



## KINETICS AND EXERGY ANALYSES OF THE DRYING OF THE POBLANO HOT PEPPER (*CAPSICUM ANNUUM*), IN FORCED CONVECTION

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### Abstract

In this work we present the numerical modeling of the kinetics of the drying of the Poblano hot pepper using a hot-air drier with forced convection. The velocity of air was 3.0 m/s and the temperatures were maintained at 40, 50, and 60 °C. The corresponding drying times for 40, 50, 60 °C were 95, 75, and 50 hours, respectively. The numerical model that more accurately describes the process was logarithmic; the criteria applied were the value of  $r^2$  close to the unity and that of  $\chi^2$  tending to zero. The appearance of the product was determined through the change in color hue, originally dark green, which at the end of the process turned to very dark brown, almost black. The change in color was registered using the Hunter's method, the initial values corresponded to dark green and the final color was black. The total change in color and chroma were almost the same for the three conditions studied.

The effective moisture diffusivity was between  $7.1 \times 10^{-10}$  and  $5.7 \times 10^{-11}$  m<sup>2</sup>/s. The exergetic efficiency of the drying chamber was as 28.75 % at drying air temperature of 40 °C, 24.70 % at drying air temperature of 50 °C, and 19.09 % at 60 °C.

**Keywords:** *Capsicum annuum*, Poblano hot pepper, convective drying, experimental drying, exergetic efficiency.

### 1. Introduction

The Poblano hot pepper (*Capsicum annuum*), is a widely-used vegetable, greatly appreciated in the Mexican gastronomy, both in its fresh state and as a dried product; the production in Mexico is approximately 400 000 tons per year, SIAP, (2004).

The best-quality Poblano hot pepper is quite big, over 12 cm in length and 8 cm wide, with a conical shape and a well-defined crevice running along its whole length. It has got thick and sometimes undulating walls, which gives it varied forms in its ripe state. Its taste is not very hot, with a strong and agreeable scent. There are three types of fresh Poblano hot pepper: green, blackish and heart-shaped. The one with the highest production and most popular in the market is the green Poblano. When dehydrated, the green Poblano hot pepper is better known as "Ancho" or "Mulato" hot pepper. This is one of the main ingredients of the mole, a characteristic hot sauce in Mexican cuisine. Its color is dark brown, almost black. Ancho hot pepper is a rich and important source of C vitamin and together with the essential amino acids supplied by corn tortillas and beans, sometimes supplemented with meat and poultry, constitutes the staple diet in Mexico. The most important production zones of Poblano hot pepper are the semi-arid valleys in the central region of Mexico, located in the states of Tlaxcala, Guanajuato, San Luis Potosi, Durango, Aguascalientes, and Zacatecas, Labore and Pozo, (1982).

Many mathematical modeling and experimental studies have been conducted on pepper drying processes, Tundle et al., (2005), experimented with bell pepper, using solar and artificial air drying methods. Condorí et al., (2001), studied the solar drying process of sweet pepper using a greenhouse-tunnel drier. The dehydration kinetics of sweet pepper, of both bleached and unbleached varieties, were investigated at drying air temperatures of 40–70 °C with increments of 5 °C and constant air velocity of 1.5 m/s [5]. Yaldiz and Ertekin, (2001), determined the drying parameters of green pepper using a solar cabinet. Kaymak-Ertekin, (2002), developed a model describing the drying mechanism of green and red peppers and investigated the effects of process variables such as air velocity and temperature with various pre-treatments. Akpınar et al., (2003), investigated the thin layer drying behavior of red pepper slices in a convective-type dryer and performed mathematical modeling using thin layer drying models. All these studies focus on the sliced product.

In this work, we present the analysis of the drying process of the Poblano hot pepper (*Capsicum annuum*), using a drying tunnel that operates with hot air in forced convection. It is of interest to study the behavior of the drying process applied to the complete pepper (not sliced), because traditionally the product is used in this form in the Mexican cuisine. The velocity of air was 3.0 m/s and the temperatures were maintained at 40, 50, and 60 °C. A numeric model that describes the drying process and also the characteristic drying curve of the product are obtained.

## 2. Material and Methods

### 2.1 Drying kinetics of poblano hot pepper

The moisture ratio was calculated using  $MR = (M_t - M_e)/(M_0 - M_e)$ , which has been simplified to  $M_t/M_0$  by some authors, Kaymak-Ertekin, (2002), Verna, et al., (1985), Mujundar, (1987), Jayas et al., (1991), Ozdemir, and Devres, (1999), and Togrul and Pehlivan, (2002).

The model developed by Page (1949), has been widely used to describe the drying characteristics of various fruits and vegetables. The model is given as,

$$MR = \exp(-kt^n) \quad (1)$$

Where MR is moisture ratio (dimensionless), k is drying rate constant (min<sup>-1</sup>), and n is the model constant.

The correlation coefficient ( $r$ ), the reduced chi-square ( $\chi^2$ ), and the root mean square error (RMSE) were used as criteria for adequacy of the fit. The lower the values of the reduced  $\chi^2$ , the better is the goodness of the fit. The RMSE

gives the deviation between the predicted and experimental values, and it is required to approach zero. These statistical analysis values can be calculated as follow,

$$\chi^2 = \frac{\sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2}{N - n} \quad (2)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2}{N}} \quad (3)$$

where  $MR_{exp,i}$  represents the experimental moisture ratio found in any measurement;  $MR_{pre,i}$  is the predicted moisture ratio for this measurement; and  $MR_{exp,mean}$  is the mean value of the experimental moisture ratio.  $N$  and  $n$  are the number of observations and the number of constants, respectively, Yaldiz and Ertekin (2001). According with these points, the logarithmic model was the best for the Poblano hot pepper, Togrul and Pehlivan D. (2004), this is,

$$MR = a \exp(-kt) + c \quad (4)$$

$a$  and  $c$  are constants.

## 2.2 Effective diffusion

The mechanism of moisture movement within a hygroscopic solid can be represented with the effective moisture diffusion. During the drying process, diffusivity is assumed to be the only physical mechanism involved in the transfer of water to material surface and can be defined by Fick's second law of diffusion for a small piece as follows, Crank, (1975),

$$\frac{\partial M}{\partial t} = D_{eff} \frac{\partial^2 M}{\partial x^2} \quad (5)$$

Assuming a symmetric mass transfer with respect to the center, a constant diffusion coefficient and no shrinkage, the effective moisture diffusivity of water in Poblano hot pepper was estimated from the change of moisture as a function of drying time, using modified Crank's equation as shown in the following equation, Singh, and Heldman, (2001):

$$MR = \frac{M_t - M_e}{M_o - M_e} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)} \exp\left(-\frac{(2n+1)D_{eff}\pi^2}{4L^2} t\right) \quad (6)$$

If we consider that only the first term of the series is significant, and if the equilibrium moisture content can be assumed 0 for the drying process [Kaymak-Ertekin, (2002) and Akpinar et al., (2003)], MR can be rearranged as,

$$MR = \frac{M_t}{M_o} = \frac{8}{\pi^2} \exp\left(-\frac{D_{eff}\pi^2}{4L^2} t\right) \quad (7)$$

Effective moisture diffusivity,  $D_{eff}$ , can be determined by plotting the experimental data of  $\ln(MR)$  versus time,  $t$ .

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

## 2.3 Color measurements

During the drying process, color measurements ( $L, a, b$ ) were performed with a Color Tec colorimeter (PCM/PSM Model, with a 20-mm sensor) in a room with controlled light. The Poblano hot pepper samples were scanned at four different locations to determine the average  $L, a$ , and  $b$  values during the measurements. In addition, the total color change  $\Delta E$  (Eq. (9)), and *chroma* (Eq. (10)), were calculated from the Hunter's  $L, a, b$  scale and used to describe the color change during drying;

$$\Delta E = \sqrt{(L_o - L_t)^2 + (a_o - a_t)^2 + (b_o - b_t)^2} \quad (9)$$

where  $L_o, a_o$  and  $b_o$  are initial values and  $L_t, a_t$  and  $b_t$  are the values at the time  $t$ , and

$$\text{Chroma} = \sqrt{a_t^2 + b_t^2} \quad (10)$$

## 2.4 Exergy analysis

The second law of thermodynamics includes the useful concept of exergy in the analysis of thermal systems. As known, exergy analysis evaluates the available energy at different points in a system. Exergy is a measurement of the quality or grade of energy and it can be destroyed in the thermal system. The second law states that part of the exergy entering a thermal system with fuel, electricity, flowing streams of matter, or other sources is destroyed within the system due to irreversibilities. The second law of thermodynamics uses an exergy balance for the analysis and the design of thermal systems. In the scope of the second law analysis of thermodynamics, total exergy of inflow, outflow, and losses of the drying chamber were estimated. The basic procedure for exergy analysis of the chamber implies the determination of the exergy values at steady-state points and the reason of exergy variation for the process. The exergy values are calculated by using the characteristics of the working medium from a first law energy balance. For this purpose, the mathematical formulations used to carry out the exergy balance are as show below, Ahern, (1980).

$$Ex = (u - u_{\infty}) + T_{\infty}(s - s_{\infty}) + \frac{P_{\infty}}{j}(v - v_{\infty}) + \frac{v^2}{2g_j} + (z - z_{\infty}) \frac{g}{g_c} \quad (11)$$

$$\sum_c (\mu_c - \mu_{\infty}) N_c + E_i A_i F_i (3T_{\infty}^3 - T_c^4 - 4T_{\infty} T_c^3 + \dots$$

The subscript  $\infty$  denotes the reference conditions. In the exergy analyses of many systems, only some of the terms shown in Eq. (11) are used but not all. Since exergy is energy available from any source, it can be developed using electrical current flow, magnetic fields, and diffusion flow of materials. One common simplification is to substitute enthalpy for the internal energy and  $PV$  terms that are applicable for steady-flow systems. Eq. (11) is often used under conditions where the gravitational and momentum terms are neglected. In addition to these, the pressure changes in the system are also neglected because of  $v \cong v_{\infty}$ , hence Eq. (11) is reduced as

$$Ex = \bar{C}_p \left[ (T - T_{\infty}) - T_{\infty} \ln \frac{T}{T_{\infty}} \right] \quad (12)$$

The inflow and outflow of exergy can be found using the above expression depending on the inlet and outlet temperatures of the drying chamber. Hence, the exergy loss is determined as, **Exergy loss = Exergy inflow – Exergy outflow**, this is,

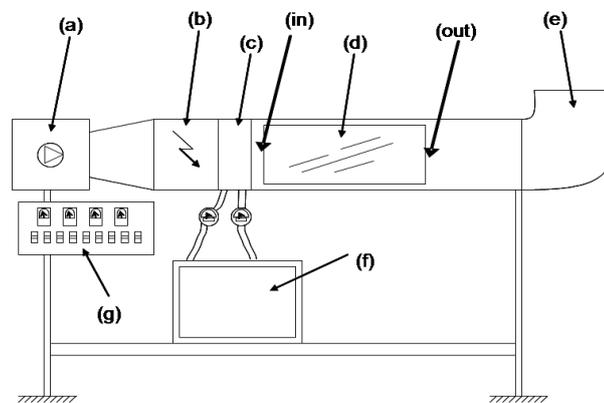
$$\sum Ex_L = \sum Ex_i - \sum Ex_o \quad (13)$$

The exergetic efficiency can be defined as the ratio of the product exergy to exergy inflow for the chamber as outlined below:

$$\eta_{Ex} = \frac{Ex_i - Ex_L}{Ex_i} = 1 - \frac{Ex_L}{Ex_i} \quad (14)$$

### 2.5 Experimental apparatus

The scheme of the drying tunnel used in this study is presented in Fig. 1. Air is conducted by means of a radial-flow fan, controlled by a variable-speed motor, a panel of electrical resistances; and an air conditioning system allows the control of the internal temperature. The test chamber is 20-cm wide x 20-cm high and 40-cm long; the air exhaust is a vertical chimney.



**Fig. 1.** Drying tunnel, a) variable-speed fan; b) electrical resistances; c) air conditioner; d) testing chamber, e) air exhaust; f) air-conditioning system, y g) controlling system

### 2.6 Instrumentation and measurement

Air and product-surface temperatures were measured using calibrated K-type thermo-pairs (0.5 °C exactitude); the relative humidity of the environment was determined using an EA25 EXTECH digital hygro-thermometer, with 0.1 % resolution. A 451112 EXTECH anemometer (0.1 m/s resolution) was used to measure the velocity of air. Mass was quantified using a BL1505 SARTORIUS balance, with a 0.001 g scale. Data acquisition was programmed using LABVIEW software.

### 2.7 Experimental procedure

Poblano hot pepper samples were bought from Tlaxcala State, the largest production site in Mexico. They were thoroughly washed with tap water, with a final rinse of DI water, and preserved under refrigeration at 4 °C. They were brought to room temperature before the drying tests.

The fan velocity was adjusted to reach 3 m/s in the testing section. The electrical resistances were operated to raise the surface temperature of the probes up to 40, 50, and 60 °C. Mass, air temperature, probe-surface temperature, and relative humidity were automatically monitored and registered in a computer. Four complete samples were evaluated in each temperature, in a total of twelve tests.

The initial humidity contents of the samples was gravimetrically determined, using a stove at 105 °C, where approximately 20 g pieces were kept for about 4 hours and cooled in a desiccator to constant weight.

### 2.8 Experimental uncertainty

Errors and uncertainties in the experiments can change from instrument selection, condition, calibration, environment, observation, and reading, and, of course test planning. In drying experiments of the Poblano hot pepper, the temperatures, velocity of drying air, weight losses were measured with appropriate instruments.

The result,  $R$ , is a given function in terms of the independent variables. Let  $w_R$  be the uncertainty in the result and  $w_1, w_2, w_3, \dots, w_n$  be the uncertainties in the independent variables. If the uncertainties in the independent variables are all given with the same odds, then the uncertainty in the result having these odds is given as, Holman, (2000):

$$w_R = \left[ \left( \frac{\partial R}{\partial x_1} w_1 \right)^2 + \left( \frac{\partial R}{\partial x_2} w_2 \right)^2 + \dots + \left( \frac{\partial R}{\partial x_n} w_n \right)^2 \right]^{1/2}$$

The total uncertainty in the measurement of the temperatures of the drying chamber inlet ( $w_{T_i}$ ), drying chamber outlet ( $w_{T_o}$ ), the probe ( $w_{T_p}$ ), and the ambient ( $w_{T_a}$ ) can arise from the thermocouples, Adam module, connection

points, and readings in the computer. The total uncertainty in the measurement of these temperature values may be calculated as follows:

$$w_{Ti} = w_{To} = w_{Tp} = w_{To}$$

$$w_{Ti} = \left[ \begin{array}{l} (w_{thermocouples})^2 + (w_{Adam})^2 + \\ (w_{connection\ point})^2 + (w_{computer\ register})^2 \end{array} \right]^{1/2}$$

$$w_{Ti} = [(0.15)^2 + (0.1)^2 + (0.1)^2 + (0.001)^2] = 0.21$$

The total uncertainty in the measurement of the time of the temperature values ( $w_{tT}$ ) and the time of the mass loss values can result from oscillation of the time meter and the computer register. The total uncertainty in the measurement of the time of the temperature and mass loss values may be calculated as follows:

$$w_{tT} = [(w_{oscillation})^2 + (w_{computer\ register})^2]^{1/2}$$

$$w_{tT} = [(0.0003)^2 + (0.001)^2] = 0.001$$

The total uncertainty in the measurement of the mass loss ( $w_{ml}$ ) can arise from the digital balance and the computer register. The total uncertainty in the measurement of mass loss may be calculated as follows:

$$w_{ml} = [(w_{digital\ balance})^2 + (w_{computer\ register})^2]^{1/2}$$

$$w_{ml} = [(0.01)^2 + (0.001)^2] = 0.1$$

The total uncertainty in the measurement of the air velocity ( $w_v$ ) can arise from the anemometer, its reading and its air leakage. The total uncertainty in the measurement of air velocity may be calculated as follows:

$$w_v = [(w_{anemometer})^2 + (w_{computer\ register})^2]^{1/2}$$

$$w_v = [(0.1)^2 + (0.001)^2] = 0.1$$

The total uncertainty in the measurement of the relative humidity of the air ( $w_\phi$ ) can result from the moisture analyzer and its reading. This uncertainty may be calculated as follows:

$$w_\phi = [(w_{moisture\ analyzer})^2 + (w_{computer\ register})^2]^{1/2}$$

$$w_\phi = [(0.1)^2 + (0.001)^2] = 0.1$$

The total uncertainties of the measured parameters during the experiments are presented in Table 1.

Table 1 Uncertainties of the parameters during experiment of the Poblano hot pepper.

| Parameter (unit)  | Value |
|---|-------|
| Uncertainty in temperature measurement                                |       |
| Drying chamber inlet temperature, $w_{Ti}$ , (°C)                     | 0.21  |
| Drying chamber outlet temperature, $w_{To}$ , (°C)                    | 0.21  |
| Probe temperature, $w_{Tp}$ , (°C)                                    | 0.21  |
| Ambient air temperature, $w_{To}$ , (°C)                              | 0.21  |
| Uncertainty in time measurement of time values, $w_{tT}$ , (min)      | 0.001 |
| Uncertainty in time measurement of mass lost values, $w_{ml}$ , (min) | 0.001 |
| Uncertainty in mass lost measurement, $w_{ml}$ , (g)                  | 0.1   |
| Uncertainty in air velocity measurement, $w_v$ , (m/s)                | 0.1   |
| Uncertainty in measurement of relative humidity, $w_\phi$ , (%)       | 0.1   |

### 3. Results and Discussion

The initial humidity of the product varied between 84 and 92 %. The temperature of the air at the entrance of the test chamber was 42 °C and the exit temperature was 38.5 °C when the sample had a mean temperature of 40 °C at the surface; the drying time was 95 hours. The initial and final contents of humidity were in average, 10.26 and 0.069 kg water/kg dm, respectively.

For the sample with a temperature of 50 °C at the surface, the air entered at 53 °C and exited at 48 °C, the drying time was 75 hours. The initial and final contents of humidity were 10.86 and 0.14 kg water/kg dm, respectively. Finally, for the sample of hot pepper with a temperature of 60 °C at the surface, the air entered and exited at 63 and 59 °C, respectively. In this case the time was the shortest, 50 hours and the initial and final contents of humidity were 10.46 kg water/kg dm and 0.087 kg water/kg dm. The three plots showing these results are presented in Fig. 2.

The plots of the drying velocity versus the contents of water for the three temperatures are presented in Fig. 3. The highest value of the initial drying velocity corresponded to the temperature of 60 °C, and amounted to 4.26 kg water/kg dm h, the lowest value was registered for the temperature of 40 °C, i. e. 2.36 kg water/kg dm h. We also present the average plot considering the three values tested, resulting in 3.66 kg water/kg dm h for the initial velocity and 0.098 kg water/kg dm h for the final one.

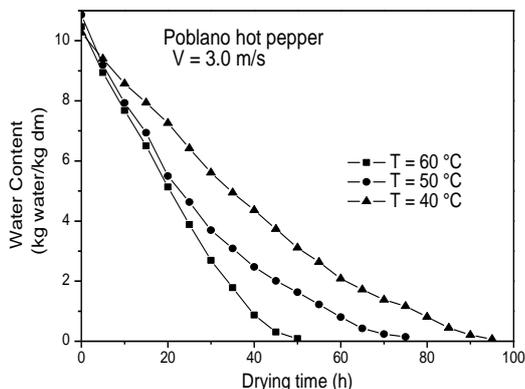


Fig. 2. Contents of humidity versus drying time for three temperatures of Poblano hot pepper; the velocity of air is 3 m/s.

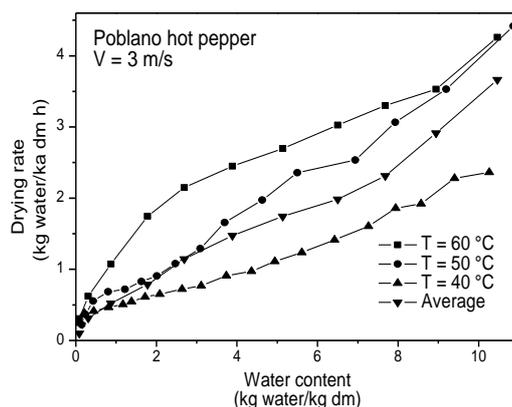


Fig. 3. Drying velocity versus water contents of Poblano hot pepper; the velocity of air is 3 m/s.

The equation that represents the average curve of the relationship of drying versus the contents of water is a third-grade polynomial curve, namely,

$$dM/dt = 0.0932 + 0.5323M - 0.0658M^2 + 0.0045M^3 \quad (15)$$

with  $r = 0.998$  and  $SD = 0.565$ .

The equation of the drying of the Poblano hot pepper is obtained by the dimensionless plot of the data in Fig. 3, obtained through the Marquardt-Levenberg’s non-linear optimization, is as follows

$$Y = 0.0211 + 1.3088 * X - 1.7594 * X^2 + 1.3243 * X^3 \quad (16)$$

with  $r = 0.998$  and  $SD = 0.0127$ , values that reflect good precision in the modeling of the physical phenomena.

This curve is known as “characteristic curve of drying” of the product [20], which is presented in Fig. 4, and defined as

$$f = \frac{\left(\frac{-dM}{dt}\right)}{\left(\frac{-dM}{dt}\right)_0} \quad (17)$$

where  $f$  is the dimensionless drying relationship. Thus, the characteristic curve of drying of the Poblano hot pepper, according to equation (17), is

$$f = 0.0211 + 1.3088MR - 1.7594MR^2 + 1.3243MR^3 \quad (18)$$

Similar results were obtained using heat pump drying techniques with green sweet pepper, Pal, et al., (2008).

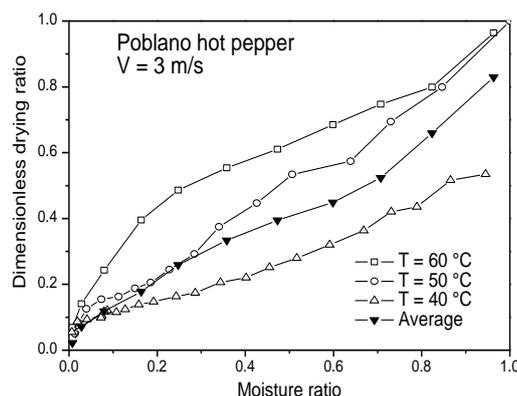


Fig. 4. Characteristic curve of drying of the Poblano hot pepper.

The Origin 7.0 software package was used to find the mathematical model that best represents the kinetics of drying of the Poblano hot pepper, applying the values of the relation of humidity, time of drying and the conditions established for  $r$ ,  $\chi^2$ , and  $RMSE$ .

For the temperature of 40 °C the initial and final humidity ratios were 0.89 and 0.006. The logarithmic mathematical model is the one that best represents the kinetics of the drying of the Poblano hot pepper ( $r = 0.998$ ,  $\chi^2 = 0.00017$  and  $RMSE = 0.0089$ ). The initial and final ratios of humidity at 50 °C were 0.87 and 0.011, respectively. Again, the best fit was obtained with a logarithmic model ( $r = 0.999$ ,  $\chi^2 = 0.00008$  and  $RMSE = 0.011$ ). Finally, for 60 °C, the ratio of initial humidity was 0.90 and for the final one was 0.0076. The mathematical model was also logarithmic with  $r = 0.998$ ,  $\chi^2 = 0.00043$ , and  $RMSE = 0.010$ . These curves are shown in Fig. 5.

The drying of hot peppers in their complete form, i. e. non-sliced, significantly influences the expected results. Most authors have worked with slices or small pieces of pepper and their results are somewhat different from ours. Akpinar et al., (2003), for example, separated the fleshy parts of peppers from their stems and seeds, and cut them into slices of 10 mm  $\pm$  0.3. For a temperature of 60 °C the drying time was 8 hours, with a velocity of air of 4 m/s. Condorí et al., (2001), who studied the solar drying of sweet pepper, found that the complete sweet pepper dried in 6.4 days, while by cutting it in its length, the drying time was reduced in approximately 4 days (requiring about 40 hours of solar energy). Our results are relevant because traditionally the Poblano hot pepper is commercialized and used in its complete form in Mexican cuisine.

The equations of the logarithmic mathematical model and the values of the restrictions for their selection are presented in table 2.

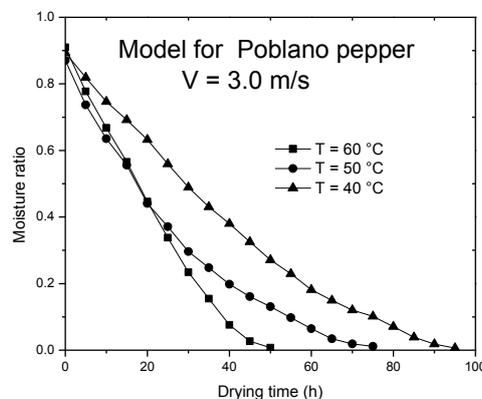


Fig. 5. Plot of the model of kinetics of drying for the Poblano hot pepper.

Table 2 Logarithmic model ( $MR = a \exp(-k t) + c$ ) for the kinetics of the drying of the Poblano hot pepper

| T °C | Equation  |
|------|---|
| 40   | $MR = 1.2719 \exp(-0.0136 t) - 0.361$<br>$r = 0.998, \chi^2 = 0.00017, RMSE = 0.0098$ |
| 50   | $MR = 0.9892 \exp(-0.0283 t) - 0.114$<br>$r = 0.999, \chi^2 = 0.00008, RMSE = 0.011$  |
| 60   | $MR = 1.5574 \exp(-0.0187 t) - 0.634$<br>$r = 0.998, \chi^2 = 0.00043, RMSE = 0.010$  |

Based on Fick's second law, effective moisture diffusivity was calculated from Eq. (8). For a temperature of 60 °C, the coefficient was  $7.1 \times 10^{-10}$  m<sup>2</sup>/s; at 50 °C the value was  $1.2 \times 10^{-11}$  m<sup>2</sup>/s, and finally at 40 °C it was  $5.7 \times 10^{-11}$  m<sup>2</sup>/s. These values are shown in Fig. 6.

These values are very small when compared to those reported in literature. For example, Kiranoudis et al., (1992) obtained the  $D_{eff}$  value of moisture for green pepper as  $8.9 \times 10^{-9}$  m<sup>2</sup>/s at a drying temperature of 70 °C. The calculated effective diffusivity ( $D_{eff}$ ) values (m<sup>2</sup>/s) of pepper slices for the sun drying process, was 50 °C of  $6.1 \times 10^{-10}$  and for 70 °C of  $4.0 \times 10^{-10}$ . The  $D_{eff}$  values for red peppers, some of which were treated with dipping solutions (cold aqueous alkali emulsion of ethyl oleate) were reported in the range of  $2.2 \times 10^{-8} - 2.7 \times 10^{-8}$  m<sup>2</sup>/s by Doymaz and Pala (2002). Kaymak-Ertekin (2002) reported a  $D_{eff}$  value of  $8.3 \times 10^{-9}$  m<sup>2</sup>/s for red pepper immersed in 10% NaCl solution for 4h at 30 °C prior to air drying at 60 °C. Ade-Omowaye et al., (2003), reported the effective diffusivity values of red bell-peppers with air drying of pulsed electric fields and partial osmotically between 0.87 and  $1.58 \times 10^{-9}$  m<sup>2</sup>/s. Alves-Filho et al., (2007), studied the drying of red pepper samples with a heat pump dried in fluidized bed at different air temperatures between -2 °C to -10 °C. Scala and Crapiste, (2008) reported that the diffusion coefficient of pepper samples which were dried in a thin layer cross-flow laboratory scale dryer with air increased with temperature, from  $5.0 \times 10^{-10}$  m<sup>2</sup>/s at 50 °C, to  $8.3 \times 10^{-10}$  m<sup>2</sup>/s at 70 °C.

The values of  $L$ ,  $a$ , and  $b$ , measured for each established time are presented in Fig.7. The initial color in each test was a very dark green; the average values of Hunter's scale were:  $L = 28$ ,  $a = -27$  and  $b = 15$ . The average final values were:  $L = 21$ ,  $a = -2.4$  and  $b = 2.2$ , corresponding to a dark brown, almost black color.

With these measurements the total color change ( $\Delta E$ ) was obtained, amounting to **28.37** for 60 °C, **29** for 50 °C and **29.27** for 40 °C. It is evident that the change was linear and almost the same for the three temperatures, as presented in Fig.8.

The variation of the chroma versus drying time can be observed in Fig.9. The initial values are approximately **31** in all cases, and the final values are **3.2** for 60 °C, **3.32** for 50 °C and **3.25** for 40 °C. It is observed that the final value is very close, regardless of the temperature.

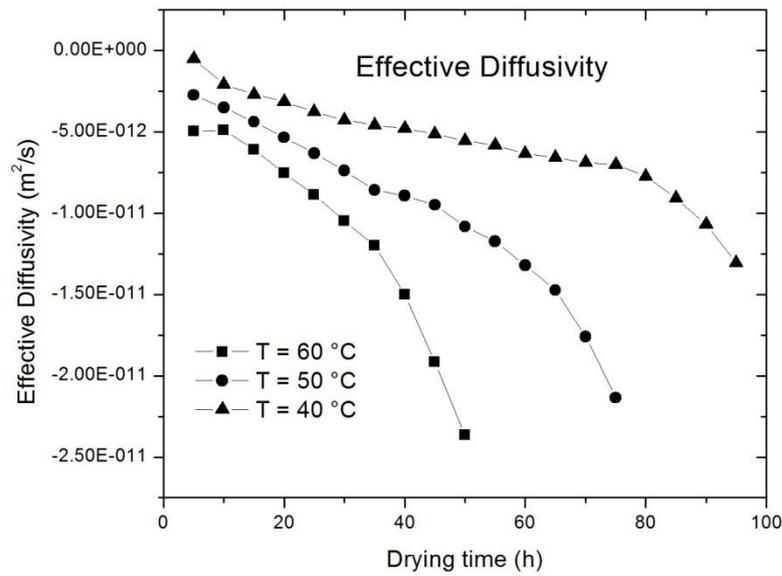


Fig. 6. Plot of the effective diffusivity versus time of drying of the Poblano hot pepper.

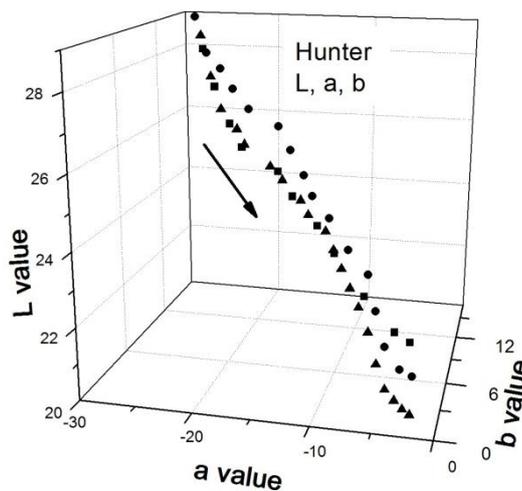


Fig. 7. Plot of the Hunter's scale *L*, *a* and *b* values versus drying time, performed on Poblano hot pepper when the velocity of air was 3.0 m/s.

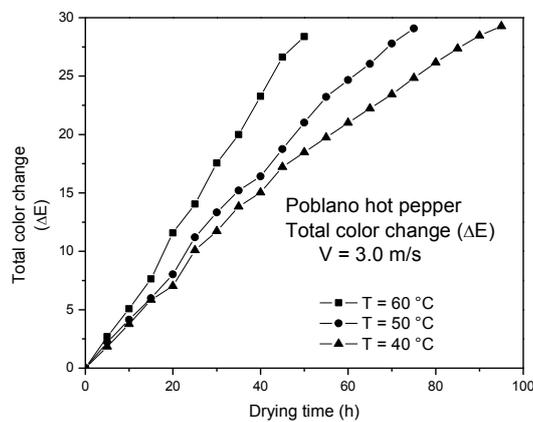


Fig. 8. Plot of the total color change versus time of drying of the Poblano hot pepper.

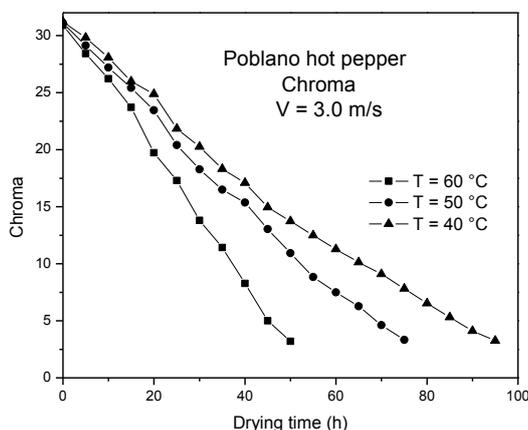


Fig. 9. Plot of the chroma value versus time of drying for the Poblano hot pepper tests.

The variation of exergy and the exergetic efficiency of the drying versus drying temperature is presented in Fig.10. The exergy inflow rates were calculated using Eq. (12), and depended on the ambient and inlet temperatures. The exergy inflow to the drying chamber varied between 0.7899 kJ/kg at drying air temperature of 40 °C and 2.8885 kJ/kg at 60 °C. The exergy out flows were between 0.5628-2.3369 kJ/kg at the same drying air temperatures. Additionally, the exergy losses were obtained in the range between 0.2271 and 0.5515 kJ/kg at drying air temperatures. With Eq. (14) we found the exergetic efficiency. The exergetic efficiency of the drying chamber decreased with the drying temperature. They were obtained as 28.75 % at drying air temperature of 40 °C, 24.70 % at drying air temperature of 50 °C, and 19.09 % at 60 °C.

These exergetic efficiencies were less than found by Akpinar, (2004), at drying air temperature of 55 °C they were between 71.00-97.42 %, 69.81-97.12 % at drying air temperature of 60 °C, and 67.28-97.92 % at drying air temperature of 70 °C, with an air velocity of 1.5 m/s. Later, Akpinar, (2005), utilizing a hot air cyclone dryer to dry eggplant slices, with temperatures between 55 - 75 °C and an air velocity of 1.5 m/s, reported exergy efficiencies between 43.34 and 100 %. Erbay and Icier (2009), dried olive leaves in a tray-dryer; their experimental parameters were T = 40-60 °C, V = 1.5 m/s, and t = 240-480 min. The exergy efficiency was found between 10.25 and 65.50 %. Icier et al., (2010), in an experimental tray-dryer tested broccoli at the conditions of = 50-70 °C and V = 1.5 m/s. The exergy efficiency of tray drying chamber varied between 59.70 and 81.92%, while the exergy efficiency of drying process was found to be in range of 8.2 and 15.9 %.

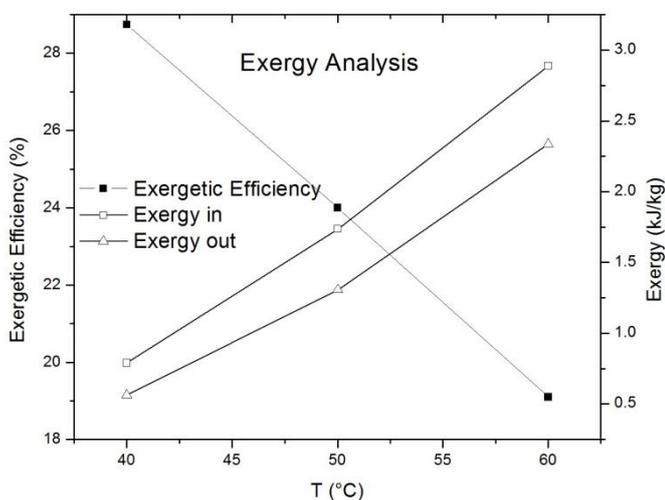


Fig. 10. Exergy analysis for the Poblano hot pepper tests.

#### 4. Conclusions

We described the drying process of the complete Poblano hot pepper, i. e., non-sliced specimens, in a forced convection tunnel with air at a velocity of 3.0 m/s. The range of time was 50-95 hours for temperatures between 60 °C and 40 °C. At 50 °C the drying time was 75 hours.

The numerical model that best described the drying process was the logarithmic one, with the three restrictions of  $r$  close to the unit,  $\chi^2$ , and RMSE close to zero. The characteristic drying curve of the product, a third order curve, was obtained.

The effective moisture diffusivity at the temperature of 60 °C was of  $7.1 \times 10^{-10}$  m<sup>2</sup>/s, at 50 °C was  $1.2 \times 10^{-11}$  m<sup>2</sup>/s, and finally at 40 °C it was of  $5.7 \times 10^{-11}$  m<sup>2</sup>/s.

The change in color was registered using the Hunter's method, the initial values corresponded to dark green and the final color was black. The total change in color and chroma were almost the same for the three conditions studied.

The exergetic efficiency of the drying chamber was as 28.75 % at drying air temperature of 40 °C, 24.70 % at drying air temperature of 50 °C, and 19.09 % at 60 °C.

**Nomenclature**

|                        |  |
|------------------------|--|
| <b>A</b>               | area (m <sup>2</sup> )                             |
| a, c                   | constants  |
| a                      | ratio red/green                                    |
| b                      | ratio yellow/blue                                  |
| <b>D<sub>eff</sub></b> | effective moisture diffusivity (m <sup>2</sup> /s) |
| <b>E</b>               | emissive power                                     |
| <b>Ex</b>              | exergy (kJ/kg)                                     |
| <b>F</b>               | shape factor                                       |
| f                      | dimensionless drying rate                          |
| <b>g</b>               | gravity (m/s <sup>2</sup> )                        |
| <b>k</b>               | Page constant (1/min)                              |
| <b>L</b>               | thickness of Poblano hot pepper (m)                |
| <b>L</b>               | lightness  |
| <b>M</b>               | moisture content (kg/kg)                           |
| <b>MR</b>              | moisture ratio (kg/kg)                             |
| <b>N</b>               | number of observations                             |
| n                      | number of constants                                |
| n                      | model constant                                     |
| <b>P</b>               | pressure (kPa)                                     |
| r                      | correlation coefficient                            |
| <b>RMSE</b>            | root mean square error                             |
| <b>SD</b>              | standard deviation                                 |
| <b>s</b>               | entropy (kJ/kg K)                                  |
| <b>T</b>               | temperature (K)                                    |
| t                      | time (min)   |
| <b>u</b>               | internal energy (kJ/kg)                            |
| <b>v</b>               | specific volume (m <sup>3</sup> /kg)               |
| v                      | velocity (m/s)                                     |
| w                      | uncertainty  |
| <b>z</b>               | altitude coordinate (m)                            |
| <b>ΔE</b>              | color change                                       |
| <b>χ<sup>2</sup></b>   | reduced chi-square                                 |
| Subscripts             |  |
| 0                      | initial  |
| 1, 2, 3                | independent variables                              |
| e                      | equilibrium  |
| exp                    | experimental                                       |
| ml                     | mass loss  |
| N                      | number of observations                             |
| n                      | number of constants                                |
| pre                    | predicted  |
| R                      | total uncertainty in measurement of result         |
| t                      | time   |
| v                      | velocity   |
| Ø                      | relative humidity                                  |

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