TOMATO INFRARED DRYING: MODELING AND SOME COEFFICIENTS OF THE DEHYDRATION PROCESS

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Infrared dehydration is more advantageous than the convective system under similar conditions, and studying this process is important to further develop equipment and procedures. Thus, the aim of this work was to study the dehydration process of tomato (*Solanum lycopersicum L.*) slices obtained by infrared drying at three different maturity stages throughout two different procedures: Firstly, the drying model was determined by applying the mass and energy balances under wet bulb temperature for the constant drying rate period and secondly, the mass effective diffusion coefficient was determined throughout the experimental data and the theory of diffusion of the liquid phase for the decreasing drying rate period. Tomato fruits cv. Santa Cruz were used. Three maturity stages were selected: green (stage 1), orange (stage 2), and red (stage 3). Mathematical models frequently used to represent drying of agricultural products were fitted to the experimental data of tomato drying. The effective diffusion coefficient was obtained by adjusting the liquid diffusion mathematical model to the experimental data of the descending period of dehydration. The two-term model was the best one to represent the tomato dehydration process. The critical moisture content for tomato dehydration was 2.97 kg_w kg_{dm}^{-1}. There is an initial dehydration period in which the drying rate reaches its maximum (approximately 1.05 kg_w kg_{dm}^{-1}, about 3 min). Three different methods were used to obtain values of the effective diffusion coefficient, including the finite element method, which had the lowest values for the least square sum of deviation 1.00×10^{-7} m^2 s^{-1}. The global coefficient of heat transfer was 12.45 W $m^{-2}K^{-1}$, and the global coefficient of mass transfer was 0.0105 m s^{-1}.

Key words: Critical moisture content, diffusion, finite element method, heat and mass transfer, mathematical modeling, *Solanum lycopersicum*.

Tomato (*Solanum lycopersicum* L.) is one of the vegetables most consumed in the world. It is a source of vitamins A and C and mineral salts, such as K and Mg. Tomato is a climacteric fruit with a short maturation and color change period, firmness, aroma, and flavor throughout shelf-life (Oliveira, 2010).

Dehydration has recently been used to increase shelf-life of several fruits and vegetables (Vasques *et al.*, 2006). Conservation through dehydration is based on the fact that microorganisms, enzymes, and the entire metabolic system of biological materials require water for their activities. A reduced amount of water decreases water activity and chemical reactions within the product, as well as the development of microorganisms (Christensen and Kaufmann, 1974). Therefore, the main objective of drying is reducing moisture content and water activity (Doymaz, 2005a; Corrêa *et al.*, 2010a; Oliveira *et al.*, 2010) since these parameters control product respiration rate and

incidence of microorganisms and insects (Corrêa *et al.*, 2010b; Goneli *et al.*, 2010a; 2010b).

Infrared dehydration is more advantageous than the convective system under similar conditions (Sharma *et al.*, 2005). When infrared is used to warm up or dehydrate wet materials, radiation encounters the exposed product, penetrates it, and radiation energy is converted into heat. The penetration depth of radiation depends on the material's properties and the radiation wavelength. When the product is exposed to radiation, it is intensively heated and the temperature gradient within the product is reduced in a short period of time.

Depending on the material to be dried, water can move through its interior by different mechanisms. In hygroscopic capillary-porous products, such as most agricultural products, the possible mechanisms of moisture movement are liquid diffusion, capillary diffusion, surface diffusion, hydrodynamic flow, vapor diffusion, and thermal diffusion (Brooker *et al.*, 1992). The effective diffusion coefficient has been studied by different researchers in different products (Campos *et al.*, 2009; Corrêa *et al.*, 2010c); this parameter illustrates the moisture movement, intrinsic to the product, towards the outside due to drying.

Heat and mass transfer is intrinsically involved in reducing grain moisture (Hall, 1980) by drying.

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Simulating the behavior of each product during dehydration is an important parameter to develop and maximize grain drying equipment (Sacilik *et al.*, 2006; Corrêa *et al.*, 2010c), as well as selecting mathematical models that will represent moisture loss during drying. Moreover, transport phenomena of food and other important biological materials is a significant link between the processing of these materials and product quality and safety (Welti-Chanes *et al.*, 2005).

Given the importance of studies on drying, the objective of this study was to model the dehydration process of tomato fruits at three different maturity stages, and also obtain the effective diffusion coefficient and global values of heat and mass transfer.

MATERIALS AND METHODS

The present work was conducted in the Laboratory of Physical Properties and Quality Evaluation of Agricultural Products at the National Grain Storage Training Center – CENTREINAR, Federal University of Viçosa, Viçosa, Minas Gerais, Brazil.

Tomato fruits cv. Santa Cruz were acquired at the local market. Three maturity stages were selected: green (stage 1), orange (stage 2), and red (stage 3). Each maturity stage had five replicates. Tomatoes were sliced approximately 5 mm thick and weighed on a digital scale with 0.001 g precision.

The study used a dryer with an infrared radiation source (model IV 2500, Gehaka, São Paulo, Brazil) for dehydration. This equipment contains a scale with 0.001 g precision and an automatic data acquisition system. The radiation source is located at a fixed distance of 15 mm from the product with an infrared power of 300 W. Dehydration was carried out at 60 ºC. The moisture ratio of the tomato during drying was obtained by Equation [1]:

$$MR = \frac{U_t^* - U_e^*}{U_i^* - U_e^*} \qquad [1]$$

where MR is the moisture ratio of the product, dimensionless; U_t^* is the moisture content of the product at a certain drying time, decimal d.b.; U_i^* is the initial moisture content of the product, decimal d.b.; and U_e^* is the equilibrium moisture content of the product, decimal d.b.

The mathematical models frequently applied to represent drying of agricultural products were fitted to the experimental data of tomato drying. These models are shown in Table 1.

The goodness of fit of the mathematical models was analyzed through non-linear regression and the Gauss Newton method with Statistica 8.0 (StatSoft, Tulsa, Oklahoma, USA). The fitness degree of each model was based on the determination coefficient (R^2), mean relative percent deviation (P), and standard error (SE). The values of P and SE for each model were calculated by Equations [2] and [3]:

Table 1. Mathematical models used to represent the drying phenomenon of tomato.

Model name	Model	Equation
Diffusion approximation (Yaldiz and Ertekin, 2001)	$MR = a \exp(-kt) + (1-a) \exp(-kbt)$	[2]
Two-term (Henderson, 1974)	$MR = a \exp(-kt) + b \exp(-gt)$	[3]
Henderson and Pabis (Henderson and Pabis, 1961)	$MR = a \exp(-kt)$	[4]
Midilli (Midilli *et al.*, 2002)	$MR = a \exp(-kt^n) + bt$	[5]
Logarithmic (Yagcioglu *et al.*, 1999)	$MR = a \exp(-kt) + b$	[6]
Verma (Verma *et al.*, 1985)	$MR = a \exp(-kt) + (1-a) \exp(-gt)$	[7]
Page (Diamente and Munro, 1993)	$MR = \exp(-kt^n)$	[8]

MR: moisture ratio, dimensionless; a, b, g, n: model parameters, dimensionless; k: drying rate, s^{-1}; t: drying time, s.

$$P = \frac{100}{n} \sum \frac{|Y - \hat{Y}|}{Y} \qquad [2]$$

$$SE = \sqrt{\frac{\sum (Y - \hat{Y})^2}{DF}} \qquad [3]$$

where P is the mean relative percent deviation (%); SE is the standard error, decimal d.b.; Y is the observed value, dimensionless; $\hat{Y}$ is the value estimated by the model, dimensionless; n is the number of observed data; and DF is the degrees of freedom of the model (number of observed data minus the number of model parameters).

The theories that govern the constant rate period of dehydration of agricultural products, according to Brooker *et al.* (1992), can be approximated to the heat and mass transfer balance studies for wet bulb temperature. Thus, the constant rate of dehydration can be represented by Equation [4]:

$$\frac{dM}{dt} = \frac{h_c A}{L}(T_\infty - T_{bu}) = \frac{h_m A}{R_v}\left(\frac{P_{vbu}}{T_{bu}} - \frac{P_{b\infty}}{T_\infty}\right) \qquad [4]$$

where h_c is the global coefficient of heat transfer (W m^{-2} K^{-1}); h_m is the global coefficient of mass transfer (m s^{-1}); L is the latent heat of vaporization (J kg^{-1}); R_v is the universal constant of water vapor (461.91 J kg^{-1} K^{-1}); A is the superficial area of tomato slices (m^2); P_{vbu} is the vapor pressure for the wet bulb temperature (Pa); $P_{v\infty}$ is the vapor pressure for dehydration temperature (Pa); T_{bu} is the wet bulb temperature (K); T_∞ is the dehydration temperature (K); and dM/dt is the constant rate of dehydration (kg s^{-1}).

Coefficients were calculated with the following parameters: plate geometric shape type, isothermal process, and neglecting volumetric shrinkage of the product.

The effective diffusion coefficient was obtained by adjusting the liquid diffusion mathematical model (Equation [5]) to the experimental data of the descending period of dehydration. This equation is the analytical solution of Fick's second law when considering the parameters of Equation [4]:

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left[-\frac{(2n+1)^2 \pi^2 D_{ef} t}{4L^2}\right] \qquad [5]$$

where L is the half thickness of the slab (m); D_{ef} is the effective diffusion coefficient ($m^2 s^{-1}$); and n is the number of equation parameters.

RESULTS AND DISCUSSION

Infrared dehydration modeling

Table 2 shows the values of P, SE, and R^2 for each model considered in the present study (Table 1) for tomato fruit drying.

Determining the coefficient (R^2) for non-linear models is not a good decision-making tool. It is necessary to analyze different statistical parameters. Thus, for model adequacy in describing a phenomenon, P values must be taken into consideration; the lowest values of P indicate a higher representation of the model for the phenomenon under study. Analyzing SE also helps to select models. Lower SE values indicate higher model reliability. Therefore, by analyzing these three statistical parameters shown in Table 2, it was concluded that the two-term model is the best one to represent infrared drying of tomato fruit.

No significant difference was observed among tomato maturity stages at a 5% probability level by the Tukey test. As a result, Figure 1 represents the tomato drying curve. This figure shows the drying values observed and estimated by the two-term model at maturity stage 1. By analyzing Figure 1, the good adjustment of the two-term model to the experimental data can be observed, which satisfactorily represents tomato drying kinetics.

Thus, it is possible to estimate the moisture content of tomato during infrared drying at 60 °C by Equation [6]:

$$MR = 0.8952 \exp(-0.1036_t) + 0.1503\exp(-0.0064_t) \quad [6]$$

Figure 1 shows that some linearity occurs at approximately 10 min after the moisture ratio is reduced followed by an exponential reduction. The critical
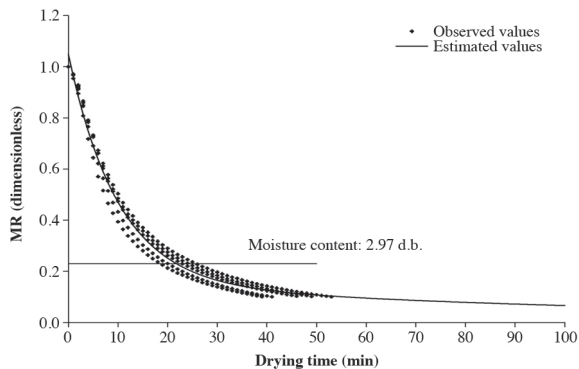

Figure 1. Observed and estimated moisture ratio (MR) values by the two-term model during drying of tomato fruits at 60 °C at maturity stage 1.

moisture content is defined at this point. This parameter divides the drying curve into two parts: before this point, it can be inferred that there is a constant falling rate period in which the velocities of moisture removal at the periphery and moisture replacement from the center to the periphery are considered to be equal; after this point of critical moisture content, a decrease in the moisture ratio with lower velocity is observed in which moisture replacement previously observed cannot supply the removal of moisture by infrared drying at the same velocity.

By analyzing the linearity of experimental data, a critical moisture content of 2.97 kg_w kg_{dm}^{-1} was found for tomato dehydration; this corroborates Brooker *et al*. (1992), who stated that the critical moisture content for the dehydration of biological products presenting a high initial moisture content ranges from 2.33 to 3.00 kg_w kg_{dm}^{-1}.

Figure 2 reports drying rate vs. drying time of tomato fruits dried at 60 °C. It can be observed in Figure 2 that there is an initial period in which the drying rate reaches its maximum value (approximately 1.05 kg_w kg_{dm}^{-1}, about 3 min). The product is being heated during this period of time. A decrease follows this increase. According to Celma *et al*. (2009), the initial evaporation occurs on the sample surface. However, this fact becomes less important over time. Therefore, moisture diffusion becomes the
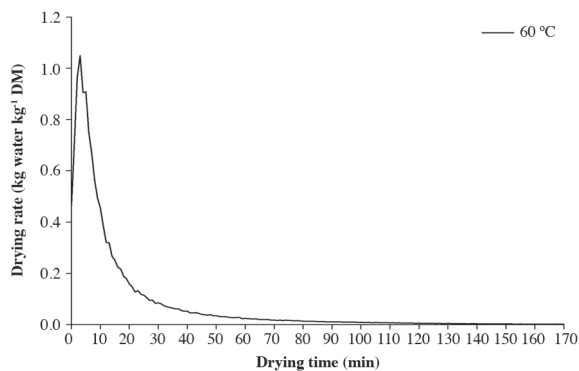
Table 2. Mean relative percent deviation (P), standard error (SE), and determination coefficient (R^2) for each mathematical model studied at 60 °C at each maturity stage.

Maturity stage	Model name	R^2 (%)	P (%)	SE (decimal d.b.)
1st	Diffusion approximation	98.50	9.30	0.03
	Two-term	98.69	9.05	0.03
	Henderson and Pabis	96.36	19.23	0.05
	Logarithmic	98.68	9.31	0.03
	Midilli	98.59	9.79	0.03
	Page	97.40	13.79	0.04
	Verma	98.49	9.30	0.03
2nd	Diffusion approximation	95.66	13.93	0.05
	Two-term	95.85	13.81	0.05
	Henderson and Pabis	92.61	26.00	0.07
	Logarithmic	95.84	13.86	0.05
	Midilli	95.71	14.17	0.05
	Page	94.10	19.67	0.06
	Verma	95.66	13.93	0.05
3rd	Diffusion approximation	97.25	11.01	0.04
	Two-term	97.40	10.86	0.04
	Henderson and Pabis	94.23	24.27	0.06
	Logarithmic	97.38	11.33	0.04
	Midilli	97.25	11.87	0.04
	Page	95.85	17.07	0.05
	Verma	97.25	11.01	0.04

Figure 2. Drying rate values versus drying time at 60 °C of tomato fruits at maturity stage 1.

main factor affecting the drying rate. This trend was also observed for other agricultural products, such as okra (*Abelmoschus esculentus* (L.) Moench; Doymaz, 2005b) and olive cake (Akgun and Doymaz, 2005).

Diffusion

For long dehydration periods (MR < 0.6), the diffusion equation can be simplified by a one-term series (Senadeera *et al.*, 2003). Therefore, assuming that D_{ef} is independent of moisture content, Equation [5] can be rewritten as follows:

$$\ln MR = \ln \frac{8}{\pi^2} - \frac{\pi^2 D_{ef}}{4L^2} \qquad [7]$$

The effective diffusion coefficient can thus be calculated by replacing the experimental data in Equation [6]. The effective diffusion coefficient is determined by plotting ln MR *vs.* drying time, in which the angular coefficient of the linear regression is $\pi^2 D_{ef}/4L^2$.

According to Karathanos *et al.* (1990), the effective diffusion coefficient of biological materials characterizes the transport of intrinsic mass in the form of water molecules, including molecular diffusion, liquid diffusion, gaseous diffusion, hydrodynamic flow, and other mechanisms. Values of D_{ef} for tomato fruits dried by infrared at maturity stages 1, 2, and 3 were 3.33, 2.78, and 3.05×10^{-7} m^2 s^{-1}, respectively.

Figure 3 shows the plotting of ln MR *vs.* drying time of tomato fruits at maturity stage 1. Although the relationship between MR and drying time exhibited a high determination coefficient ($R^2 = 97.99\%$), it can be observed in Figure 3 that there is a nonlinear tendency of this relationship in the final stage of drying. Celma *et al.* (2009) reported that the effective diffusion coefficient depends on moisture content when this nonlinearity is observed. These authors reported a relationship between D_{ef} and moisture content represented by Equations [8] and [9]:

$$F_0 = -0.0851 - 0.4052 \ln MR \qquad [8]$$

$$D_{ef} = \frac{F_0 L^2}{t} \qquad [9]$$

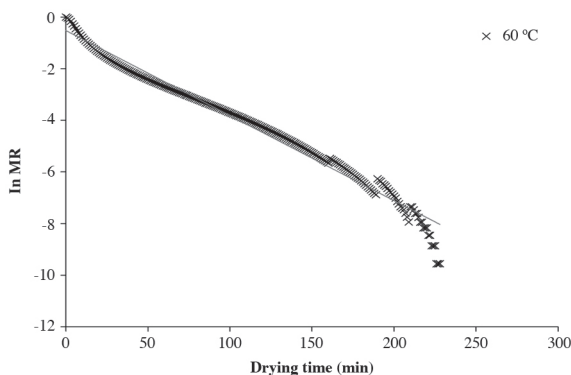where F_0 is the Fourier number, dimensionless.

Figure 3. Plotting of ln moisture ratio (MR) versus drying time of tomato fruits at maturity stage 1.

Values were found by this method for the effective diffusion coefficient of 3.75, 3.42, and 3.80×10^{-7} m^2 s^{-1} at maturity stages 1, 2, and 3, respectively. The values of these two methods were different and the ANSYS 5.3 (ANSYS, Canonsburg, Pennsylvania, USA) software system was used to detect which method showed the lowest error using the finite element method.

The finite element method (FEM), with its optimization routines, has been recently applied because it is easy to use for complex models and geometries (Gastón *et al.*, 2002). This methodology was used to determine the effective diffusion coefficient of wheat with spherical and ellipsoidal geometries (Gastón *et al.*, 2002); to determine D_{ef} values of different apple tissues (Veraverbeke *et al.*, 2003); and to obtain D_{ef} values during the soaking of rice by considering the expansion feature (Bakalis *et al.*, 2009). Therefore, D_{ef} values were found by using the two abovementioned methods and a geometry representing the shape of tomato samples.

Moisture transfer within tomato fruit was close to the liquid diffusion theory without generating water inside the control volume and is represented by Equation [10]. The initial condition is stated by Equation [11] by considering that water distribution at the beginning of the process is homogeneous. The boundary condition is represented by Equation [12] by considering the water vapor mass equilibrium between the product and the drying air:

$$\frac{\delta U_t^*}{\delta t} = D_{ef} \nabla^2 U_t^* \qquad [10]$$

$$U_t^* (t = 0) = U_i^* \ln \Omega \qquad [11]$$

$$U_t^* = U_e^* \ln \Gamma \qquad [12]$$

where Ω is the control volume and Γ is the contour surface.

The equilibrium moisture content was calculated by the two-term equation. The geometry of the product was approximated to a sphere with an equivalent diameter of 70.55 mm. This diameter was calculated based on the mean of characteristic dimensions obtained with a 0.01 mm precision digital caliper. The analysis was carried out with a 45° angle semi-circle because of geometric symmetry.

A mesh with quadrangular elements and axis symmetry at the surface control was created. Geometry, mesh generation, and model implementation were carried out with the ANSYS 5.3 software system. Simulation results were compared with experimental data in each effective diffusion coefficient. The D_{ef} values were selected with the least square sum of deviations (Equation [13]) between experimental and simulated data.

$$RSD = \sum_{j=1}^{n} (Y_j - \hat{Y}_j)^2 \qquad [13]$$

where RSD is the least square sum of deviations; Y_j is the observed value; $\hat{Y}_j$ is the average value predicted by the model; and n is the number of observed values.

Table 3 shows the values of the effective diffusion coefficient at each tomato maturity stage and the values of

Table 3. Values for effective diffusion coefficients (D_{ef}) and least square sum of deviations (RSD) at each maturity stage of tomatoes obtained with different methods.

Maturity stage	D_{ef} ($\times 10^{-7}$ m² s⁻¹)	RSD (decimal d.b.)
1	3.33	0.0138
	3.75	0.0152
2	2.78	0.0162
	3.42	0.0197
3	3.05	0.0136
	3.80	0.0129

RSD obtained for each method. The RSD values ranged from 0.0129 to 0.0197 moisture content d.b. Despite these low values none of the methods were able to effectively predict the drying curve (Figure 4). Therefore, an optimization procedure of D_{ef} values was simulated with the ANSYS 5.3 software system. The D_{ef} value was 1.00 × 10⁻⁷ m² s⁻¹ (RSD = 0.0009 d.b.).

Table 4 shows a wide variation among products and among cultivars of the same product. This trend is probably due to differences in the chemical composition, physical structure, and geometry of the products; these values can vary with boundary conditions, drying methods, and prediction methods of D_{ef} values (Campos *et al*., 2009; Goneli *et al*., 2009; Corrêa *et al*., 2010c).

Mass transfer coefficients

The global coefficient of heat transfer (h_c) was 12.45 W m⁻² K⁻¹ and the global coefficient of mass transfer (h_m) 0.0105 m s⁻¹. The values of h_m in the present work corroborate the values reported by Touré and Kibangu-Nkembo (2004), who found 0.00974 m s⁻¹ for natural dehydration of mango fruits with solar energy, 0.00475

m s⁻¹ for cassava roots, and 0.00876 and 0.00943 m s⁻¹ for two banana cultivars, respectively. Furthermore, the values of h_c were expected since, according to Bird *et al*. (2004), the values of the global coefficient of heat transfer for free convection is between 3 and 20 W m⁻² K⁻¹.

CONCLUSIONS

Dehydration kinetics by infrared drying of tomato slices can be similar to the theoretical studies on heat and mass transfer mechanisms. The values found for the global coefficient of heat and mass transfer were 12.45 W m⁻² K⁻¹ and 0.0105 m s⁻¹, respectively. An effective diffusion coefficient of 1.00 × 10⁻⁷ m² s⁻¹ was found through an optimization procedure using the finite element method. The two-term model was the best to represent the tomato dehydration process, and the critical moisture content for tomato dehydration was 2.97 kg_w kg_{dm}⁻¹. The drying rate reached its maximum value (1.05 kg_w kg_{dm}⁻¹) at 3 min of dehydration.

Secado de tomate por infrarrojo: modelación y algunos coeficientes del proceso de deshidratación. La deshidratación por infrarrojo es más ventajosa que el sistema convectivo, en condiciones similares, y el estudio de este proceso es importante para el desarrollo de equipos y procedimientos. Por tanto, el presente trabajo tuvo como objetivo el estudio del proceso de deshidratación en tres diferentes estados de maduración de rebanadas de tomate (*Solanum lycopersicum* L.) por medio del secado por infrarrojo, usando dos métodos: aproximación del período constante de deshidratación a la teoría de la transferencia de calor y masa para el termómetro de bulbo húmedo; y al período decreciente de la deshidratación a la teoría de difusión de líquidos. Se utilizaron frutos de tomate cv. Santa Cruz. Tres estados de maduración fueron obtenidos: verde (estado 1), naranja (estado 2) y rojo (estado 3). Modelos matemáticos usualmente utilizados para representar el secado de productos agrícolas fueron ajustados a los datos experimentales del secado de tomate. El coeficiente de difusión efectivo fue obtenido por medio del ajuste del modelo matemático de difusión líquida a los datos experimentales del período decreciente de deshidratación. El modelo Dos Términos representó mejor el proceso del secado de rebanadas de tomate. La humedad crítica para la deshidratación de tomate fue 2.97 kg_w kg_{dm}⁻¹. Existe un período inicial de deshidratación en que la tasa de secado alcanzó el máximo (aproximadamente 1.05 kg_w kg_{dm}⁻¹, alrededor de 3 min). Tres diferentes métodos fueron utilizados para obtener los valores del coeficiente efectivo de difusión, incluyendo el
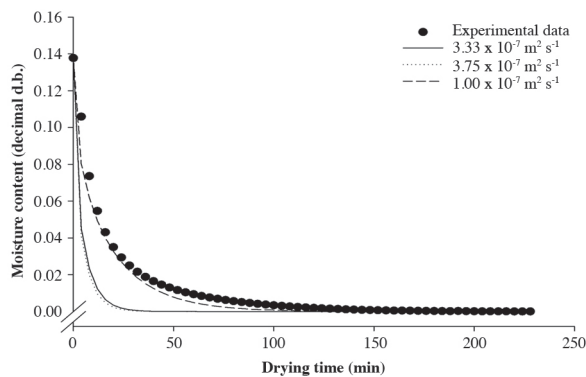
Figure 4. Moisture content variation of tomato fruits dried at 60 °C at maturity stage 1 as a function of different values of effective diffusion coefficient.

Table 4. Effective diffusion coefficients (D_{ef}) of different agricultural products.

Product	D_{ef} (m² s⁻¹)	Reference
Coffee (cv. Catuaí Vermelho)	2.145 to 2.702 × 10⁻¹¹	Campos *et al*. (2009)
Coffee (cv. Catuaí Amarelo)	5.98 × 10⁻¹¹	Corrêa *et al*. (2010c)
Tomato by-products	0.1147 to 9.078 × 10⁻⁹	Celma *et al*. (2009)
Grape	0.5 to 1.0 × 10⁻⁹	Çağlar *et al*. (2009)
Onion	1.0 × 10⁻⁸	Mota *et al*. (2010)
Tomato (cv. Santa Cruz)	1.0 × 10⁻⁷	Present work

método de elementos finitos, en que presentó los menores valores de la suma de desviaciones mínimas al cuadrado, 1.00×10^{-7} m² s⁻¹. El coeficiente global de transferencia de calor fue 12.45 W m⁻² K⁻¹, y el coeficiente global de transferencia de masa fue 0.0105 m s⁻¹.

Palabras clave: humedad crítica, difusión, método de elementos finitos, transferencia de calor y masa, modelación matemática, *Solanum lycopersicum*.

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