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Experimental study of the kinetics and shrinkage of tomato slices in convective drying

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This work focuses on the convective drying of tomato slices with hot air at temperatures of 50 and 60°C and at velocities of 0.1, 0.25 and 0.5 m.s^{-1}. The kinetics and drying rates are determined according to the temperature and velocity of the drying air. The equation of "Gaussian", used for the first time and in this work, is more adaptable to the drying curves. Two methods have been used to determine the coefficient of effective diffusion (with and without the effect of shrinkage). The energy of activation is evaluated with the Arrhenius relationship. In this study, we are interested in the phenomenon of shrinkage, in particular, and the evolution of the relative thickness of the slice of tomato according to drying duration and moisture content. The study shows that on hot air drying, the influence of velocity is dominant as compared to temperature. We observed that for the same final moisture content, the final relative thickness of the product is not constant. It varies depending on the operating conditions.

Key words: Tomato drying, drying kinetics, drying speed, coefficient of effective diffusion, activation energy, shrinkage.

INTRODUCTION

Tomato (*Lycopersicon esculentum*) is a native plant of South America. It is the second vegetable crop after potatoes. The entire world production exceeded 161 million tons in 2012 (FAO, 2012). Tomatoes and tomato derived products are rich in nutrients and sanitary components, because they are good sources of carotenoids (in particular, lycopene), ascorbic acid (vitamin C), vitamin E, flavonoids and potassium (Alexandre et al., 2008).

In developing countries such as Burkina Faso, the tomato is a seasonal product. In addition, it is highly perishable and records huge losses during the period of maximum production (Manashi et al., 2011). In order to make it available on the market as long as possible after harvest, the products are most often subjected to the drying process. Drying also reduces the weight of the product. Considering the importance of drying, especially for developing countries, several studies have already been carried out on various products to optimize one or more parameters. We can quote for example the study of Bathiebo et al. (2009) on the drying of grains of maize in a vertical channel with a constant heat flux on walls. The importance of the tomato has led recently several authors to conduct various studies. Giuseppe et al. (2008) have

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examined the effects of partial dehydration of cherry tomatoes at different temperatures and showed that there is no direct relationship between the loss of carotenoid and changes in temperature and time. Heredia et al. (2009) studied the effect of some physical variables of the process (temperature, duration of processing and osmotic composition of the solution) on the colour and changes in carotenoids (lycopene and β-carotene) during the osmotic dehydration of cherry tomato slices. They show among other things that the colour changes were mainly due to the composition of the liquid phase and shrinkage. Cernîşev and Galina (2007) have studied the influence of the drying process on the quality and nutritional value of tomato, and have come to the conclusion that the sun-dried tomatoes are rich in antioxidants, vitamins and particular lycopene and β-carotene.

Drying is a complex phenomenon and we must repeat and diversify the study conditions in order to report more realistically the course of the drying process. The models of drying processes that describe the phenomenon of the drying of agricultural materials are grouped into three main categories, namely theoretical, semi-theoretical and empirical (Ebru, 2006).

During the drying process, water is transferred from the inside to the outside of the product, so there is water diffusion. Water diffusion is a process that has a very important effect on the phenomenon of drying of agricultural products. Knowledge of this phenomenon allows a better description of drying kinetics, a better interpretation of the results and better simulations. This is the way we estimate the coefficient of diffusion of tomato with different experimental conditions, through Fick's second law.

During the drying process, some products simultaneously undergo great changes in volume and surface (Lima et al., 2002). This shrinkage phenomenon particularly affects the diffusion rate of the material, which is one of the main parameters governing the drying process; it also has an influence on the drying rate (André et al., 2004). Najmur and Subodh (2006) reported in their work that the heat transfer coefficient increases with the shrinkage. Marcelo and Paulo (2011) showed in their work on potato that shrinkage must be taken into account in the modeling of the curve of drying kinetics. Another important consequence of shrinkage is the decrease in the rehydration capacity of the dry product (Mayor and Sereno, 2004). During drying, shrinkage occurs in all directions of the product, which justifies studies on the different sides. In fact, studies have focused on shrinkage along the diameter, length and thickness of the product.

Although, most of the works on the shrinkage of the products deal with volume shrinkage; the phenomenon of shrinkage is related to drying conditions such as temperature, velocity and the humidity of the drying air. The effect of temperature on shrinkage remains problematic

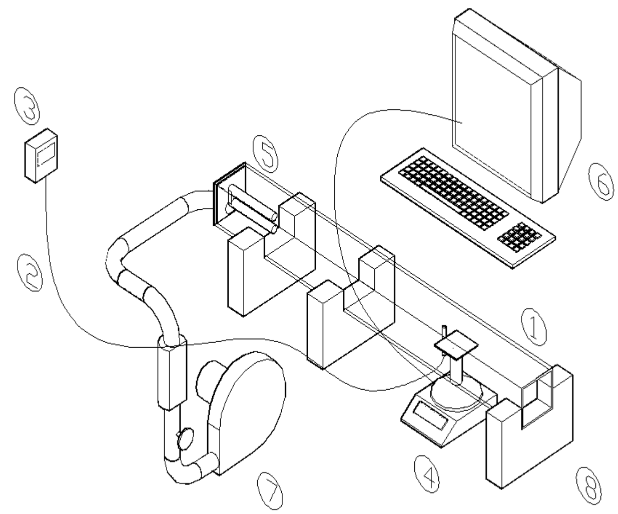

Figure 1. Diagram of the experimental setup. 1: tunnel dryer, 2: thermocouple cable, 3: temperature displayer, 4: scales, 5: heater resistance, 6: PC, 7: blowing device, 8: holder.

as reported in the findings of various works. According to Alireza and Mehdi (2009), temperature increases the rate of cell shrinkage following an Arrhenius-type behavior. Mc Minn and Magee (1997) and Wang and Brennan (1995) in their work on potato, show that the increase in temperature reduces the phenomenon of shrinkage.

In the literature, there are few studies on the evolution of the thickness of tomato during its drying depending on the main physicochemical parameters governing the process.

Objective of this work

1. To determine experimentally within fixed aero-thermal parameters, the influences of temperature and velocity of drying air on the drying kinetics of the tomato slice and the advancement of shrinkage of tomato slices.
2. To determine experimentally the influence of shrinkage on the coefficient of effective diffusion.

MATERIALS AND METHODS

The tomatoes used were purchased from Brussels market in the month of October and November. Before each drying experiment, the tomatoes were washed, and cut into 1.9 x 1.8 x 0.7(cm) slices with a medium-sized, parallelepiped knife. The dryer used for our measurements was built at the TIPs laboratory, (Transfer Interface Process, Service) of the Université libre de Bruxelles. It is a tunnel dryer composed of a plexiglass parallelepiped-shaped tube of cross-sectional shape of 10.5 cm^2 (Figure 1). Inside the device is placed a holder with the sample of tomato to dry. The air is heated with two heating resistances located inside the dryer and its temperature is given by an adjustable digital display device. A blowing device, connected to the dryer is used for circulating air inside the tunnel. The air flow is adjustable by means of a valve. The mass of the sample is measured every five minutes, using Sartorius brand electric scales with a precision of 0.01 g connected to a computer. Every five minutes, a camera provides photos of the tomato slice during drying. The photographs will allow us to follow the evolution of the thickness of the tomato during drying. The experimental setup is shown in Figure 1.

The initial water content was determined by measuring the mass of the sample before and after passage in an oven at 70°C for 24 h. The average water content determined is 17.5 kg water/kg of dry material or 94.6% in wet basis, which is in accordance with the data of literature (Ibrahim, 2007)

The experiments are carried put under several experimental conditions in order to highlight the effect of temperature and drying air velocity on the evolution of water content and the thickness of the slice of tomato during the drying process. The experimental temperatures are 50 and 60°C, to avoid the destruction of the vitamins, and experimental velocity are 0.1, 0.25and 0.5 $m.s^{-1}$ to approximate air velocity in natural convection.

Mathematical formulation

Moisture content and dry mass

The mass of the product after passing through the oven at 70°C constitutes its dry mass. When the initial water content is known, dry mass is determined by the following mathematical relationship:

$$m_s = \frac{m_0}{1 + X_0} \tag{1}$$

The water content in dry basis during drying at time "t" is determined by the following mathematical expression:

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

or

$$X(t) = \frac{m(t)(X_0 + 1) - m_0}{m_0} \tag{3}$$

The final water contents sought is that from which the product no longer deteriorates and keeps its nutritional and organoleptic qualities. This final water content is therefore a characteristic of the product, in the case of tomato; it is about 10%.

Drying velocity

The drying rate is determined by the following equation:

$$DR = -\frac{X^*_{t+dt} - X^*_t}{dt} \tag{4}$$

With X_t^* as the relative water content at the time "t", X_{t+dt}^* the relative water content at the time t+dt and t is the drying time.

Drying curve

The drying curve is generally represented by the water content reduced with time. The reduced water content is determined by the following expression:

$$X^* = \frac{X - X_e}{X_0 - X_e} \tag{5}$$

Where, X^* represents the content of reduced water, X represents the content of water at a time "t", X_e represents the water content at equilibrium.

This expression of the reduced water content can be approximated by the following expression:

$$X^* = \frac{X}{X_0} \tag{6}$$

The error is very small (Manashi et al., 2011).

The theoretical, empirical or semi-empirical expressions are used to account for the drying curve. These models generally derive from the simplification of the general solution of the set of Fick's second law except for the ''Gaussian equation'' used in this work which gives a better correlation. The correlation coefficient R^2 is used to evaluate the model, at the χ^2 statistical parameter and the square root of the mean systematic error RMSE. These parameters are given by the following relations:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(X^*_{pre,i} - X^*_{exp,i}\right)^2}{\sum_{i=1}^{N}\left(\overline{X^*_{pre}} - X^*_{exp,i}\right)^2} \quad \text{(Mortaza et al., 2009)} \tag{7}$$

$$\chi^2 = \frac{\sum_{1=1}^{N}\left(X^*_{exp,i} - X^*_{pre,i}\right)^2}{N - Z} \tag{8}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(X^*_{exp,i} - X^*_{pre,i}\right)^2} \tag{9}$$

The Gaussian equation is stipulated in the following expression:

$$X^* = a_1 \exp\left(-\left((-t - b_1)/c_1\right)^2\right) + \cdots + a_6 \exp\left(-\left((-t - b_6)/c_6\right)^2\right) \tag{10}$$

$X^*_{exp,i}$ is the experimental reduced water content at point i, $X^*_{pre,i}$ is the reduced water content predicted at point i. N represents the number of points, Z is the number of constants in the model.

The best model is the one that has the highest possible value of R^2 (close to 1), χ^2 and RMSE should be as small as possible (Ruiz Celma et al., 2012).

Shrinkage

Some scholars use volumetric ratio to express shrinkage ($\frac{V}{V_0}$). Shrinkage is also studied as a function of the relative variation of the thickness of the product. Various relationships are observed on the evolution of thickness depending on the water content, and based on experimental parameters. Indeed, some authors such as Lucia et al. (2007) for the 'chitosan' conclude linear relationship between variation in thickness and water content in the form:

$$\frac{L}{L_0} = a.X + b \tag{11}$$

Hashemi et al. (2009) for the bean, got the result:

$$\frac{L}{L_s} = 1 + \alpha.X \quad (12)$$

In these expressions, L_o, L, L_s respectively indicate the thickness of the sample at the initial time, at a time "t" and the thickness of the dry sample, a and b are constant, α is the coefficient of linear shrinkage. But some authors such as Kingsly et al. (2007) for the jujube, found a quadratic function to express shrinkage in thickness depending on the water content in the form:

$$\frac{L}{L_0} = a.X^2 + b.X + C \quad (13)$$

In this study, we present the evolution of a slice of tomato flesh during its drying, depending on the experimental conditions and its water content.

Effective diffusion coefficient

For the determination of the diffusion coefficient, Fick's second law was used considering the unidirectional movement of water and the slice of tomato as an infinite plate. The equation of Fick's second law is as follows:

$$\frac{\partial X}{\partial t} = D_{eff}\frac{\partial^2 X}{\partial x^2} \quad (14)$$

Where, X is the water content, D_{eff} ($m^2.s^{-1}$) is the effective diffusion coefficient, t(s) is the drying time and x is the direction of water propagation. The solution proposed by Crank (1975) is that when assuming that initial water content is uniform, and the process isothermal, the solution is:

$$X^* = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(\frac{-(2n+1)^2\pi^2 D_{eff}.t}{4.L^2}\right) \quad (15)$$

Where, X^*, shows the reduced water content, L (m) half the thickness of the sample and n ($n \in N$) the number of limits taken into account.

Equation (15) can be simplified at the first term of the series for long periods of drying. This gives:

$$X^* = \frac{8}{\pi^2}\exp\left(\frac{-\pi^2 D_{eff}.t}{4.L^2}\right) \quad (16)$$

Taking the logarithm of Equation 16, we obtained Equation 17, whose representation in function of time is linear within a certain value of the water content.

$$\mathrm{Ln}(X^*) = \mathrm{Ln}\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}.t}{4.L^2}\right) \quad (17)$$

The slope of this line is: $K = -\frac{\pi^2 D_{eff}}{4.L^2}$ (18)

Therefore: $D_{eff} = -\frac{4.k.L^2}{\pi^2}$ (19)

Figure 4 shows the representation of $\ln(X^*)$ as a function of time. The values of the average effective diffusion coefficient for the various experiments are shown in Table 1, where we can see that the effective diffusion coefficient increases with both temperature and velocity of drying air.

In the present case of our study, the representation of $\ln(X^*)$ as a function of drying time is not quite linear as we really observe a curvature towards the end. Thus, Equation 17 considers that the diffusion coefficient is constant for a given temperature. Figure 5 illustrates the dependence of the effective diffusion coefficient as a function of the water content of the product. The Fourier number is used. It has already been proposed in the work of Ruiz Celma et al. (2012) to assess the effective diffusion coefficient as a function of water content.

If $F_0 = \frac{D_{eff}.t}{L^2}$ where, F_0 is the number of Fourier, Equation 16 becomes:

$$X^* = \frac{8}{\pi^2}\exp\left(\frac{-\pi^2}{4}F_0\right) \quad (20)$$

When taking the logarithm of Equation (20), we can express the number of Fourier with the following expression:

$$F_0 = \frac{4}{\pi^2}\mathrm{Ln}\left(\frac{8}{\pi^2}\right) - \frac{4}{\pi^2}\mathrm{Ln}(X^*) \quad (21)$$

The effective diffusion coefficient is expressed by the equation:

$$D_{eff} = \frac{F_0 L^2}{t} \quad (22)$$

RESULTS AND DISCUSSION

The drying process is stopped when the water content of the product has reached the equilibrium moisture content of the experimental conditions (8% <HR <10%) or a water content of dry basis range between 0.099 and 0.1 kg water/kg dry matter.

Determining the water content was made on a dry basis by using the formula of Equation 3 above. Relative water contents (X/X_0) are used to compare effectively the influence of aero-thermal parameters such as temperature and velocity of the drying air on the drying kinetics and the drying rate of the product. Thicknesses have also been reduced to relative thicknesses for the same reasons.

Effect of temperature and air velocity on the drying kinetic

For these experiments, we used the temperatures and velocities of drying air presented above. To determine the influence of temperature, the air velocity is fixed (V is

Table 1. Value of the activation energy depending on the experimental conditions.

Air velocity ($m.s^{-1}$)	Air temperature (°C)	Average effective diffusion coefficient (10^{-6}) [$m^2.s^{-1}$]	Activation energy Ea ($kJ.mol^{-1}$)
0.1	50	1.33	25.77
	60	1.77	
0.25	50	2.6	33.26
	60	3.79	
0.5	50	3.56	32.42
	60	5.11	

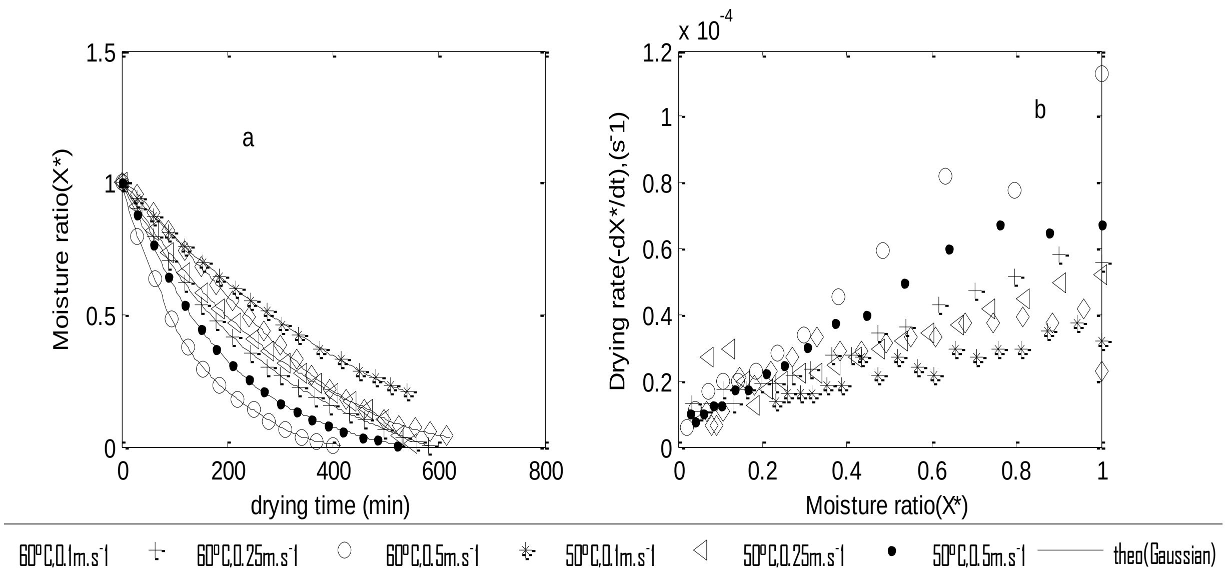

Figure 2. a) Evolution of water content as a function of time and experimental conditions; **b)** drying rate as a function of relative water content and experimental conditions.

constant), its temperature is varying, and the opposite is used for determining the influence of the air velocity.

At fixed air velocity, drying is naturally all the more fast as the temperature is high (Figure 2a). Figure 2a also allows us to observe the effect of air velocity on the evolution of water content during drying. We noticed that the effect of air velocity is dominant, as compared to that of temperature. Indeed we noted that at 60°C with a velocity of 0.25 $m.s^{-1}$, drying is less efficient than at 50°C under an air velocity of 0.5$m.s^{-1}$. The increase in velocity and temperature of the drying air accelerates the drying process of tomato.

Influence of temperature and air velocity on the drying rate

The drying rate in Figure 2b shows a single phase, the stage of drying with decreasing velocity which suggests that the drying of tomato is governed by a phenomenon of diffusion. Figure 2b shows that drying rate increases with air velocity. This is also observed by Salah et al. (2012) regarding the drying of apple. Drying rate also increases with air temperature according to Figure 2b. This is also observed by Abano et al. (2011), regarding the drying of tomato. But an analysis of the effect of these two parameters indicates that the effect of the air velocity is much greater.

Influence of temperature and air velocity on the phenomenon of shrinkage

Drying involves the water loss of the sample, leading to deformation of the skeleton of the sample. This phenomenon reduces the size of the sample. In the present work, the thickness of the slice of tomato was measured and reduced to relative thickness (e/e_0).

The resulting images (Figure 3) are processed using software called GIMP. The processing of images to

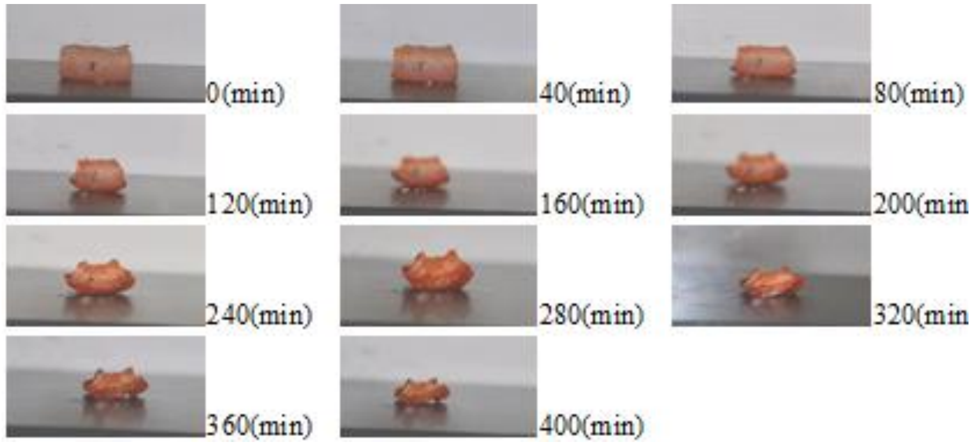

Figure 3. Evolution of the slice of tomato during drying.

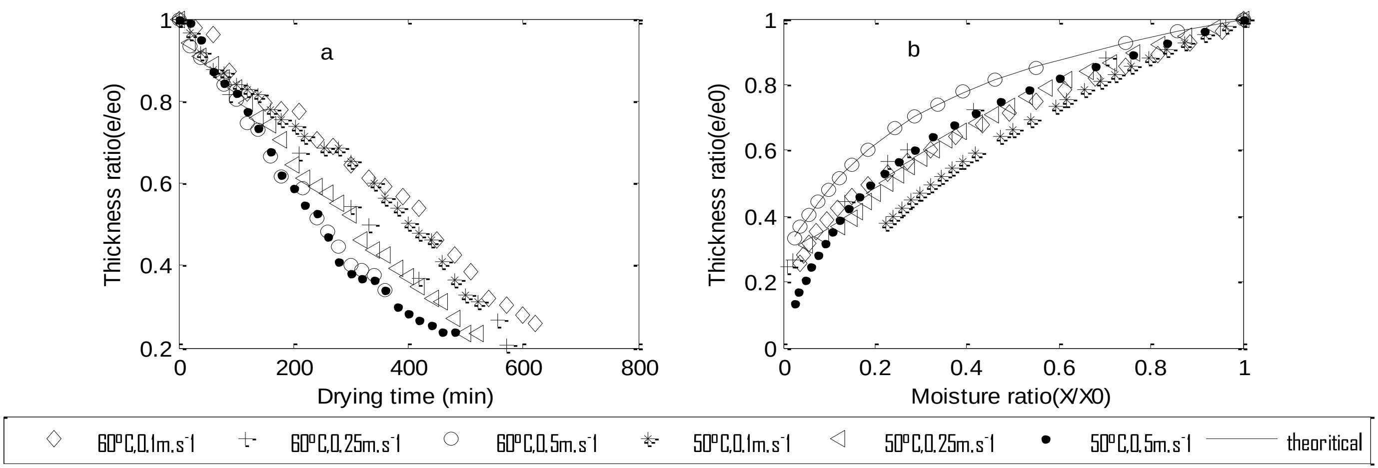

Figure 4. a) Evolution of the relative thickness as a function of drying time and experimental conditions; b) Shrinkage of the tomato slice according to relative water content.

assess shrinkage has already been used by other authors such as: Zhengyong et al. (2008) to measure changes in the size of pineapple, mango and banana during drying, Alireza and Mehdi (2009) to determine the effect of temperature and drying air on the shrinkage of the potato,

Lucia et al. (2007) to determine the evolution of the thickness of the 'chitosan' during its drying.

Figure 4a shows an almost linear decrease of the thickness of the slice of tomato with drying time.

It was observed that the air velocity had more pronounced effect on the shrinkage as compared to temperature. This constitutes another argument in favor of the dominant role of drying air velocity in this temperature range. The shrinkage is more pronounced as the air velocity is high.

Nevertheless, temperature (50 and 60°C) does not significantly influence the phenomenon of shrinking of the slice of tomato and it was also noted that the increase in the latter slightly disadvantages shrinkage. A typical result for the temperature was obtained by Mc Minn and Magee (1997) and Wang and Brennan (1995) on the potato.

Figure 4b shows that for relative water content fixed at 0.25, very different relative thicknesses are observed according to the selected operating conditions, including 0.41, 0.52, 0.55, 0.56, 0.58 and 0.67. Then, it is noticed that the final volume of the material is not only due to lossof water and it is likely that other physicochemical mechanisms related to the intrinsic nature of the material, determine the final shrinkage of the product.

Modelization of the curve of drying

The drying curves were adapted to the respective models, logarithmic (Henderson and Pabis, 1961; Verma et al., 1985; Aghbasho et al., 2009) the two terms, the

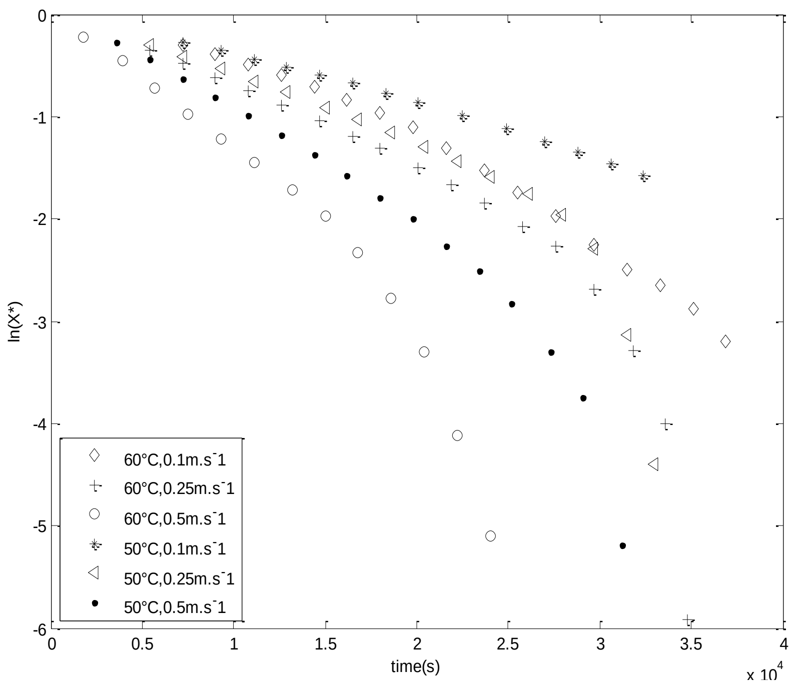

Figure 5. Representation of $\ln(X^*)$ as a function of time and experimental conditions.

modified (Henderson and Pabis, 1961; Wang and Singh, 1978) models, and to Gaussian equation (this work).

The parameters were evaluated through the Marquardt-Levenberg method of non-linear least squares algorithm. The best representation of the drying curve is obtained for the coefficient of the nearest possible correlation to 1, and the smallest possible values (close to zero) of χ2 and RMSE (Zhengfu et al., 2007). We can state that the Gaussian equation used in this work, represents better the drying kinetics of the samples of tomato flesh (Figure 2a).

Modelization of the curve of shrinkage according to water content

The best model obtained is a function of degree 5 (Figure 4b) represented as follows:

$$f(x) = a.x^5 + b.x^4 + c.x^3 + d.x^2 + g.x + h \quad (23)$$

Where, f represents e/e_0; a, b, c, d, e, f are constant and x represents X^*

Effective diffusion coefficient and activation energy

Effective diffusion coefficient

This effective diffusion coefficient of foodstuffs characterizes their intrinsic property of mass and moisture transport including molecular diffusion, liquid diffusion, vapor diffusion, hydrodynamic flow and other mechanisms Ruiz Celma et al. (2012)

Figure 6 shows that the value of the effective diffusion coefficient evolves in the same direction as temperature and air velocity and opposite direction with the water content. We also noted here that the curves of larger diffusion coefficients are those where the air velocity is higher despite the fact that temperatures are different. This shows the complexity of expressing this coefficient correctly.

By using Fick's equation and considering shrinkage, we noted that the effective diffusion coefficient presents a rather complex evolution (Figure 7). Indeed effective diffusion presents two phases: a first phase where it evolves in opposite direction with the water content until it reaches a maximum and a second phase where it evolves in the same direction as the water content.

This behavior of effective diffusion coefficient can be interpreted by the various mechanisms which control drying. Thus, in the first phase of drying, the diffusion of liquid water could be the principal mechanism of mass transfer. While drying progresses, the diffusion of the water vapor would be prevalent. This behavior was observed by several authors.

Activation energy

The Arrhenius expression enables us to determine the

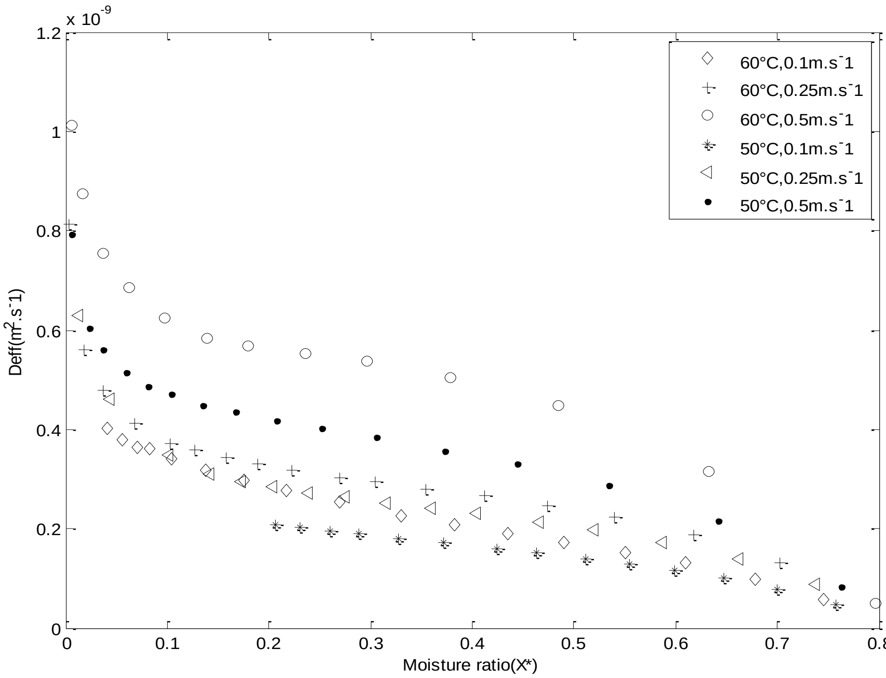

Figure 6. Representation of the effective diffusion coefficient D_{eff} without taking into account shrinkage as a function of the relative water content X* and experimental conditions.

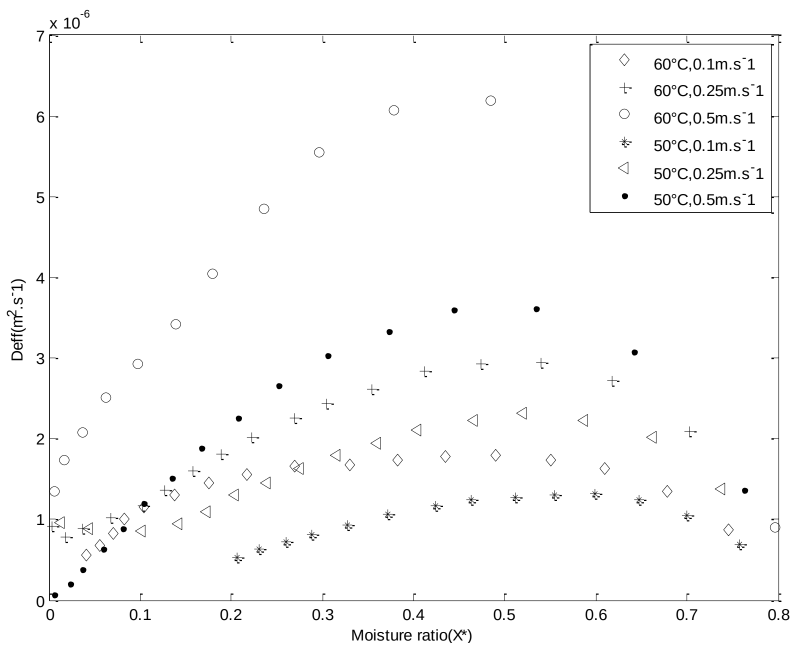

Figure 7. Representation of the effective diffusion coefficient D_{eff} as a function of the relative water content X* when shrinkage is included.

activation energy, which connects the latter to the diffusion coefficient through the following expression:

$$D_{eff,avg} = D_0 . \exp\left(-\frac{E_a}{R(T+273)}\right) \quad (24)$$

Where, D_0 is a constant of Arrhenius, E_a is the activation energy, T is temperature (°C) and R is the perfect gas constant.

It is necessary to express the average effective coefficient of diffusion according to the water content. The following relation is used:

$$D_{eff,avg} = \frac{\int_{X^*initial}^{X^*final} D(X^*)dX^*}{\int_{X^*initial}^{X^*final} d(X^*)} \quad (25)$$

Equation (24) is taken as a logarithm, which gives Equation 26 as follows:

$$Ln(D_{eff}) = Ln(D_0) - \frac{E_a}{R(T + 273)} \quad (26)$$

The graphical representation of equation $\ln(D_{eff})$ as a function of the reverse of temperature gives a straight line whose slope is

$$P = -\frac{Ea}{R} \quad \text{where, } E_a = -P.R \quad (27)$$

The values of the activation energy found are shown in Table 1. The activation energy like the diffusion coefficient varies with experimental conditions.

Conclusion

An experimental study on the kinetics of shrinkage and evolution of thickness of a tomato slice during its drying was carried out. During this study, it was shown that Gaussian's equation used for the first time better adapts to the studied curves of experimental shrinkage.

The results confirmed the positive effect of temperature and air velocity on the kinetics of drying. We have also noticed a clear dependence of the effective diffusion coefficient on the water content of the product. The complexity of the effective diffusion coefficient has also been observed, which depicts that drying process is governed by several mechanisms. The obvious difference between the expressions of effective diffusion coefficient with or without taking into account the shrinkage of the product also shows the importance of taking shrinkage into account in the studies of simulation of drying kinetics.

Conflict of interests

The authors did not declare any conflict of interest.

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