

Effects of temperature on both drying kinetics and color of Italian tomato

Efeito da temperatura sobre a cinética de secagem e a cor do tomate italiano

Títulos abreviados:

Drying of Italian tomato using convective drying

Secagem de tomate italiano usando secagem convectiva

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ABSTRACT

This study evaluated the influence of temperature on drying kinetics and color of Italian tomato of sliced and cut into quarters using different dehydration strategies based on laboratory-convective dried and convective oven drier. The mathematical modeling of drying curves and the effective diffusivity were evaluated. It was verified that tomatoes dried in the laboratory-scale drier presented lower drying time. In addition, the drying time of sliced tomatoes were lower than the cut ones. The proposed drying model presented a satisfactory fitting of the experimental data, showing that the use of global kinetic models presents an alternative to predict the drying profiles at different temperature. It was verified that De_{eff} for tomatoes dried in convective laboratory-scale drier were higher than for oven convective drier, in both cuts. The drying time has strong influence in darkening of the sample and it was verified a tendency in increase the red saturation index with the temperature. The best product quality was obtained using convective laboratory-scale drier at lower drying times. The tomato cut in four parts showed characteristics of final product similar to those sliced tomatoes. However, the slices tomato dried at temperature of 60 °C showed less drying time.

Keywords: laboratory-scale drier; oven drier; effective diffusivity; color parameters.

RESUMO

Este estudo avaliou a influência da temperatura na cinética de secagem e na cor de tomate italiano cortados em fatias e em quarto partes usando diferentes estratégias de desidratação usando secador convectivo em escala piloto e estufa com circulação de ar. A modelagem matemática das curvas de secagem e da difusividade efetiva foram avaliadas. Foi verificado que os tomates secos em secador em escala de laboratório apresentaram um menor tempo de secagem. Além disso, o tempo de secagem dos tomates cortados em fatias foi inferior ao daqueles cortados em partes. O modelo de secagem proposto apresentou um ajuste satisfatório dos dados experimentais mostrando que o uso do modelo de cinética global apresenta uma alternativa para prever perfis de secagem em diferentes temperaturas. Foi verificado que os valores de difusividade efetiva dos tomates secos em secador em escala de laboratório foram superiores aos daqueles secos em estufa convectiva em ambos os cortes. O tempo de secagem apresentou grande influência no escurecimento das amostras e foi verificado uma tendência ao aumento do índice de saturação vermelho com a temperatura. A secagem no secador em escala laboratorial apresentou melhor qualidade do produto final e menores tempos de secagem. Os tomates cortados em quatro partes apresentaram características semelhantes aos cortados em fatias. Todavia, os tomates cortados em quatro partes secos a 60 °C foram secos em menores tempos.

Palavras-chave: secador em escala laboratorial ; estufa; difusividade efetiva; parâmetros de cor.

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| Nomenclature | | | |
|------------------------------|--|----------------|---|
| M | Moisture | $MR_{exp,i}$ | experimental moisture ratio |
| MR | moisture ratio | $MR_{pred,i}$ | predicted moisture ratio |
| M_0 | initial moisture | D_{eff} | effective diffusivities ($m^2 s^{-1}$) |
| M_e | equilibrium moisture | L_0 | half thickness (m) |
| n, a, b, c, k, k_0 , k_1 | empirical constants in the drying models | N | positive integer |
| T | temperature ($^{\circ}C$) | L^* , DL^* | luminance, variation of luminance |
| R^2 | correlation coefficient | a^* , Da^* | red saturation index, variation of red saturation index |
| c^2 | reduced chi-square parameter | b^* , Db^* | yellow saturation index, variation of yellow saturation index |
| t | time (min) | | |

INTRODUCTION

The tomato is one of the most consumed vegetables in the world both as fresh in salads and in processed forms in sauces, juices, soups, ketchup, or sun-dried tomatoes (MURATORE *et al.*, 2008). Among the vegetables, the tomato is one of the most important crops in terms of production and economic value; it is the second in vegetable acreage in the world and first in industrialized volume (FAO, 2013). Tomato production worldwide reached 146 million tons in 2011, according to FAOSTAT, and therefore considered the most important vegetable grown in the world. China was the largest producer with 48.576 million tons and Brazil was the eighth largest producer with about 4.416 million tons (FAO, 2013).

The most vegetables are highly perishable, with limited shelf life at room temperature. This fact, coupled with inadequate control of initial quality, incidence and severity of injury, exposure to improper temperature and delay between harvest and consumption, resulting in significant losses in quality of fruits such as tomatoes (RAUPP *et al.*, 2009; EVRANUZ, 2011). Due to the great compatibility of the tomato with the dehydration process, this technique has been identified as one of the main alternatives to reduce losses and add value to raw material (JANGAM; MUJUMBAR; LAW, 2010; PURKAYASTHA *et al.*, 2011), transforming it from a product often undervalued due to the excess supply in a

differentiated product that targets a new market, winning consumers (SOUSA *et al.*, 2010, SILVA *et al.*, 2010; CRUZ; BRAGA; GRANDI, 2012). Drying is the most common form of food to preserve and prolong the food self-life. The main objective in drying agricultural products is the reduction of the moisture content to a level that does not allow the development of microorganisms slows the chemical reactions, reduces packaging and transportation costs due to reduced weight and volume, and extends the storage period (EVRANUZ, 2011). Moreover, in recent years, fresh tomatoes and tomato products have attracted scientific interest due to its antioxidant activity, which is related to the content of lycopene present in the fruit (CHANG *et al.*, 2006; MONTEIRO *et al.*, 2008; KOBORI *et al.*, 2010).

The physical and chemical properties of food are modified, due to changes in water content of the surface and center of food occur at the different speeds along the drying (JANGAM; MUJUMBAR; LAW, 2010; CRUZ; BRAGA; GRANDI, 2012). The observed changes are due to hardening, movement of soluble solids and retraction (KROKIDA; PHILIPPOPOULOS, 2005). High temperatures or long drying times can cause serious damage to product flavor, color and nutrients, and reduce the rehydration capacity of the dried product (DOYMAZ, 2007; HEREDIA; BARRERA; ANDRÉS, 2007; MURATORE *et al.*, 2008; CRUZ; BRAGA; GRANDI, 2012). The damages are most common pigment degradation, especially carotenoids like lycopene (responsible for the red color in tomatoes) and chlorophyll, and browning reactions such as Maillard condensation of hexoses and amino components, and oxidation of ascorbic acid. Other factors affecting color include fruit pH, acidity, processing temperature and duration, fruit cultivar and heavy metal contamination (MARFIL; SANTOS; TELIS, 2008; MURATORE *et al.*, 2008). Consumer demand has increased for processed products that keep more of their sensory properties and their nutritional value, so that it has become necessary to optimize drying conditions in order to achieve certain characteristics related to colour, texture and water content (HEREDIA; BARREA; ANDRÉS, 2007; CRUZ; BRAGA; GRANDI, 2012).

Knowledge of drying behavior is important in the design, simulation and optimization of drying process (MOVAGHARNEJAD; NIKZAD, 2007; JANGAM; MUJUMBAR; LAW, 2010). The drying behavior and model simulation of different natural material has been studied by several researchers (DOYMAZ, 2007; SACILIK, 2007; MAZUTTI *et al.*, 2010; SANJINEZ-ARGANDOÑA *et al.*, 2011; PURKAYASTHA

et al., 2011; DEMIRAY; TULEK, 2012). These models are useful tools to estimate the time for reduction of product moisture content under different drying conditions, and how to increase the drying process efficiency (SACILIK, 2007; SANJINEZ-ARGANDOÑA, 2011). Empirical mathematical correlations are usually used to describe the drying behavior of natural materials. These equations may be considered as oversimplified solutions of the diffusion equation. The original solution is a simple exponential equation and is known as Newton's equation. However, the original equation has been modified by several researchers to fit the experimental data (SOGI et al., 2003). The drying behavior of tomato is also described in terms of empirical correlations (DOYMAZ, 2007; MOVAGHARNEJAD; NIKZAD, 2007; SACILIK, 2007; SANJINEZ-ARGANDOÑA, 2011; PURKAYASTHA et al., 2011; DEMIRAY; TULEK, 2012).

In this sense, the main objective of this study was to evaluate the influence of temperature on drying kinetics and color of Italian tomato using different dehydration strategies. It was evaluated the drying kinetics of tomatoes sliced and cut into quarters using a convective laboratory-scale dryer and an oven with forced air circulation. In addition, the mathematical modeling of drying curves and the determination of effective diffusivity was presented.

MATERIALS AND METHODS

1. Raw material

Fresh Italian tomatoes (*Lycopersicon esculentum* Mill), obtained from local markets in Erechim, Brazil, were sorted visually for color (bright red), firmness, size (diameter 4.5 – 5.0 cm and length 7.0 – 9.0 cm) and physical damage absence.

2. Moisture content

The moisture content of tomato samples was determined by using the drying and sterilization oven (FANEM, model 320-SE, Guarulhos, SP, Brazil), at 105 °C for 12 h or until their weight remained constant, in according with method 925.10 (AOAC, 1997).

3. Experimental apparatus

Drying experiments were carried out in a laboratory-scale drier was designed by University Regional Integrada do Alto Uruguai e das Missões

researchers. The drier consists basically of three basic units, a fan providing the desired air velocity, a heating and heating control unit and a drying chamber. The heating control unit has an electrical heater (3800 W) placed inside a duct. The drying chamber, of 30x30x50 cm, was made from a galvanized metal sheet of 1.5 mm thickness having a single door opening at the front for insertion and removal of sample. The temperature and relative humidity in drying chamber were continuously recorded at 1 min intervals throughout runs with the help of this software connected to a PC and was measured directly using the PT100 (Novus, Porto Alegre, RS, Brazil) thermo-resistance, located in the center of the chamber. The air coming from the heater to the desired temperature entered the bottom of the chamber and passes through the product. The product is fixed tray in the chamber. The air velocity was measured using a hot-wire anemometer (Instrutherm, model AD 250, São Paulo, SP, Brazil) with the measurement range of 0.5 m s⁻¹. The amounts of material were weighed on an analytical balance (Toledo, model 9094, São Bernardo do Campo, SP, Brazil) with 0.5 g accuracy. The oven drying was performed in an oven with air renewal and circulation (Marconi, model MA 037, Piracicaba, SP, Brazil).

4. Drying procedures

The tomato samples were cut in slices (1.0 cm thick) and into quarters (approximately 2.5 cm radius). Each type of cut was subjected to drying at 40, 50 and 60 °C in both laboratory-scale drier air and in the oven with air circulation. In this way, the experiments were carried out using a factorial arrangement 2 x 2 x 3 totally casualized, that is, two kinds of tomatoes cutting, two kinds of dry equipments and three drying temperatures, totalizing 12 experiments with 3 repetitions. Drying kinetics was carried out in triplicate and the results were expressed by means and respective standard deviation. In each experiment, about 500 g of tomato samples were used. After the system started for at least half an hour to reach steady conditions for the operation temperatures, the samples were uniformly put into the sample basket as a single layer. Moisture losses of samples were recorded at 15 min intervals by two hours and 30 min, during the drying time in analytical balance (Toledo, model 9094-1, São Bernardo do Campo, SP, Brazil), subsequently thereafter for determination of drying curves. Drying was continued until no further changes in their mass were observed (about 15% moisture).

5. Mathematical modeling of experimental data

Moisture content (M) is defined as the ratio of moisture content to dry matter and is determined for each of the experimental data. Table 1 consists of ten mathematical equations which are frequently used to fit empirical correlations for describing the drying behavior of natural products.

Table 1 - Mathematical models applied to the drying curves

| Model no. | Model | References |
|-----------|---|-------------------------|
| 1 | $MR = \exp(-k \times t)$ | Bruce (1985) |
| 2 | $MR = \exp(-k \times t^n)$ | Menges; Ertekin (2006) |
| 3 | $MR = \exp(-(k \times t)^n)$ | White et al., (1981) |
| 4 | $MR = a \times \exp(-k \times t)$ | Henderson; Pabis (1961) |
| 5 | $MR = a \times \exp(-k_0 \times t) + b \times \exp(-k_1 \times t)$ | Henderson (1974) |
| 6 | $MR = a \times \exp(-k \times t) + b$ | Togrul; Pehlivan (2002) |
| 7 | $MR = a \times \exp(-k \times t) + (1 - a) \times \exp(-k \times a \times t)$ | Yaldiz et al., (2001) |
| 8 | $MR = \exp(-k \times t^n) + b \times t$ | Midilli et al., (2002) |
| 9 | $MR = a \times \exp(-k_0 \times t) + b \times \exp(-k_1 \times t) + c \times \exp(-k_2 \times t)$ | Togrul; Pehlivan (2002) |
| 10 | $MR = 1 + a \times t + b \times t^2$ | Wang et al., (2007) |

These equations which express the moisture ratio (MR) as a function of time, have been used to fit the drying kinetics of the tomato. In these models, MR represents the dimensionless moisture ratio (MOVAGHARNEJAD; NIKZAD, 2007; DEMIR; GUNHAN; YAGCIOGLU, 2007; SANJINEZ-ARGANDOÑA et al., 2011), namely:

$$MR = \frac{(M - M_e)}{(M_0 - M_e)} \quad (1)$$

Where M is the moisture content of the product, M_0 is the initial moisture content of the product and M_e is the equilibrium moisture content. The values of M_e are relatively small compared to M and M_0 for long drying times and accordingly one (DOYMAZ, 2007; SACILIK, 2007; MAZUTTI et al., 2010; SANJINEZ-ARGANDOÑA et al., 2011), can write:

$$M = \frac{M}{M_0} \quad (2)$$

To choose the best kinetic model to represent the drying kinetics of tomatoes, we used the data obtained using the convective oven with tomatoes cut into four parts to temperatures of 40, 50 and 60 °C. Since, the modeling was carried considering a single thin layer. The parameters of each model were estimated, considering a single set of parameters for all temperatures. To make possible to estimate a global parameter collection, the parameters k, k_0 and k_1 were expressed in function of temperature (Eq. 3).

$$k = k_0 + k_1 \times T \quad (3)$$

All the parameters (n, a, b and c) of models 1-10 (Table 1) were estimated for a temperature range from 40 to 60°C using the algorithm of Levenberg-Marquardt of software Statistica 8.0 (Statsoft Inc., Tulsa, OK, USA).

6. Correlation coefficients and error analysis

The ability of the tested mathematical model to represent the experimental data was evaluated through the correlation coefficient (R^2) and the reduced chi-square (c^2) parameter. The higher the R^2 and lower the c^2 values, the better is the fitting procedure (TOGRUL; PEHLIVAN, 2004; MAZUTTI et al., 2010; SANJINEZ-ARGANDOÑA et al., 2011). The chi-square (c^2) can be calculated according to Eq. 4:

$$\chi^2 = \frac{\sum_{i=1}^N (MR_{\text{exp},i} - MR_{\text{pred},i})^2}{N-z} \quad (4)$$

Where $MR_{\text{exp},i}$ and $MR_{\text{pred},i}$ are the experimental and predicted moisture ratio, respectively, N is the number of observations and z is the number of parameters. In this study, the nonlinear or linear regression analysis was performed using the statistica software Statistica 8.0 (Statsoft Inc., Tulsa, OK, USA).

7. Calculation of effective diffusivities

The effective diffusivity of the samples was estimated by using the simplified mathematical Fick's second diffusion model. The solution of Fick's second law in slab geometry, with the assumption that moisture migration was caused by diffusion, negligible shrinkage, constant diffusion coefficients and temperature was as follows Eq. 5 (Crank, 1975):

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-\frac{(2n+1)^2 \pi^2 D_{eff} t}{4L_0^2}\right) \quad (5)$$

For long drying periods, Eq. 5 can be further simplified to only the first term of the series and the moisture ratio MR was reduced to M/M_0 because M_e was relatively small compared to M and M_0 (Crank, 1975). Then, Eq. 5 can be written in logarithmic form to according Eq. 6:

$$\ln MR = \ln \frac{8}{\pi^2} - \frac{\pi^2 D_{eff} t}{4L_0^2} \quad (6)$$

Where: MR is the dimensionless moisture ratio, L_0 is the half thickness of the slab in sample in m, n is a positive integer, and D_{eff} is the effective diffusivity in $m^2 s^{-1}$.

The effective diffusivity is typically calculated by plotting experimental drying data in terms of $\ln(MR)$ versus drying time (Crank, 1975). From Eq. 6, a plot of $\ln(MR)$ versus the drying time gives a straight line with a slope of:

$$\text{slope} = -\frac{\pi^2 D_{eff}}{4L_0^2} \quad (7)$$

8. Color measurements

The color parameter measurement of fresh and dehydrated tomatoes was determined by direct reading with a Minolta Chroma meter (Minolta, model CR400, Osaka, Japan). The fresh and dry tomato samples were carefully placed in a special black cup covered with optical glass for color measurement. The instrument had an area of view of 25.4 mm and was used with a D65 illuminant as a reference at an observation angle of 10. The coordinates of the colour (CIE) obtained were L^* (luminance) range from zero (black) and 100 (white), a^* (red saturation index) in $-a^*$ (green) to $+a^*$ (red), and b^* (yellow saturation index) in $-b^*$ (blue) to $+b^*$ (yellow). The results were analyzed by analysis of variance (ANOVA) models and the significant F test. The multiple comparisons of means were performed by use of the Tukey test at 5% probability of error. Data processing

and statistical analysis were obtained using the statistical program Statistica 8.0 (Statsoft Inc., Tulsa, OK, USA).

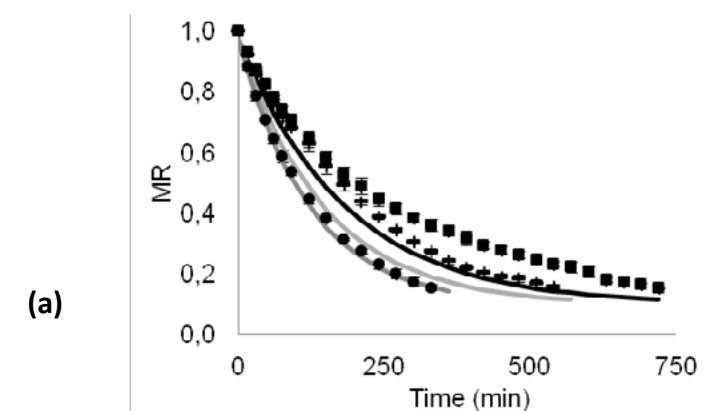
RESULTS AND DISCUSSION

1. Convective drying kinetics

Figures 1a and 1b present the experimental and simulated kinetic data obtained in the laboratory-scale drier and the oven driers, respectively, for tomatoes cut in four parts at 40, 50 and 60 °C. The lowest drying time of the tomatoes cut in four parts dried in laboratory-scale drier was obtained at 60 °C, which was about 330 minutes, whereas at 40 °C the drying time was higher than 660 minutes. The initial average moisture content was found to be $94.0 \pm 1.0\%$ (w.b.).

As expected, the drying time required to achieve a final moisture ratio of 0.15 in the oven with forced air circulation was higher than those obtained in the laboratory-scale drier. By example, at 60 °C the required time was about 780 minutes that is almost three times higher than that obtained in the laboratory-scale drier at the same temperature. According to Krokida; Philippopoulos (2005) to maintain an acceptable safety level of dried foods in terms of microbial contamination and oxidation it is desirable to dry the material until moisture ratio lower than 0.15.

Figure 1 - Experimental and predicted convective drying kinetics of the tomatoes for temperatures of (■) 40 °C, (-) 50 °C and (●) 60 °C dried in laboratory-scale drier and cut in four parts (a), dried in convective oven drier and cut in four parts (b). The lines represent the mathematical model fit the data (—) 40 °C, (—) 50 °C and (—) 60 °C.



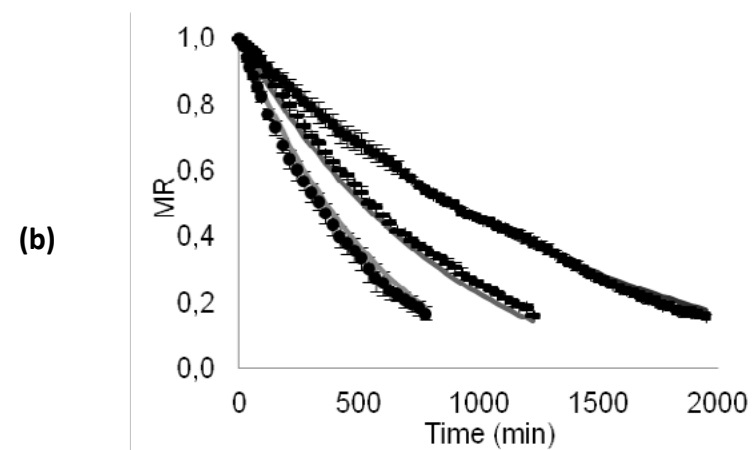
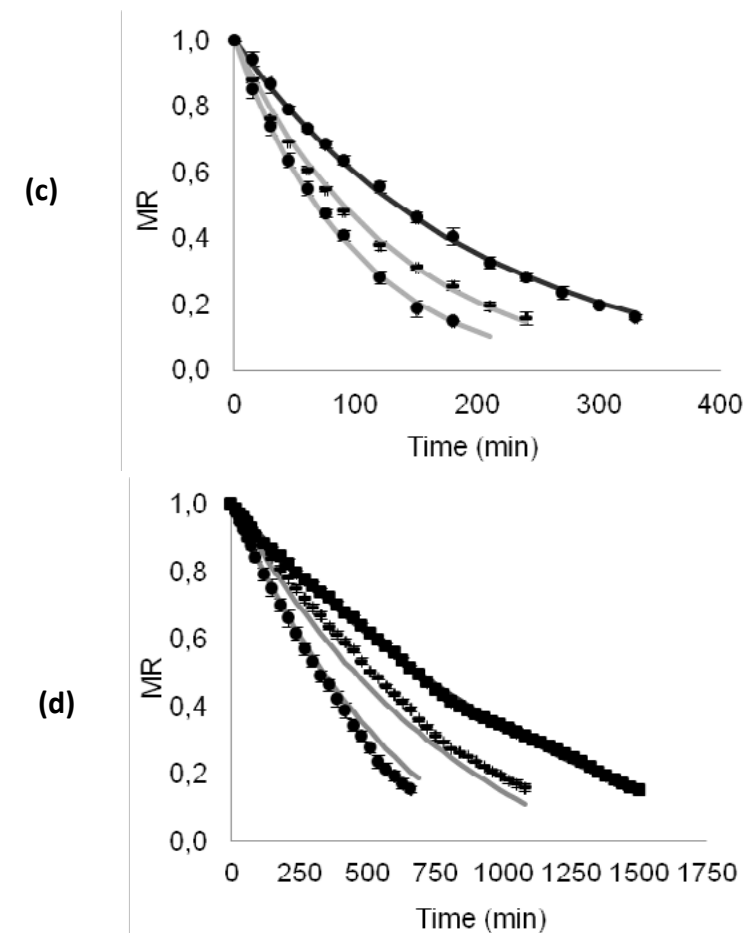


Figure 2c and 2d present the experimental and simulated kinetic data obtained in the laboratory-scale drier and the oven driers, respectively, for tomatoes cut in slices at 40, 50 and 60 °C. In a similar way that previous case, the lowest time was obtained for the temperature of 60 °C in the laboratory-scale drier, which was about 180 minutes. At 40 and 50 °C in the laboratory-scale drier the drying times were 330 and 240 minutes, respectively. In the oven with forced circulation of air, the drying time at 60 °C was 660 minutes.

Several authors reported different drying times for tomato cut in four parts and slices, because the time required to reduce the moisture ratio to any given level is dependent on the drying condition. Sanjinez-Argandoña et al., (2011) studying the influence of geometry and drying temperature on the kinetics of tomato cut in four parts and halves, using tray-drier, at temperature of 60 and 70 °C, showed that the samples reaching equilibrium after 16.5 hours to process. However, the authors observed that to obtain a product with final moisture content of 45%, the drying times to 60 and 70 °C were 12.5 hours and 10 hours, respectively. While, Romero-Peña; Kieckbusch (2003) using a tray-drier to dry sliced tomato and obtained drying time of 250 and 150 minutes at temperatures of 60 and 80 °C, respectively. And Demiray; Tulek (2012) studying about the thin-layer drying tomato slices in a convective hot air dryer obtained drying time of 1.200, 840, 720, 600 and 480 min at temperature 60, 70, 80, 90 and 100_°C, respectively, to achieve a final moisture ratio of 10 % (w.b.).

Figure 2 - Experimental and predicted convective drying kinetics of the tomatoes for temperatures of (■) 40 °C, (-) 50 °C and (●) 60 °C dried in laboratory-scale drier and sliced (c), dried in convective oven drier and sliced (d). The lines represent the mathematical model fit the data (—) 40 °C, (—) 50 °C and (—) 60 °C.



The main factors that affect the drying time are the physical-chemical properties of material, the geometrical arrangement of the product to the surface heat transfer, velocity and temperature of the air, characteristics of drier and previous treatment to drying (DOYMAZ, 2007; HEREDIA; BARRERA; ANDRÉS, 2007; MURATORE et al., 2008; SANJINEZ-ARGANDOÑA et al., 2011; DEMIRAY; TULEK, 2012). The lower drying time obtained in laboratory-scale drier, for both cuts, in relation to oven, may be due velocity, type of air flow drying and characteristics of drier. According Azoubel; Murr (2003) in study about drying kinetics of the tomatoes at temperature of 50 and 70 °C, with air velocity of 0.7 to 2.6 m s⁻¹, observed that to increase temperature and air velocity resulted in higher rates of moisture removal, reducing the drying time. Borges et al., (2010)

studying the drying of bananas by forced convection, at temperature of 50 and 70 °C and two velocities (0,14 e 0,42 m s⁻¹) verified that increased air velocity influences the drying of two banana varieties, in both formats, accelerating the drying.

As can be seen, the drying times for sliced tomato were always lower than those obtained for the cut in four parts at the same temperature for both, laboratory-scale drier and oven driers. This behavior can be attributed to larger contact area with the air flow and smaller thickness (1 cm) of sliced tomatoes, which may have facilitated the mass and heat transfer. According Sanjinez-Argandoña et al., (2011), the drying tomato, cut in four parts, was the process that showed the highest drying rate at both temperatures compared to tomato halved. Borges et al., (2010) studying the drying of bananas by forced convection, at temperature of 50 and 70 °C, cut in cylinder and disk, observed that the disk format resulted in higher drying rates in both temperatures, due to its larger contact area with the hot air flow.

In addition, the increase of temperature from 40 to 60°C decreases the drying time, since results in a faster evaporation of water from the solids, favoring the drying rate, ie there is greater heat transfer and mass. Several authors reported that drying rates increased with the increase in temperature for drying (NAGLE et al., 2008; KAYA; AYDIN; DINCER, 2008; BORGES et al., 2010; SANJINEZ-ARGANDOÑA et al., 2011; CRUZ; BRAGA; GRANDI, 2012). Cruz; Braga; Grandi (2012) studying the drying tomatoes, halved, in a experimental convective fixed bed dryer, with air velocity of 0.5 m s⁻¹, at temperature of 55, 65, 75 and 85 °C obtained drying time approximately 28, 23, 20 and 18 h, respectively, in order to obtain final moisture content of 64%. These drying times were higher than those found in this study.

Experimental data of Figure 1b were used to select the most appropriated model to simulate the drying kinetics. Table 2 shows the values of R² and c² for the 10 models evaluated in this work. From these results, it is observed that the best kinetic model to represent the drying process of tomato is the model 6 described in Table 1 (TOGRUL; PEHLIVAN, 2002), since it showed the highest R² and lowest value of c². Thus, this model was considered in the development of other stages of work. This model is a modification of the exponential or logarithmic model, based on Newton's Law (LEWIS, 1921), with inclusion of a second coefficient, known as Single Exponential Model of three parameters or Logarithmic model

(CARLESSO et al., 2007). Thus, this model has been used by several researchers in studies of drying agricultural products (HENDERSON, 1974; YALDIZ et al., 2001; MIDILLI et al., 2002; TOGRUL e PEHLIVAN, 2002; WANG et al., 2007; MAZUTTI et al., 2010; PURKAYASTHA et al., 2011).

Table 2 - Statistical results of the 10 models for the kinetic drying of tomatoes cut in four parts at temperatures of 40, 50 and 60 °C

| Model number | R ² | c ² |
|--------------|----------------|-----------------------|
| 1 | 0.9895 | 7.20x10 ⁻⁴ |
| 2 | 0.9900 | 6.96x10 ⁻⁴ |
| 3 | 0.9925 | 5.26x10 ⁻⁴ |
| 4 | 0.9907 | 6.48x10 ⁻⁴ |
| 5 | 0.9909 | 6.51x10 ⁻⁴ |
| 6 | 0.9929 | 4.96x10 ⁻⁴ |
| 7 | 0.9909 | 6.47x10 ⁻⁴ |
| 8 | 0.9905 | 5.57x10 ⁻⁴ |
| 9 | 0.9909 | 6.61x10 ⁻⁴ |
| 10 | 0.9665 | 2.44x10 ⁻³ |

Based on the results of Table 2, the parameters of Eq. 6 were estimated for each system for a temperature range from 40 to 60 °C. Eq. 8a and 8b are related to the drying of tomatoes cut in four parts using the laboratory-scale drier:

$$MR = 0.874220 \times \exp(-k \times t) - 0.097508 \quad (8a)$$

where

$$k = -0.002890 + 0.000136 \times T \quad (8b)$$

The Eq. 9a and 9b are related to the drying of tomatoes cut in four parts using the oven convective drier:

$$MR = 1.15458 \times \exp(-k \times t) - 0.151477 \quad (9a)$$

where

$$k = -0.001236 + 0.000047 \times T \quad (9b)$$

Eq. 10a and 10b are related to the drying of tomatoes cut in slices using the laboratory-scale drier:

$$MR = 1.0221 \times \exp(-k \times t) - 0.0241 \quad (10a)$$

where

$$k = -0.004923 + 0.000248 \times T \quad (10b)$$

The Eq. 11a and 11b are related to the drying of tomatoes cut in four parts using the oven convective drier.

$$MR = 1.2938 \times \exp(-k \times t) - 0.2861 \quad (11a)$$

where

$$k = -0.000755 + 0.000037 \times T \quad (11b)$$

In all equations above (9-11) T = temperature (°C), t = time (min) and k = drying rate constant (min⁻¹).

The analysis of variance (ANOVA) was used to validate the model, where was verified that all models are valid, since the calculated F values were several times higher than the tabled one (data not shown). The regression coefficients obtained for models concerning to the drying of tomatoes cut in four parts using laboratory-scale drier and convective air circulation oven were 0.9920 and 0.9929, respectively, whereas for the sliced tomatoes the regression coefficient were 0.9981 and 0.9897, respectively, showing that their predictions are reliable. In addition to the statistical analysis showing the models reliability it is seen from Figure 1 and Figure 2 a good agreement between calculated and experimental data. This result shows that the use of global kinetic models is an alternative to predict the drying profiles at different temperature those used during the estimation of parameters, making the model really an interesting tool to be used during the kinetic evaluation of process within of the temperature range evaluated.

Several authors use different mathematical models to describe the behavior of the drying process. For example, Purkayastha et al., (2011) in study about drying characteristics of blanched tomato slices, in hot air convective in order to select a suitable form of the drying curve, six different thin layer drying models were fitted to the experimental data. The goodness of fit tests indicated that the Logarithmic model gave the best fit to experimental results, as in this study. Differently, Sanjinez-Argandoña et al., (2011) used the Page model to describe the drying kinetics of tomatoes and observed that the mathematical model provided good fit in all test conditions.

2. Determination of effective diffusivities

Table 3 presents the values of effective diffusivities (D_{eff}) obtained for the tomatoes sliced and cut in four parts for temperature ranging from 40 to 60 °C in both systems convective laboratory-scale drier and oven drier.

Table 3- Values of effective diffusivities (m² s⁻¹) obtained from different drying conditions

| Temperature (°C) | Tomato quarters | | Tomato slices | |
|------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| | laboratory-scale drier | Oven | laboratory-scale drier | Oven |
| 40 | 2.746 x 10 ⁻⁹ | 0.950 x 10 ⁻⁹ | 0.929 x 10 ⁻⁹ | 0.202 x 10 ⁻⁹ |
| 50 | 3.803 x 10 ⁻⁹ | 1.479 x 10 ⁻⁹ | 1.284 x 10 ⁻⁹ | 0.287 x 10 ⁻⁹ |
| 60 | 5.920 x 10 ⁻⁹ | 2.429 x 10 ⁻⁹ | 1.830 x 10 ⁻⁹ | 0.473 x 10 ⁻⁹ |

The effective diffusivities for the tomatoes cut in four parts and dried in the convective laboratory-scale drier ranged from 2.75 x 10⁻⁹ m² s⁻¹ to 5.92 x 10⁻⁹ m² s⁻¹, whereas for the samples dried in the oven convective drier the values ranged from 0.950 x 10⁻⁹ m² s⁻¹ to 2.43 x 10⁻⁹ m² s⁻¹, for temperature ranging from 40 to 60 °C, respectively. For the tomatoes sliced and dried in the convective laboratory-scale drier the effective diffusivities ranged from 0.929 x 10⁻⁹ m² s⁻¹ to 1.83 x 10⁻⁹ m² s⁻¹, whereas for the samples dried in the oven convective drier the values ranged from 0.202 x 10⁻⁹ m² s⁻¹ to 0.473 x 10⁻⁹ m² s⁻¹, for temperature ranging from 40 to 60 °C, respectively.

The values of D_{eff} obtained in the laboratory-scale drier, in both cuts, were always higher than those obtained in the convective oven-drier, indicating that the air velocity increase the rate of water evaporation from sample. In addition, the D_{eff} showed higher values with increasing temperature used in all experiments studied. The effective diffusivity it is not intrinsic to the material and is affected by temperature, air velocity and surface area of thermal exchange. The data concerning the effective diffusivities of dried samples of tomato obtained in this study are in accordance with those reported in the literature (DOYMAZ, 2007; SACILIK, 2007). The values of D_{eff} increased with temperature in all experiments, which is in accordance with other studies. Doymaz (2007) reported values of D_{eff} ranging from 5.65 x 10⁻¹⁰ to 7.53 x 10⁻¹⁰ m² s⁻¹ for samples pre-treated with ethyl oleate and in the range 3.91 x 10⁻¹⁰ to 6.65 x 10⁻¹⁰ m² s⁻¹ for the non-treated ones for temperature ranging from 55 to 70 °C. Akanbi; Adeyeme; Ojo, (2006) verified values of D_{eff} in the range 3.72 x 10⁻⁹ to 1.23 x 10⁻⁸ m² s⁻¹ during drying tomatoes for temperature ranging from 45 to 75 °C. Purkayastha et al., (2011) in study about drying of tomato slices in hot air convective, reported values of D_{eff}

varied from 0.5453×10^{-9} to $2.3871 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$ for temperature range for 50-70 °C Demiray; Tulek (2012) observed the effective moisture, of tomato slices dried in a convective hot air dryer varied from 1.015×10^{-9} to $2.650 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$ over the temperature range studied.

3. Color

Table 4 presents the data concerning the color parameters obtained during the drying of tomatoes cut in four parts in both systems, laboratory-scale and convective oven driers.

Table 4 - Color parameters in terms of luminance (L*) and red saturation index (a*) measured before and after the drying of the tomatoes cut in four parts obtained from different drying conditions

| Dryer | Time | L* | | | a* | | |
|------------------------|---------|------------------|-------------|--------------|-------------|-------------|-------------|
| | | Temperature (°C) | | | | | |
| | | 40 | 50 | 60 | 40 | 50 | 60 |
| Laboratory-scale drier | initial | 44.25±1.32a | 44.09±7.27a | 45.11±4.31a | 18.13±4.83a | 18.20±2.15b | 13.93±2.59b |
| | end | 42.77±6.11a | 43.96±4.35a | 43.73±3.93a | 21.57±3.64a | 22.94±1.65a | 24.80±2.18a |
| | D | -1.48 | -0.13 | -1.38 | 3.44 | 4.74 | 10.87 |
| Oven | initial | 43.01±0.29a | 44.72±1.22a | 48.01±12.00a | 15.12±2.80a | 14.14±3.56a | 12.55±2.64a |
| | end | 39.66±0.63b | 41.04±0.89b | 45.82±2.95a | 17.09±3.01a | 18.33±5.70a | 17.17±4.75a |
| | D | -3.36 | -3.68 | -2.19 | 1.97 | 4.20 | 4.62 |

Different letters in the same column represent a significant difference at 95% (p<0.05 - Tukey test).

The data are presented in terms of luminance (L*) and red saturation index (a*) measured before and after the drying. The results also are expressed in terms of percent of variation during the drying. L* did not presented significant reduction after the drying in laboratory-scale drier for all temperatures, since ΔL^* were -1.48, -0.13 and -1.38 for temperatures of 40, 50 and 60 °C, respectively. However, for tomatoes dried in the convective oven drier was obtained significant, reduction in the L* values, except for a temperature of 60 °C, since ΔL^* were -3.36, -3.68 and -2.19 for temperatures of 40, 50 and 60 °C, respectively. The reduction of parameter L* indicates the darkening of the sample, where it is possible to associate the drying time with the darkening (RAUPP et al., 2007). By example, the samples dried in laboratory-scale drier presented a lower drying time than the samples dried in the convective oven drier. This could be verified for the data obtained in the convective oven drier, since the increase of temperature from 50 to 60 °C decreases the darkening of sample, probably due to the fact that at 60°C the drying time is lower than at 50 °C. In addition, may have occurred the action of polyphenol oxidases and peroxidases enzymes in samples of tomatoes, since the 30-50 °C is the optimum temperature of activity of these enzymes (JANG; MOON, 2011).

The values of parameter a* obtained show a tendency in increase the red saturation index with temperature in both system, although the intensification of a* was significant higher for the samples dried in laboratory-scale drier, at temperature 50 and 60 °C (Table 4).

Table 5 presents the data concerning the color parameters obtained during the drying of sliced tomatoes in both systems, laboratory-scale and convective oven driers.

Table 5 - Color parameters in terms of luminance (L*) and red saturation index (a*) measured before and after the drying of the tomatoes sliced obtained from different drying conditions

| Dryer | Time | L* | | | a* | | |
|------------------------|---------|------------------|-------------|-------------|-------------|-------------|-------------|
| | | Temperature (°C) | | | | | |
| | | 40 | 50 | 60 | 40 | 50 | 60 |
| Laboratory-scale drier | initial | 43.93±1.38a | 46.69±2.36a | 39.71±2.40a | 18.43±0.95a | 20.31±0.90b | 20.10±2.23b |
| | end | 48.91±2.31a | 45.80±4.59a | 41.20±1.34a | 18.56±2.27a | 23.27±1.48a | 25.48±1.62a |
| | D | 4.98 | -0.89 | 1.48 | 0.14 | 2.96 | 5.38 |
| Oven | initial | 49.02±5.08a | 43.87±3.46a | 40.50±1.67a | 18.67±1.66a | 17.59±0.68a | 14.78±2.07a |
| | end | 39.27±1.8b | 42.84±5.9a | 39.52±1.48a | 21.11±2.17a | 19.00±0.86a | 17.26±0.25a |
| | D | -9.75 | -1.03 | -0.97 | 2.44 | 1.42 | 2.48 |

Different letters in the same column represent a significant difference at 95% (p<0.05 - Tukey test).

The data were presented in a similar way as above. In a similar way, L^* did not presented significant reduction after the drying in laboratory-scale drier for all temperatures. However, for tomatoes dried in the convective oven drier was obtained significant reduction in the L^* values, for tomatoes dried at 40 °C. This result corroborates with the hypothesis pointed out above, where the drying time has strong influence on the darkening of the sample. In Table 5 is clearly demonstrated that at 40 °C is obtained the highest values of variation of ΔL^* , where this variation is higher in convective oven drier than in laboratory-scale drier. In a similar way of the tomatoes cut in four parts, the values of parameter a^* to slices tomatoes showed the tendency to increase the red saturation index with temperature, mainly for the samples dried in the laboratory-scale drier, in which the intensification of a^* was significant higher for the samples dried at temperature 50 and 60 °C (Table 5). Muratore et al., (2008) verified to increase the red color of tomatoes after the drying, since the values of a^* increased with the temperature.

The darkening observed in the dried tomatoes could be associated to Maillard reaction, ascorbic acid oxidation, hexose condensation and amine compounds, which result in the formation of brown pigments as high as the contact with drying air, in addition to possible action of polyphenol oxidase and peroxidase enzymes (MARFIL; SANTOS; TELIS, 2008; JANG; MOON, 2011). Sacilik (2007) verified reduction in the values of L^* and a^* increasing the drying temperature from 50 to 60 °C for treated and non-treated samples, indicating that the tomato color is maintained only at low temperatures. Similarly Cruz; Braga; Grandi (2012) observed to increase in the darkening with to increase temperature of tomato drying.

The red pigment of tomato is due to the presence of lycopene. When the lycopene is found dissolved in solvents as is the case of fresh tomato (high water content) its color is red with low intensity or orange. However, with thermal treatment can occur the isomerization of lycopene to *cis* and *trans* forms, where the *cis* form present a color red more intense (DEMIRAY; TULEK; YILMAZ, 2013). Increased tomato lycopene also occurs due to greater release of cellular matrix when the fruits are submitted to heat (TOOR; SAVAGE, 2006). Cruz; Braga; Grandi (2012) verified increase in the lycopene content with increasing drying temperature. Lycopene content increases due to the thermal treatment also were observed by others (HEREDIA et al., 2010; PURKAYASTHA et al., 2011).

However, certain limits of processing temperatures to be considered, above which degradation reactions may occur (PURKAYASTHA et al., 2011). Demiray; Tulek; Yilmaz (2013) also observed a decrease of the lycopene content during tomato drying at temperatures between 60 and 100 °C. Purkayastha et al., (2011) observed that slices tomato dried at 50 and 60 °C had high amount of L^* and a^* values. Drying of slices at 50 °C revealed optimum retention red hue, whereas, drying at higher temperature (65 and 70 °C) resulted in a considerable decrease colour quality of the slices. In addition, these authors observed increased lycopene content with increasing the drying temperature of 50 to 60 °C and reduction with increase of 65 to 70 °C.

This work evaluated the influence of temperature on drying kinetics and color of Italian tomato using different dehydration strategies based on laboratory-scale drier and convective oven drier. It was evaluated the drying kinetics of tomatoes sliced and cut in four parts using a convective laboratory-scale dryer and an oven with forced air circulation. In addition, was presented the mathematical modeling of drying curves and the determination of effective diffusivity. It was verified that tomatoes dried in the laboratory-scale drier presented lower drying time than those dried in convective oven drier. In addition, the drying time of sliced tomatoes were lower than cut in four parts. The proposed drying model presented a satisfactory fitting of the experimental data, showing that the use of global kinetic models is an alternative to predict the drying profiles at different temperature those used during the estimation of parameters. It was verified that D_{eff} for tomatoes, convective laboratory-scale drier were higher than for oven convective drier, in both cuts. Related to the color, it was verified that the drying time has strong influence on the darkening of the sample. However, the darkening of sample was more intense for samples dried in the convective oven drier. Related to the red saturation index it was verified the tendency to increase its value with the temperature in both system, although the intensification was higher for the samples dried laboratory-scale drier. Therefore, the convective drying in a dryer on the laboratory scale showed the lowest drying time, higher values of effective diffusivity, low browning and further intensification of the red color indicating that this method technologically feasible, since it presents better quality of final product at lower drying times. The tomato cut in four parts showed characteristics of final product similar to those sliced tomatoes. However, the slices tomato dried at temperature of 60 °C showed less drying time.

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