparison of boundary conditions to describe drying of turmeric (*Curcuma longa*) rhizomes using diffusion models

Wilton Pereira da Silva · Cleide M. D. P. S. e Silva ·
Josivanda Palmeira Gomes

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Abstract Turmeric is harvested with high moisture content and should be dried before the storage. It is observed that drying is quickest when the rhizomes are peeled and cut in small cylindrical pieces. In order to describe the process, normally a diffusive model is used, considering boundary condition of the first kind for the diffusion equation. This article uses analytical solutions considering boundaries conditions of the first (model 1) and third (model 2) kinds coupled to an optimizer to describe the drying process. It is shown that, for model 1, the fit of the analytical solution to the experimental data is biased, despite the good statistical indicators (χ^2 equal to 1.7095×10^{-3} and coefficient of correlation R^2 of 0.9988). For model 2, the errors of the experimental points about the simulated curve can be considered randomly distributed, and the statistical indicators are much better than those obtained for model 1: $\chi^2 = 3.5596 \times 10^{-4}$ and $R^2 = 0.9996$.

Keywords Analytical solution · Effective mass diffusivity · Convective mass transfer coefficient · Cauchy boundary condition · Finite cylinder

Introduction

Curcuma longa is a native plant from India used as spice and also to obtain extracts. Due to the importance of its components as anti-oxidant, anti-inflammatory, anti-mutagenic, anti-carcinogenic and anti-microbial, among others, several studies about this agricultural product are found in the literature (Negi et al. 1999; Kim et al. 2000; Quiles et al. 2002; Surh 2002; Inano and Onoda 2002; Mohanty et al. 2004; Prasad et al. 2006; Xia et al. 2007; Adaramoyea et al. 2009; Chen et al. 2010; Yue et al. 2010). In general, when the product is harvested, the rhizomes contain high moisture content. According Silva et al. (2007), water is a constituent part present in high concentration in fresh food. It influences considerably the taste, the process of digestion and the physical structure of agricultural products. Practically all of the deterioration processes taking place in food are influenced in some way or other by the concentration and mobility of water in its interior. So, after the harvest and before the storage or transportation, in general, the rhizomes are submitted to the drying process. Some works describing drying of turmeric are found in the literature. For instance, Prasad (2009) described drying of *Curcuma longa* in open sun, and the thermal behavior of the process was investigated. In this research, the effect of the difference between the product temperature (at the surface) and the temperature surrounding on the convective heat transfer coefficient was studied. On the other hand, Prathapan et al. (2009) investigated the effect of the heat treatment on curcuminoid; color value and total polyphenols of fresh turmeric rhizome. According Devahastin and Niamnuy (2010), not only nutritional changes occur during drying but also other ones including physical and micro-structural changes which are of importance and need to be optimized, preferably through the use of various modeling

W. P. da Silva (✉) · C. M. D. P. S. e Silva
Departamento de Física,
Universidade Federal de Campina Grande,
Campina Grande, PB, Brazil
e-mail: wiltonps@uol.com.br

C. M. D. P. S. e Silva
e-mail: cleidedps@uol.com.br

J. P. Gomes
Engenharia Agrícola, Universidade Federal de Campina Grande,
Campina Grande, PB, Brazil
e-mail: josi@deag.ufcg.edu.br

approaches. Naturally, the own drying process needs be optimized and, for this, a model can be useful.

In order to describe a drying process, mathematical models are frequently used. Among these models, the liquid diffusion is very found in the drying description of agricultural products (Mulet et al. 2005; Hacıhafızoglu et al. 2008; Silva et al. 2009, 2010a). In order to solve the diffusion equation, in many of these researches the boundary condition of the first kind is assumed in the solution. In addition, the effective mass diffusivity and the volume of the solid are considered constant during the whole process (Mulet et al. 2005; Hacıhafızoglu et al. 2008; Silva et al. 2009). For these assumptions, considering a simple geometry, the diffusion equation can be solved analytically (Mulet et al. 2005; Hacıhafızoglu et al. 2008; Silva et al. 2009, 2012). On the other hand, if the boundary condition is of the third kind, normally the diffusion equation is solved numerically (Wu et al. 2004; Mulet et al. 2005; Olek and Weres 2007; Da Silva et al. 2012), although a few analytical solutions are also found in the literature (Silva et al. 2010a, b). It is worth pointing out that in some works, as in Mulet et al. (2005), two analytical solutions are presented for the boundary condition of the first kind, and one numerical solution is proposed for the boundary condition of the third kind. According Silva et al. (2010b), a possible reason for the lack of analytical solutions in the literature for diffusion problems with boundary condition of the third kind could be the large quantity of roots of the characteristic equation that must be determined in order to cover the entire domain of the mass transfer Biot number, when many terms of the series are taken account.

For the *Curcuma longa* rhizomes, the drying time depends on the size of the cut pieces and also if the product was peeled (removed peridermis) or not. For instance, according Mulet et al. (2005), peeled rhizomes, cylindrical-shaped, with 10.0 mm of height and radius of 5.0 mm are dried from dimensionless moisture content of 1 to 0.2 into 9,400 s. If the pieces contain shell (with peridermis, and therefore the radius is 6.5 mm), the drying time is 23,900 s. Thus, it seems to be economically advantageous to dry the peeled product in small pieces. In their researches, Mulet et al. (2005) assumed boundary condition of the first kind in order to describe the drying kinetics of peeled rhizomes. However despite the good statistical indicators obtained in the simulation of drying kinetics, a visual inspection of the curve seems to indicate a biased fit. Thus, it appears appropriate to examine whether the boundary condition of first kind for the diffusion equation is really adequate to describe the drying process.

The main objective of this article is to analyze what is the appropriate boundary condition for the diffusion equation used to describe drying of peeled rhizomes of *Curcuma longa*, cut into a cylindrical shape. With this objective, analytical solutions are coupled to an optimizer in order to

identify the better boundary condition. Once the appropriate boundary condition is identified and the process parameters are determined for an experimental dataset, the whole drying is described in detail.

Material and methods

In order to obtain the analytical solution for the diffusion equation in a finite cylinder, the following assumptions should be established: the cylinder must be considered homogeneous and isotropic; the moisture distribution within the cylinder should be initially uniform, with axial symmetry; the properties of the hot air used in drying should remain constant during the whole process; the only drying mechanism is liquid diffusion; the dimensions of the finite cylinder do not vary during the process; the effective mass diffusivity and the convective mass transfer coefficient do not vary during the process.

Analytical solution

A finite cylinder of radius R and height L is shown in Fig. 1. A position within the cylinder can be given by the coordinates (r, y) defined through the system of axes r and y with origin at the centre of the cylinder.

In order to describe a drying process, the diffusion equation can be written as follows:

$$\frac{\partial X}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(rD \frac{\partial X}{\partial r} \right) + \frac{\partial}{\partial y} \left(D \frac{\partial X}{\partial y} \right), \quad (1)$$

where X is the moisture content (dry basis), D is the effective mass diffusivity, t is the time, r and y define a position within cylinder. On the other hand, the boundary condition of the third kind, also called Cauchy boundary condition, is defined by:

$$-D \frac{\partial X(r, y, t)}{\partial r} \Big|_{r=R} = h[X(r, y, t) \Big|_{r=R} - X_{eq}], \quad (2)$$

and

$$-D \frac{\partial X(r, y, t)}{\partial y} \Big|_{y=\pm L/2} = h[X(r, y, t) \Big|_{y=\pm L/2} - X_{eq}], \quad (3)$$

where h is the convective mass transfer coefficient and X_{eq} is the equilibrium moisture content (dry basis). Equation (2) refers to an infinite cylinder with radius R while Eq. (3) refers to an infinite slab with thickness L . The composition of these two simple geometries generates the finite cylinder. In these two equations it was imposed the same value h , which means same resistance to the water flux in every surfaces.

Fig. 1 Finite cylinder (radius R and height L)

The analytical solution of Eq. (1) in the position (r, y) at an instant t , with the boundary conditions given by Eqs. (2) and (3), is obtained by separation of variables (Luikov 1968; Crank 1992):

$$X(r, y, t) = X_{eq} - (X_{eq} - X_i) \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} A_{n,1} A_{m,2} J_0(\mu_{n,1} \frac{r}{R}) \cos(\mu_{m,2} \frac{y}{L/2}) \times \exp\left[-\left(\frac{\mu_{n,1}^2}{R^2} + \frac{\mu_{m,2}^2}{(L/2)^2}\right)Dt\right], \quad (4)$$

in which X_i is the initial moisture content. The coefficients $A_{n,1}$ e $A_{m,2}$ are defined as follows:

$$A_{n,1} = \frac{2Bi_1}{J_0(\mu_{n,1}) (Bi_1^2 + \mu_{n,1}^2)}, \quad (5)$$

and

$$A_{m,2} = (-1)^{m+1} \frac{2Bi_2 (Bi_2^2 + \mu_{m,2}^2)^{1/2}}{\mu_{m,2} (Bi_2^2 + Bi_2 + \mu_{m,2}^2)}, \quad (6)$$

in which Bi_1 and Bi_2 are the mass transfer Biot numbers for the infinite cylinder and infinite slab, respectively, and are given by

$$Bi_1 = \frac{hR}{D}, \quad (7)$$

and

$$Bi_2 = \frac{h(L/2)}{D}. \quad (8a)$$

In Eq. (5), J_0 is the Bessel function of first kind and zero order.

An expression for h can be obtained from Eq. (7), and this expression can be substituted into Eq. (8a). Thus, the mass transfer Biot number for the infinite slab can be given in the following way:

$$Bi_2 = \frac{Bi_1(L/2)}{R}. \quad (8b)$$

In Eq. (4), (5) and (6), $\mu_{n,1}$ and $\mu_{m,2}$ are respectively the roots of the characteristic equations for the infinite cylinder and infinite slab. The expressions for such equations are:

$$\frac{J_0(\mu_{n,1})}{J_1(\mu_{n,1})} = \frac{\mu_{n,1}}{Bi_1}, \quad (9)$$

and

$$\cot \mu_{m,2} = \frac{\mu_{m,2}}{Bi_2}. \quad (10)$$

In Eq. (9), J_1 is the Bessel function of first kind and first order.

The expression to determine the average moisture content at time t can be given in the following way:

$$\bar{X}(t) = \frac{1}{V} \int X(r, y, t) dV. \quad (11)$$

where V is the volume of the finite cylinder.

Substituting Eq. (4) into Eq. (11), the following result is obtained:

$$\bar{X}(t) = X_{eq} - (X_{eq} - X_i) \times \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} B_{n,1} B_{m,2} \exp\left[-\left(\frac{\mu_{n,1}^2}{R^2} + \frac{\mu_{m,2}^2}{(L/2)^2}\right)Dt\right], \quad (12)$$

in which $\bar{X}(t)$ is the average moisture content at time t , in dry basis.

The coefficient $B_{n,1}$ is given by:

$$B_{n,1} = \frac{4Bi_1^2}{\mu_{n,1}^2 (Bi_1^2 + \mu_{n,1}^2)}, \quad (13)$$

and the coefficient $B_{m,2}$ is defined by the expression:

$$B_{m,2} = \frac{2Bi_2^2}{\mu_{m,2}^2 (Bi_2^2 + Bi_2 + \mu_{m,2}^2)}. \quad (14)$$

An auxiliary program was developed in Fortran, and the first 16 roots of Eq. (9) were calculated for 452 specified values of mass transfer Biot numbers from $Bi_1=0$ (which corresponds to an infinite resistance of water flux at the surface) up to $Bi_1=200$ (which practically corresponds to an equilibrium boundary condition). Similarly, in another program, the first 16 roots of Eq. (10) were calculated for 472 specified values of mass transfer Biot numbers from $Bi_2=0$ up to $Bi_2=200$. Note that a dataset with 14,784 roots (7,232 for the infinite cylinder and 7,552 for the infinite slab) was created in order to extract results from Eqs. (4) and (12).

For an infinite cylinder, the expression for the mass transfer Biot number was defined by Eq. (7). On the other hand, for a specified value of Bi_1 , the value of Bi_2 can be calculated from Eq. (8b). If the roots corresponding to Bi_2 are not available into the dataset previously defined with 7,552 values for the infinite slab, they can be calculated by linear interpolation, using the available values. Then, for a given mass transfer Biot number Bi_1 (infinite cylinder), the correspondent Bi_2 (infinite slab) is also defined and, consequently, the roots $\mu_{n,1}$ and $\mu_{m,2}$ are determined as was discussed. So, the coefficients $A_{n,1}$, $A_{m,2}$, $B_{n,1}$, and $B_{m,2}$ are calculated using Eqs. (5), (6), (13) and (14), respectively. Thus, Eqs. (12) and (4) can be used to determine, respectively, $\bar{X}(t)$ and $X(r, y, t)$ or the correspondent dimensionless values.

Equation (12) can be rewritten to express the dimensionless moisture content, which is defined as follows:

$$\bar{X}^*(t) = \frac{\bar{X}(t) - X_{eq}}{X_i - X_{eq}} = \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} B_{n,1} B_{m,2} \exp \left[- \left(\frac{\mu_{n,1}^2}{R^2} + \frac{\mu_{m,2}^2}{(L/2)^2} \right) Dt \right]. \quad (15)$$

In this paper, the experimental data obtained for drying kinetics will be analyzed in the dimensionless form, as defined in Eq. (15).

Determination of the process parameters

In order to determine D and h for an experimental dataset, the algorithm developed by Silva et al. (2010a) will be adapted for a finite cylinder. The objective function to be minimized is given by (Bevington and Robinson 1992; Taylor 1997):

$$\chi^2 = \sum_{i=1}^{N_p} [\bar{X}_i^{\text{exp}} - \bar{X}_i^{\text{ana}}(D, Bi_1)]^2 \frac{1}{\sigma_i^2} \quad (16)$$

where $\bar{X}_i^{\text{exp}}$ is the i^{th} experimental point of the average moisture content; $\bar{X}_i^{\text{ana}}(D, Bi_1)$ is the average moisture content at the same point, calculated from Eq. (12) with

256 terms (16×16); σ_i is the standard deviation of the experimental average moisture content at the point i ; D is the effective mass diffusivity; and N_p is the number of experimental points. For a specified value of Bi_1 (and consequently Bi_2), the chi-square depends only on a single variable, namely the effective mass diffusivity. Thus, optimum values of D can be determined for each one of the 452 Bi_1 defined for the cylinder. The better D is determined by the minimum χ^2 among the 452 minima calculated. Each one of the 452 optimization process was accomplished as recommended by Silva et al. (2009). According these authors, an initial value close to zero (1×10^{-20}) is attributed to D , and replaced into Eq. (12). Thus, $\bar{X}_i^{\text{ana}}$ can be calculated for a given time and, consequently, χ^2 can be determined for a set of experimental data through Eq. (16). Then, the value of D is doubled, and a new χ^2 is calculated. The new χ^2 is compared with the former value. If the new value is lower than the foregoing, D is again doubled, the corresponding value of χ^2 is calculated, and compared with the former one. This procedure is repeated until the last calculated χ^2 is greater than the anterior value. Note that, even starting with a modest initial value for the D , the subsequent values grow geometrically, ensuring a quick optimization process. On the other hand, the antepenultimate and ultimate values of D , denoted as D_a and D_b , respectively, define a region which contains the minimal value of χ^2 . The penultimate value of the effective mass diffusivity corresponds to the smallest value of χ^2 obtained in this interval. The latter procedure can be refined between D_a and D_b , subdividing this interval in n_v values of D uniformly distributed. Then, a more refined interval can be obtained, and this procedure can be repeated until a convergence criterion is satisfied. On the other hand, if the statistical weights $1/\sigma_i^2$ were not obtained from the experiment and are, therefore, unknown, a constant value (for instance, $1/\sigma_i^2 = 1$) should be artificially attributed to all experimental points, meaning the same statistical weight for all of them.

The described optimizer was coupled to Eq. (12), and the source code was developed in a computer with Intel Pentium IV and 2 GB RAM. The source code was compiled in Compaq Visual Fortran (CVF) 6.6.0 Professional Edition, using the programming option QuickWin Application, and the platform Windows Vista. Criterion of convergence was stipulated in this article as 1×10^{-16} . Note that if the dataset are given in the dimensionless form, Eq. (15) must be used instead Eq. (12).

Once D and h are determined by optimization, Eq. (4) is used to calculate the moisture distribution as function of the position (r, y), at time t . Graphs representing the drying kinetics and contour plots showing the moisture distributions in specified times are also carried out by the developed software.

Material

An experimental data set obtained by Mulet et al. (2005) referring to the drying kinetics of *Curcuma longa* rhizomes will be analyzed in this paper, in order to test the two diffusion models to describe the process. In one of their experiments, Mulet et al. (2005) used peeled rhizomes, cut in cylindrical pieces with height $L=10.0$ mm and radius $R=5.0$ mm. The temperature of the hot air was kept in 70°C and its velocity was 4.5 ms^{-1} . The obtained data set were analyzed by the authors in the dimensionless form, using Eq. (15). Because the pieces are peeled, the authors considered that the boundary condition of the first kind, also named Dirichlet boundary condition, was adequate to describe the drying process.

In the experiment, Mulet et al. (2005) did not determine the statistical weights of the experimental points (dimensionless average moisture contents) and, in the present article, these statistical weights will be made equal to 1. In order to determine the equilibrium moisture content, the relationship between water activity and moisture content of *Curcuma longa* rhizomes was obtained using a NOVASINA TH/RTD 200 electric hygrometer (Switzerland). The Henderson model was considered to describe the desorption equilibrium isotherm.

For the drying conditions employed in the experiment, liquid diffusion models appear to be reasonable, despite a possible anisotropy and heterogeneity of the sample. In this paper, it will be supposed that these characteristics occur in a little scale and can, therefore, be discarded as well as the shrinkage (Baronas et al. 2001; Kulasiri and Woohead 2005; Mulet et al. 2005; Ricardez et al. 2005; Olek and Weres 2007; Silva et al. 2010b).

Results and discussion

Equation (15) was fitted to the experimental dataset and the obtained results, considering boundary condition of the first (model 1) and third (model 2) kinds, are presented in the

following. Comparison between the two models is made using the statistical indicators chi-square (χ^2) and determination coefficient (R^2); and also average error and error distribution about the simulated curves.

Model 1: boundary condition of the first kind

The optimization process considering no resistance at the surfaces (mass transfer Biot number with a known value, stipulated as $Bi_1=200$) and effective diffusivity unknown (boundary condition of first kind) results in: $D=3.46 \times 10^{-10}\text{ m}^2\text{ s}^{-1}$; $R^2=0.9988$ and $\chi^2=1.7095 \times 10^{-3}$. The relation between chi-square and the effective mass diffusivity can be observed in Fig. 2a, in the vicinities of the optimal point. Using the value obtained for the effective mass diffusivity, the drying kinetics simulation together with the experimental data can be shown through Fig. 2b.

The obtained statistical indicators appear to be reasonable. However, Fig. 2b indicates that the first experimental points are above the simulated curve while the last ones are below this curve. This means that there is not a random distribution of the experimental points about the simulated curve. So, defining the error of each point i by

$$\text{error}_i = \bar{X}_i^{\text{exp}} - \bar{X}_i^{\text{ana}}, \quad (17)$$

the dispersion graphs for model 1 can be visualized in Fig. 3.

An inspection of Fig. 3 enables to affirm that the errors are correlated with the values of the experimental average moisture content. For instance, it is possible fit a polynomial of the third degree to the points $(\bar{X}^{\text{exp}}, \text{error})$ with certain success. So, despite good statistical indicators resulting of model 1, the adequacy of a second model will be investigated in this article.

Fig. 2 **a** Chi-square in the vicinities of the optimal point; **b** Drying kinetics of *Curcuma longa* rhizomes for the boundary condition of the first kind

Fig. 3 Error dispersion for the drying kinetics with boundary condition of the first kind showing: **a** average error; **b** polynomial (third degree) fitting

Model 2: boundary condition of the third kind

An optimization process considering the mass transfer Biot number and the effective mass diffusivity as unknown values (boundary condition of the third kind) results in: $D = 3.85 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$; $h = 4.62 \times 10^{-6}$ ($Bi_1 = 60.00$); $R^2 = 0.9996$ and $\chi^2 = 3.5596 \times 10^{-4}$. The relation between chi-square and the mass transfer Biot number can be observed in Fig. 4a. Using the values obtained for D and h , the drying kinetics simulation together with the experimental data can be shown through Fig. 4b.

The dispersion graphs for model 2 can be visualized in Fig. 5.

The results obtained for the two optimization processes can be summarized in Table 1, which also presents the statistical indicators for the two models.

Using Eq. (4) and the parameters obtained for model 2, the drying kinetics referring to the points 1, 2 and 3 at the surface (Fig. 1) can be simulated and the results are shown through Fig. 6, which also shows the superposition of these three curves.

The moisture distributions in the rectangle 0123 (Fig. 1), at four specified instants, are shown in Fig. 7.

It is interesting to note that if Bi_1 and Bi_2 are considered infinite, Eq. (9) is written as $J_0(\mu_{n,1}) = 0$, and Eq. (10) as $\cot \mu_{m,2} = 0$ which results in $\mu_{m,2} = (2m - 1)\pi/2$, with $m = 1, 2, \dots, \infty$. Additionally, Eq. (13) results in $B_{n,1} = 4/\mu_{n,1}^2$, and Eq. (14) in $B_{m,2} = 2/\mu_{m,2}^2$. Thus, Eq. (12) is now the solution for the diffusion equation with boundary condition of the first kind (Luikov 1968).

For peeled rhizomes (in pieces), considering the boundary condition of the first kind, the results of the present article, using analytical solution, are identical to those obtained by Mulet et al. (2005). However, these authors did not investigate whether there might be some resistance to the water flux at the surfaces of cylindrical pieces. In fact, according to the present article, the consideration of the Cauchy boundary condition resulted in a mass transfer Biot number equal to 60. This value is really very large but suggests a certain resistance to the water flux at the boundaries, which could be considered.

For the Dirichlet boundary condition, Tab. 1 shows a chi-square about five times greater than the value obtained using the Cauchy boundary condition. In addition, for this last boundary condition, the error distribution about the

Fig. 4 **a** Chi-square in the vicinities of the optimal point; **b** Drying kinetics of *Curcuma longa* rhizomes for the boundary condition of the third kind

Fig. 5 Error dispersion for the drying kinetics with boundary condition of the third kind showing: **a** average error; **b** polynomial (third degree) fitting

simulated curve can be considered random (Fig. 5) while for the Dirichlet boundary condition the error distribution is biased (Fig. 3). A visual inspection in Figs. 3 and 5 makes it possible to affirm that model 2 results in a fit better than that model 1. Note that the determination coefficients of these curves presented in Figs. 3b and 5b reveal the same conclusion. In addition, for the Cauchy boundary condition, the average error is very close to zero, indicating that the model 2 is really superior to model 1.

Note that in different points at the surface highlighted in Fig. 1 (points 1, 2 and 3), the drying kinetics occurs in a different way (Figs. 6 and 7). Although the drying kinetics of the regions defined by the points 1 and 3 are virtually identical, they are significantly different from the drying kinetics for the region defined by the point 2 (Fig. 6). For the region defined by the point 2, almost instantaneously the local moisture content reaches the equilibrium value, but for the regions defined by the points 1 and 3, this affirmation is not true. This means that the small resistance to the water flux at the surface really is important to rigorously describe the drying process.

Due to some heterogeneity and anisotropy, the diffusion process in a given direction can be a little different from the diffusion in other direction. In addition, models analyzed do not consider the shrinkage and the variation of the diffusivity caused by the dimensional variation during the drying process. Thus, in this article, the values of the parameters determined by optimization and used in the simulation of the drying process really should be interpreted as effective values for the two investigated models.

It is worth note that the calculation of the roots of the characteristic equations for the finite cylinder (infinite

cylinder and infinite slab) and their organisation in tables accessible to the developed software is rather tedious, involving the determination of 14,784 values. However, the computational implantation of the algorithm is simple, which is a favourable characteristic of the procedure used in this article. Another aspect favourable is that the user only needs to inform the input set of experimental data because the optimization algorithm scans every the domain of the mass transfer Biot number and effective mass diffusivity.

As a final comment, the time for the execution of the developed software for finite cylinders strongly depends on the number of experimental data used for the realization of the optimization process. In the present study, for example, the total time for the determination of the parameters by fitting of the model 2 to 19 pairs $(t, \bar{X}^*)$ was 2.5 min.

Conclusion

Model 1, commonly used in the literature to model the drying type approached in this article, reasonably describes the drying kinetics of peeled rhizomes (in pieces) of *Curcuma longa* (chi-square χ^2 equal to 1.7095×10^{-3} , and coefficient of correlation R^2 of 0.9988). However, the simulated curve is strongly biased. Better results are obtained with model 2, which considers the resistance to the water flux at the surface. In this case, despite the inclusion of a small resistance at the surface, the statistical indicators obtained for the drying kinetics are much better

Table 1 Process parameters and statistical indicators obtained for the two models

	$D \text{ (m}^2\text{s}^{-1}\text{)}$	$h \text{ (ms}^{-1}\text{)}$	$\chi^2 \times 10^3$	R^2	Average error $\times 10^4$	Error distribution
Model 1	3.46×10^{-10}	—	1.7095	0.9988	9.7950	Biased
Model 2	3.85×10^{-10}	4.62×10^{-6}	0.35596	0.9996	0.8811	Random

Fig. 6 Local moisture content versus time at the region defined by: **a** point 1; **b** point 2; **c** point 3; **d** superposition of the curves (**a**), (**b**) and (**c**)

Fig. 7 Moisture distribution at instants: **a** $t=539.8$ s; **b** $t=2159.0$ s; **c** $t=3,779$ s; **d** $t=5,938$ s

($\chi^2=3.5596 \times 10^{-4}$ and $R^2=0.9996$). In addition, the simulated curve has a distribution of errors that can be considered random, with an average value very close to zero.

The two models analyzed in this article presuppose restrictive assumptions as constant volume and effective mass diffusivity, and also homogeneous and isotropic medium. However, even if the obtained results were not considered completely satisfactory, these results could be used as initial values in other optimization processes which use numerical solutions. Such solutions would take into account the mentioned restrictions.

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