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A Semi-Empirical Approach for Predicting the Effects of Shrinkage on the Convective Mass Transfer Evolution During the Solar Drying of Foodstuffs

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ABSTRACT

This study analyzes and compares convective mass transfer coefficients: obtained directly from the drying kinetics and considering the theoretical diffusion model, taking into account shrinkage effect. Theoretical analysis allowed obtaining a modified Biot number. The reduction of the wet exchange surface is identified, from measurements of the drying kinetics, shrinkage phenomenon, surface temperature and parameters of dying air. This is the external surface, concerned with the exchanges with drying air. A significant decrease occurs at the beginning of the drying process and tends to a value close to zero when the product is dry. The evolution of convective mass transfer coefficient, during the drying process, can be evaluated. An important drop is observed. The decreasing of the convective mass transfer coefficient, during the drying process of shrinking products, is evaluated.

1. INTRODUCTION

Drying kinetics are derived from experimental evaporation rate and are used to characterize the behavior of drying products. This behavior is influenced by physical properties of product and drying air parameters. Generally, two main periods are identified: a period of constant drying rate and a period of decreasing drying rate. For convective drying, heat and mass transfer coefficients are used to predict transfers between product and drying air. During the constant drying rate, convective heat and mass transfer coefficients are calculated directly, from experimental drying curves or obtained from measurements in boundary layers [1].

Mechanisms of internal and external heat and mass transfer can also be analyzed using analytical methods of mass transfer equation with interfacial resistance [2, 3]. In these last studies and others, the convective mass transfer coefficient was calculated using correlations, which was obtained from analogy between thermal and concentration boundary layers. A methodology for determination of mass transfer coefficient from drying kinetics, using solutions of the diffusion model was proposed and used in the studies [4-7].

Mass transfer coefficient has been obtained with moisture content at various temperatures, but the effect of shrinkage has not been taken into account. Moreover, considerable shrinkage occurs in high moisture contents fruits and vegetables during drying; moisture diffusivity model for these products is not accurate when shrinkage is neglected [8]. Otherwise, in majority of studies, which are concerned with convective drying, the mass transfer coefficient was found or was applied as constant, during the period of constant drying rate.

Experimental drying kinetics of foodstuffs, show a continuous decrease of the evaporation rate during the drying process. There is no clearly observed, period of constant drying rate. The transport of moisture takes place predominately, in a falling rate period. The phenomena, which involved in this decrease, are mainly, related to the reduction in the internal moisture content in the product and surface conditions. A linearly decreasing of the convective heat and mass transfer coefficients with the surface content moisture in the first falling period, can be so, assumed in most cases [9, 10].

The convective mass transfer coefficient depends from the diffusion coefficient of vapor in air, external characteristic length of the solid and Sherwood number dimensional analysis shows that, convective mass transfer coefficient may be calculated from [11]:

$$k_m = \Phi(Sh, D_v, d_c) \tag{1}$$

where, D_v is the diffusion coefficient of vapor in air, which depends from the air temperature and pressure; d_c is an external characteristic length of the solid; *sh* is the Sherwood number, which is given, for forced convection, as:

$$Sh = \Phi(Re, Sc) \tag{2}$$

Many correlations are available, in the literature, to calculate the Sherwood number, which are adapted for different conditions of air, various geometries and different situations. Food products' drying involves also, an important shrinkage phenomenon, which should be taken into account in analysis or modeling of a drying process. The external characteristic length (d_c) should be affected by this phenomenon, which implies a variation of this coefficient, during the drying process.

The determination of the convective mass transfer coefficient must hold all of these observations and the evolution of this coefficient during drying should be must clarified. The objective of this study is to analyze convective mass transfer evolution and to identify transfer coefficient during drying of foodstuffs, with considering the reduction of exchange surface and the shrinkage phenomena.

2. MATERIALS AND METHODS

2.1 Drying kinetics

The average dry-basis moisture content describes the mass of water contained in the solid at each instant with respect to the mass of the solid in the dry state. It is defined as:

$$\bar{X}(t) = \frac{m^w(t)}{m_s} = \frac{m(t) - m_s}{m_s} \tag{3}$$

Mass of the dry solid (m_s) remains constant during all the drying process, so:

$$\frac{\bar{X}(t) - \bar{X}_{eq}}{\bar{X}_0 - \bar{X}_{eq}} = \frac{m^w(t) - m^w_{eq}}{m^w_0 - m^w_{eq}} \tag{4}$$

To describe the thin layer drying process, the most commonly used basic equation is [12]:

$$\frac{m^w(t) - m^w_{eq}}{m^w_0 - m^w_{eq}} = \alpha_0 \exp(-\alpha t) \tag{5}$$

The coefficient α is the drying coefficient and the coefficient α_0 is a dimensionless coefficient, called the lag factor.

2.2 Convective mass transfer coefficient

2.2.1 Drying kinetics

Convective mass transfer coefficient can be obtained directly, from the drying rate:

$$\dot{m}_{ev} = k_m S_{exch}\left(\rho^v_{surf} - \rho^v_\infty\right) \tag{6}$$

Drying rate ($\dot{m}_{ev}$)can be expressed as:

$$\dot{m}_{ev} = -m_s \frac{d\bar{X}(t)}{dt} = -\rho_s V_0 \frac{d\bar{X}}{dt} \tag{7}$$

So, convective mass transfer coefficient is:

$$k_m = \frac{\rho_s V_0 \left(\bar{X}_0 - X_{eq}\right)\alpha\alpha_0 \exp(-\alpha t)}{S_{exch}\left(\rho^v_{surf} - \rho^v_\infty\right)} \tag{8}$$

The principal difficulty to applying (Eq. (8)) is the identification of the wet exchange surface (S_{exch}), which is decreasing during the drying process. This is the external surface, concerned with the exchanges with drying air. It depends on the moisture content and the apparent dimensions of the product, which decrease for shrinkable products.

The evolution of k_m during the drying process:

$$\frac{k_m}{k_{m0}} = \frac{S_0}{S_{exch}} \frac{\left(\rho^v_{surf} - \rho^v_\infty\right)_0}{\left(\rho^v_{surf} - \rho^v_\infty\right)} \exp(-\alpha t) \tag{9}$$

For shrinkable product and applying (Eq. (8)) between the drying beginning ($t = 0, S = S_0, \bar{X} = \bar{X}_0$) and in any time, the following ratio can be obtained:

2.2.2 Obtaining from the diffusion model

Unsteady diffusion equation, with constant average diffusion coefficient, which takes account of all moisture transport, is usually, used to describe the drying of food.

In one dimensional Cartesian coordinates, the governing equation can be given as follows:

$$\frac{\partial X}{\partial t} = D_{eff} \frac{\partial^2 X}{\partial y^2} \tag{10}$$

With:

Initial condition:

$$X(y,0) = X_0 \tag{11}$$

At the center:

$$\frac{\partial X}{\partial y} = 0 \tag{12}$$

At the surface:

$$-D_{eff} \frac{\partial X}{\partial y} = k_X \left(X_{surf} - X_\infty\right) \tag{13}$$

Crank [13] gives solutions of (Eq. (10)), for different geometries and boundary conditions, in series form. Volume average moisture content can be expressed as:

$$\frac{\bar{X} - \bar{X}_{eq}}{\bar{X}_0 - \bar{X}_{eq}} = \sum_{n=1}^{\infty} A_n \exp\left(-\mu_n^2 Fo_m\right) \tag{14}$$

where, A_n is a term, which depends from the geometry of the considered solid and μ_n is obtained from Bi_m, which relates the ratio of the external convection to the internal moisture diffusion and can be calculated from:

$$Bi_m = \frac{k_X l}{D_{eff}} \tag{15}$$

And Fourier number, which expresses the dimensionless time, is:

$$Fo_m = \frac{D_{eff} t}{l^2} \tag{16}$$

where, l is a characteristic dimension (smallest distance from center to surface).

Considering the condition (Fo>2), this infinite sum is well approximated only, by the first term [14]. The comparison between this first series term and Eqns. (4) and (5) gives:

$$A_1 = \alpha_0 \quad (17)$$

$$\alpha t = \mu_1^2 Fo_m \quad (18)$$

Which gives:

$$\alpha = \frac{\mu_1^2 D_{eff}}{l^2} \quad (19)$$

With the condition ($0.1<Bi_m<100$) [6, 15, 16] have developed the following expressions, for practical applications in drying process:

$$A_1 = \exp\left(\frac{\Gamma Bi_m}{\Lambda + Bi_m}\right) \quad (20)$$

$$\mu_1 = \sum_{n=0}^{4} \gamma_n A_1^n \quad (21)$$

where, γ_n, Γ and Λ are coefficients, which have been reported for each case, in these references.

The convective mass transfer coefficient is generally, determined according to the drying air parameters (temperature, humidity, speed), the setup, geometric shape and dimensions of the product ...; although it can also be obtained from experimental curves of drying kinetics following this calculation procedure:

- By regression calculations, coefficients α_0 and α are obtained from the experimental results;
- Factor μ_1 can be calculated, using Eqns. (17) and (21);
- Diffusion coefficient (D_{eff}) can be obtained from Eq. (19);
- Biot number (Bi_m) is then determined, using Eq. (20);
- Then the coefficient (k_X) is deduced from Eq. (15).

Considering the ratio, which expressed the evolution of (k_X) between the drying beginning and any time of the process and using Eqns. (15) and (19) give:

$$\frac{k_X}{k_{X_0}} = \frac{\frac{Bi_m}{l} D_{eff}}{\frac{Bi_m}{l_0} D_{eff0}} = \frac{\frac{Bi_m}{l} \frac{\alpha l^2}{\mu_1^2}}{\frac{Bi_m}{l_0} \frac{\alpha l_0^2}{\mu_1^2}} \quad (22)$$

In close interrelationship with (k_X), diffusion coefficient (D_{eff}) is also, affected by external parameters of drying air [17] and shrinkage phenomenon [18].

According to previous relationships (Eqns. (17) to (21)), parameters (Bi_m) (α) and (μ_1) remain constant during the drying process but for shrinking product, (l_0) is different from (l), (Eq. (22)) is simplified to:

$$\frac{k_X}{k_{X0}} = \frac{l}{l_0} \quad (23)$$

2.2.3 Shrinkage effect

To characterize shrinkage, the following ratio can be defined:

$$S_b = \frac{V}{V_0} \quad (24)$$

Table 1. Effect of isotropic shrinkage on the evolution of diffusion and convection coefficients

	Sphere $l = R$	Cube $l = \frac{a}{2}$	Parallelepiped (With neglecting lateral surfaces) $l = \frac{ep}{2}$
S_b	$\frac{\frac{4}{3}\pi R^3}{\frac{4}{3}\pi R_0^3} = \left(\frac{l}{l_0}\right)^3$	$\frac{a^3}{a_0^3} = \left(\frac{l}{l_0}\right)^3$	$\frac{l}{l_0} = \frac{S}{S_0}$
$\frac{D_{eff}}{D_{eff0}} = \left(\frac{l}{l_0}\right)^2$	$S_b^{2/3}$	$S_b^{2/3}$	$\left(\frac{S_0}{S}\right)^2 S_b^2$
$\frac{k_X}{k_{X0}} = \frac{l}{l_0}$	$S_b^{1/3}$	$S_b^{1/3}$	$\left(\frac{S_0}{S}\right) S_b$

In most cases, shrinkage is not homogeneous and can be multidirectional, especially for shapes other than spherical. It depends on the structure of the product and the drying air flow. For an isotropic shrinkage, the convective mass transfer coefficient can be calculated, with the shrinkage ratio (S_b), for different usual shapes, between the drying beginning and any time of the process, using Eqns. (23) and (24). Results are given in (Table 1). The spherical shape is considered as the reference case.

2.2.4 Relation between (k_m) and (k_X)

Mass transfer coefficients are defined using phenomenological concept and depend from the driving force, which are expressed: by $\left(\rho_{surf}^v - \rho_\infty^v\right)$ for (k_m) and by (X_{surf}-X_∞) for (k_X).

The coefficient (k_X) with (X_{surf}-X_∞) is useful because the condition expressed by (Eq. (13)) is more adapted to obtain an analytical solution of the mathematical problem, which is similar to the conduction heat transfer [19] and resolved by [13]. But, the definition of (X_∞) is not physically, as clear. Also, it is noted that (X_∞) does not appear in the solution, but it is just needed, to reflect the values obtained for the convective mass transfer coefficient.

The condition expressed by (Eq. (13)) may also, be written as [3]:

$$-\rho_s D_{eff} \frac{\partial X}{\partial y} = k_m \left(\rho_{surf}^v - \rho_\infty^v\right) \quad (25)$$

This writing considers the same (k_m), which is defined in (Eq. (6)), so by comparison between these two equations, considering Eqns. (13) and (25), the following expression can be obtained:

$$\frac{k_X}{k_m} = \frac{\left(\rho_{surf}^v - \rho_\infty^v\right)}{\rho_S \left(X_{surf} - X_\infty\right)} \quad (26)$$

Mass transfer Biot number defined in (Eq. (15)), is also, written as:

$$Bi_m = \frac{\left(\rho^v_{surf} - \rho^v_\infty\right)}{\rho_S} \frac{1}{\left(X_{surf} - X_\infty\right)} \frac{k_m l}{D_{eff}} \quad (27)$$

Biot number developed in Eq. (27) is similar to the modified Biot number, which was proposed in the studies [2, 20] and was used to represent the mass transfer equation in terms of mass relation concentration (X).

2.3 The wet exchange surface

During the drying process and as a consequence of the reduction of product moisture content, the capillary forces, which diffuse to the surface, could no longer compensate the surface evaporation. A reduction of the wet surface, which participates in convective mass exchange, occurs.

The wet exchange surface (Sexch) is not exactly the exposed surface. The reduction of the transfer surface during the drying is a phenomenon, which has to be adapted to characteristics of each material [21, 22]. For shrinking products, the wet surface reduction phenomenon is more accentuated by the change of dimensions during drying.

Moreover, the relation between (X_{surf}-X_∞) and (ρ^v_{surf}-ρ^v_∞) can be studied, considering the interface food-air. At equilibrium, relations between product moisture content and the water activity are established experimentally. Several models are suggested to fit this curves (G.A.B., B.E.T., Oswin, …) and many equations are derived and proposed for modeling the behavior of each product [23, 24]. To obtain an analytical solution, [2] have introduced an averaged equilibrium constant (α_{eq}) that must not change during the drying process:

$$\alpha_{eq} = \frac{1}{\left(X_0 - X_{eq}\right)} \int_{X_0}^{X_{eq}} \frac{Y^{air}}{X} dX \quad (28)$$

with, Y^{air} the moisture content of air ($Y^{air}=\rho^v/\rho^{air}$).

A linear equilibrium relation between food and air moisture content is also, obtained:

$$Y^{air} = \alpha_{eq} X \quad (29)$$

This assumption, for the mathematical description of interfacial mass transfer, was adopted and justified, in many research works [19, 25, 26].

So:

$$\frac{\rho^v_{surf} - \rho^v_\infty}{X_{surf} - X_\infty} = \frac{\rho^{air} Y^{air}_{surf} - \rho^{air} Y^{air}_\infty}{X_{surf} - X_\infty} = \frac{\rho^{air} \alpha_{eq} \left(X_{surf} - X_\infty\right)}{X_{surf} - X_\infty} \quad (30)$$

Then, the ratio $\left(\left(\rho^v_{surf} - \rho^v_\infty\right)/\left(X_{surf} - X_\infty\right)\right)$, which expresses the two types of driving force, should remain constant or vary slightly during the drying process, Eq. (26) leads to the ratio (k_X/k_m) also, constant:

$$\frac{k_X}{k_m} = \frac{k_{X0}}{k_{m0}} \quad (31)$$

So:

$$\frac{k_X}{k_{X0}} = \frac{k_m}{k_{m0}} \quad (32)$$

This relationship could have been intuitively deduced.

From Eqns. (9), (23) and (32), the following relation may be deduced:

$$S_{exch} = S_0 \frac{l_0}{l} \frac{\left(\rho^v_{surf} - \rho^v_\infty\right)_0}{\left(\rho^v_{surf} - \rho^v_\infty\right)} \exp(-\alpha t) \quad (33)$$

This relation may be applied to determine the evolution of the exchange surface (S_{exch}), which is not a measurable quantity, unlike (l_0/l), which can be deduced, considering the shrinkage phenomenon during the drying process. So, the convective mass transfer coefficient (k_m) can be deduced, from Eq. (6).

2.4 Experimental investigations

Experiments were carried out in an experimental dryer as showed in Figure 1. The air parameters have been kept constant during drying process, (temperature=51 ± 1.5℃, velocity=0.4 ± 0.05 m/s and relative humidity was measured between 8.3 and 11%). The experimental product chosen is potato. Two different cuttings were considered (Figure 5):

- Form (1) cubical shape (1.6 cm x 1.6 cm x 1.6 cm)
- Form (2) rectangular parallelepiped shape (7 cm x 1.2 cm x 1.2 cm)

Weight and dimensions of samples has been measured, at regular time intervals, simultaneously with surface temperature of the products, which has been measured by an infrared pyrometer (Raytek, accuracy: ± 0.75%, response time: 250 ms, resolution: 0.1℃).

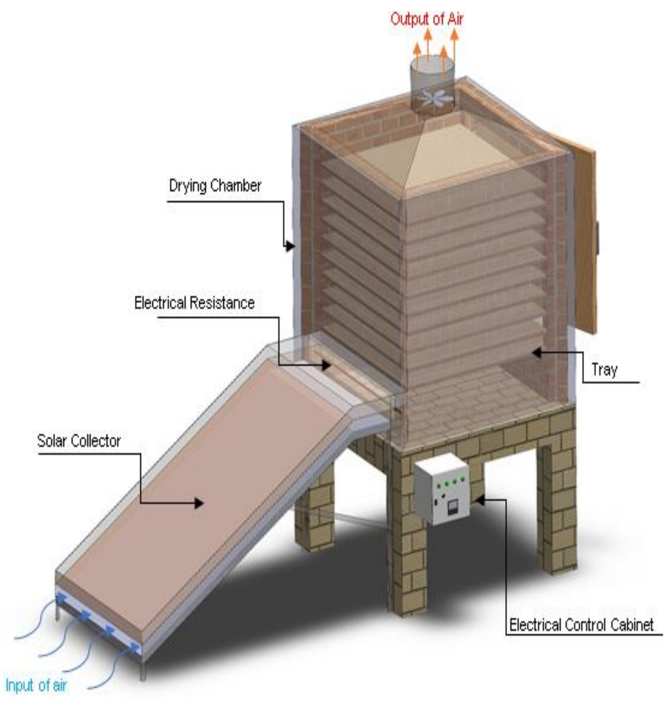

Figure 1. Experimental solar dryer

3. RESULTS AND DISCUSSIONS

3.1 Drying kinetics

Figures 2 and 3 show the evolution of the dimensionless moisture content, during the drying process, respectively for cubical and parallelepipedal form. The value of equilibrium moisture content was taken equal to 5% [23]. Drying rate is influenced by the resistance to internal and external transfers. The internal resistance depends on the level of moisture content in the product and the distance between the center of the product and the external exchange surface. Considering the same conditions of air drying, the external resistances depend on the wet exchange surface, which vary during the drying process. Cubic samples dry slightly faster than those of parallelepipedal form.

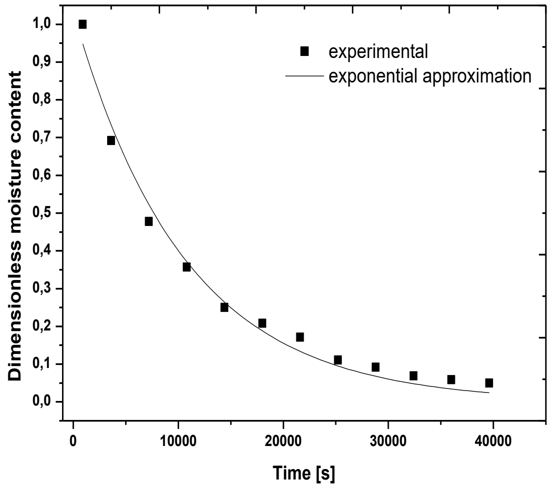

Figure 2. Experimental and exponential approximation dimensionless moisture content -form (1)

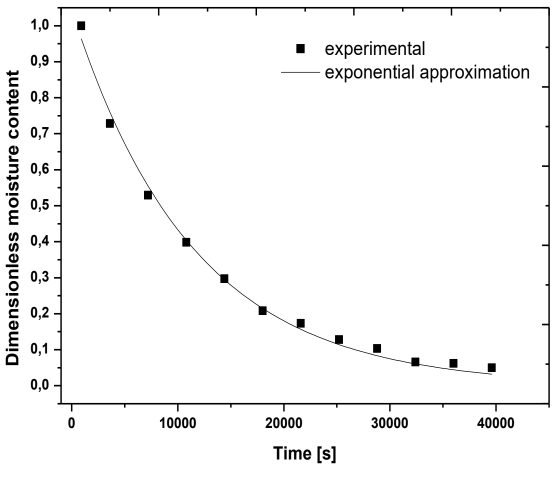

Figure 3. Experimental and exponential approximation dimensionless moisture content -form (2)

Figure 4 confirmed these observations; the surface temperature has a continuous increase for all samples, indicating an absence of a period of constant drying rate. The surface temperature shows the same trend for the two forms, but the cubic form temperature is slightly higher than that of the parallelepipedal form, as the surface temperature is growing faster for samples that reach lower moisture.

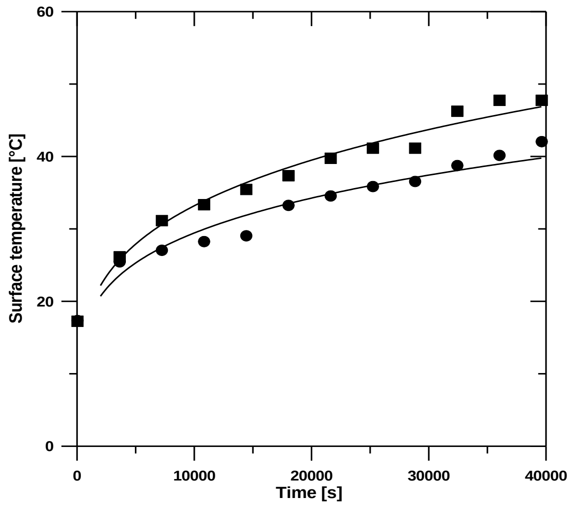

Figure 4. Measured surface temperature during the drying process (■ form (1), ● form (2))

In absence of a period of constant drying rate, the drying kinetics curves show exponential variation, as that predicted by model (Eq. (6)). Coefficients (α_0) and (α) were estimated using a non-linear regression. The fitting quality was evaluated using the coefficient of determination (R^2). Drying kinetics curves can be well approximate (Figure 1 and 2) using the values of coefficients in (Table 2):

Table 2. Coefficients of exponential approximation

	α (1/s)	α_0	R^2
form (1)	9.46E-05 ±0.000000884	1.03236 ±0.003034	0.987
form (2)	8.78E-05 ±0.000000483	1.04319 ±0.0012	0.995

3.2 The shrinkage

As it is apparent on Figure 5, shrinkage phenomenon is a consequence of foodstuffs drying. The product may lose up to 50% of its initial volume. Results, in Figure 6, represent the average of more than ten samples for each shape and show, practically, a linear evolution, from the beginning of the drying up to about 10% of moisture content. This evolution is similar to that obtained in the studies [27, 28]. Below 10% of moisture content, there is a change in the behavior of the product.

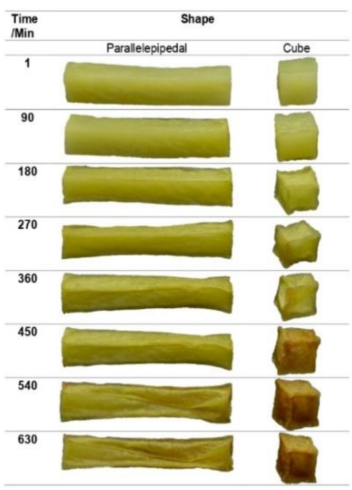

Figure 5. Shrinkage of potato during convective drying

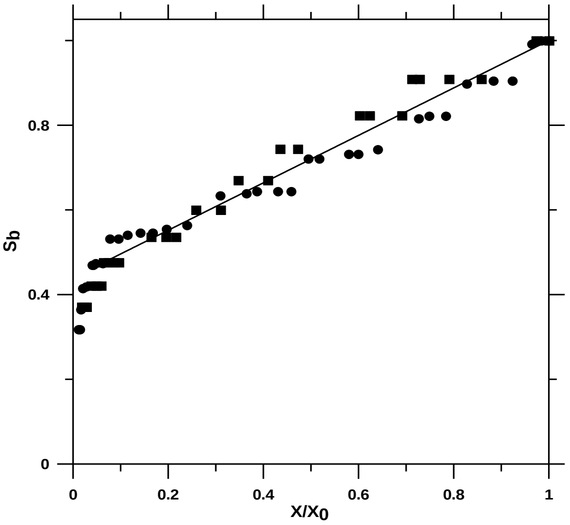

Figure 6. Experimental data for shrinkage of potato (■ form (1), ● form (2))

3.3 Convective mass transfer coefficient and wet surface reduction

Considering previously developed relations, mass transfer coefficient during drying is shown in Figure 7. Results exhibit a significant drop in this coefficient, which is a consequence of the drop in the moisture content of the product. The decrease of this coefficient can also be represented as a function of moisture content of the product (Figure 8). It is more important for low moisture ratio and reaches 62.5% of the initial value at the end of drying.

With the decreasing of the internal moisture content, the surface is no longer supplied and becomes dry. This ratio decreases continuously, during the drying process because especially, the shrinking phenomenon, which modify the geometrical parameters and because of the lowering of the moisture content of the product. Figure 9 shows the influence of the shrinkage on the evolution of the convective mass transfer coefficient. A comparison, between the two forms and an isotropic shrinkage of a spherical shape, shows that the behavior of the cubic form is closer to this ideal case.

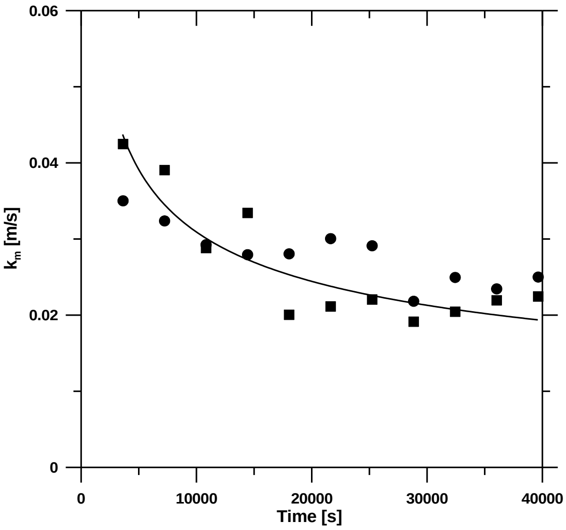

Figure 7. Convective mass transfer coefficient during the drying process (■ form (1), ● form (2))

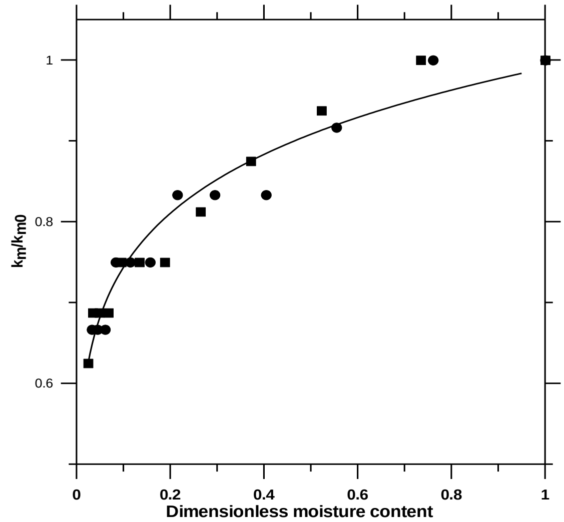

Figure 8. Evolution of the convective mass transfer with the moisture content (■ form (1), ● form (2))

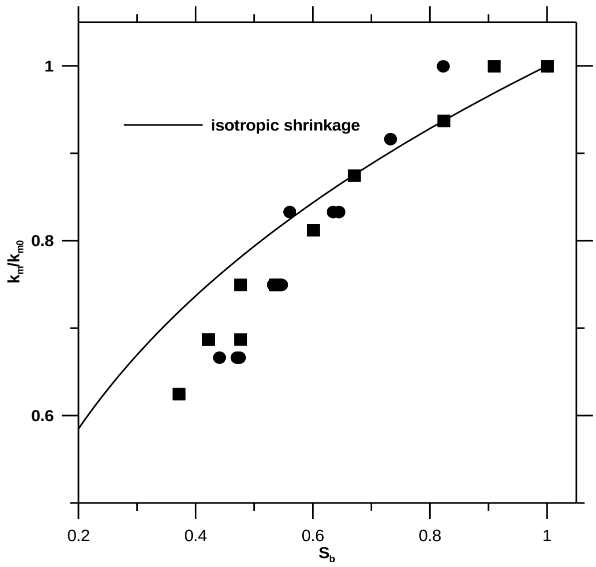

Figure 9. Evolution of the convective mass transfer with the shrinkage ratio (isotropic shrinkage: $k_m/k_{m0} = S_b^{1/3}$) (■ form (1), ● form (2))

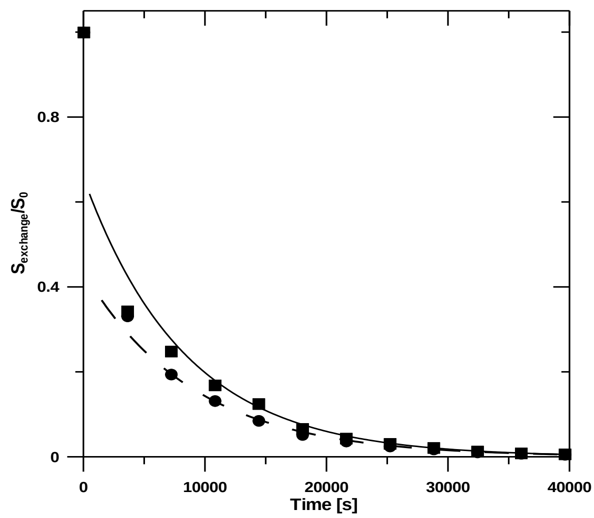

Figure 10. Reduction of the exchange surface during the drying process (■ form (1), ● form (2))

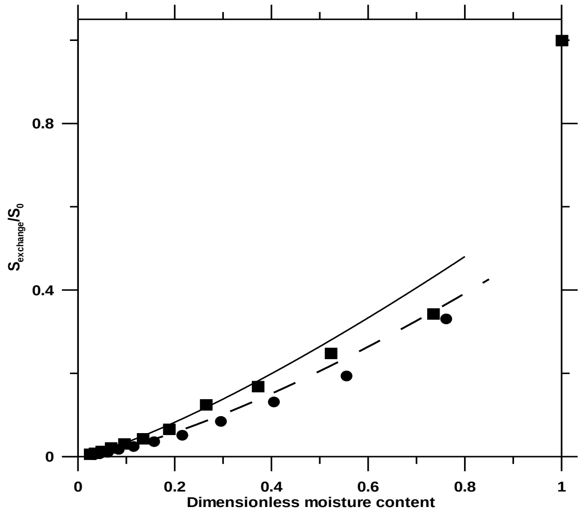

Figure 11. Reduction of the exchange surface with moisture content (■ form (1), ● form (2))

The reduction of the wet exchange surface (Figure 10 and 11) is calculated according to the Eq. (33), considering the drying kinetics, shrinkage, surface temperature, temperature and moisture of air-drying measurements. It is the available surface moisture, which should be participating to the external exchange. These results show a reduction to a value less than 40% from the drying beginning and it tends to zero at the drying end. These results are in accord with those reported in [9, 22]. The decreasing of the convective mass transfer coefficient, during the drying process, is confirmed.

4. CONCLUSIONS

Experimental investigations show the influence of shrinkage on the drying kinetics of foodstuffs. Convective mass transfer coefficient was obtained using two methods: directly from the drying kinetics and using the diffusion model, considering the shrinkage phenomena. The relation between these two coefficients was established, a modified Biot number was obtained. The ratio of the mass transfer coefficient, during the drying process, was identified with the wet exchange surface.

For the mathematical description of interfacial mass transfer, the assumption of a linear equilibrium relation between food and air moisture content is considered.

An important decreasing of the wet exchange surface and the convective mass transfer coefficient, occur during the drying of shrinking foodstuffs process.

The wet exchange surface was obtained from experimental data concerning drying kinetics and shrinkage phenomena. Convective mass transfer coefficient was also, deduced from the evaporation rate, the surface temperature, parameters of dying air and the wet exchange surface evolution.

The Eq. (33) can be used to evaluate the reduction of the wet surface of all shrinkable products. Evolution of the convective mass transfer, during the drying, can be calculated using Eq. (8) and experimental measurable data.

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NOMENCLATURE

D_{eff}	Effective diffusion coefficient (m² s^{-1})
D_v	Diffusion coefficient of vapor in air (m² s^{-1})
d_c	External characteristic dimension (m)
k_m	Convective mass transfer coefficient (m s^{-1})
k_X	Convective mass transfer coefficient, as defined in (Eq. (15)) (m s^{-1})
l	Internal characteristic dimension (smallest distance from center to surface) (m)
m	Total mass (m=m^w+m$_s$) (kg)
m^w	Mass of moisture content in product (kg)
m_s	Mass of dry solid (kg)
$\dot{m}_{ev}$	Rate of moisture evaporation (kg s^{-1})
S	surface (m²)
t	time (s)
V	volume (m^3)
X	Dry basis moisture content (kg (of H_2O) kg^{-1} (of dry solid))
$\bar{X}$	Volume average dry basis moisture content (kg (of H_2O) kg^{-1} (of dry solid))
y	space coordinates (m)
Y^{air}	Moisture content in air [kg (of H_2O) kg^{-1} (of dry air))
ρ_s	Product density (kg m^{-3})
ρ^v	H_2O vapor density (kg m^{-3})
α	Drying coefficient (s^{-1})
α_0	lag factor
α_{eq}	Averaged equilibrium coefficient

Dimensionless numbers

$Bi_m = \frac{k_X l}{D_{eff}}$	Mass transfer Biot number
$Fo_m = \frac{D_{eff} t}{l^2}$	Mass transfer Fourier number
$Re = \frac{\rho_\infty v d_c}{\mu}$	Reynolds number
$Sc = \frac{\mu}{\rho_\infty D_v}$	Schmidt number
$Sh = \frac{k_m d_c}{D_v}$	Sherwood number

Subscripts

0	initial
eq	equilibrium
exch	exchange
surf	at the surface
∞	Drying air (outside the boundary layer)

Superscript

air	surrounding air
v	vapor
w	moisture