Acta Scientiarum

http://www.uem.br/acta
ISSN printed: 1806-2563
ISSN on-line: 1807-8664
Doi: 10.4025/actascitechnol.v35i2.10286

Analysis of convective drying kinetics of yellow passion fruit bagasse

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ABSTRACT. This study aimed to analyze the convective drying in fixed bed of yellow passion fruit bagasse. Firstly, the initial moisture of the bagasse was determined in stove, at 105 ± 3ºC for 24 hours. In the drying tests, it was collected the bagasse mass values over time, by using a convective dryer, operated at four temperatures (35, 45, 55 and 65ºC) and three air flow speeds at 0.8, 1.0 and 1.3 m s^{-1}. Having the curves of the drying and of drying rates, it was observed that the temperature had a great influence on the bagasse drying, since as the temperature increases, the drying time is shortened, increasing thus the drying rate. The curves of drying and of drying rate were fitted to the models proposed by Page (1949 apud MOTTA LIMA et al., 2003)and Motta Lima et al. (2002), and the models set by Hogdes (1982) and Toffoli (2005 apud SANTOS et al., 2008), respectively. Other mathematical models were also fitted for each drying process, such as: Simple Exponential, Page, Henderson and Pabis, Logarithm, two-term exponential model, and Wang and Singh model. The best model was chosen by analysis of the highest R^2 and F-test, and the lowest root mean square error.

Keywords: convective drying, drying curves, mathematical models adjustments.

Análise da cinética de secagem do bagaço do maracujá amarelo

RESUMO. Este trabalho teve por objetivo analisar a secagem convectiva em leito fixo do bagaço do maracujá amarelo. Primeiramente, determinou-se a umidade inicial do bagaço em estufa, durante 24h a 105 ± 3ºC. Nos ensaios de secagem, foram coletados os valores de massa do bagaço em função do tempo, utilizando-se um secador convectivo, operado em quatro temperaturas (35, 45, 55 e 65ºC) e três velocidades do ar de 0,8, 1,0 e 1,3 m s^{-1}. Por meio das curvas de secagem e da taxa de secagem, observou-se que a temperatura exerce grande influência na secagem do bagaço, pois quando se aumenta a temperatura ocorre a diminuição do tempo de secagem e consequente aumento na taxa. As curvas de secagem e de taxa de secagem foram ajustadas aos modelos propostos por Page (1949 apud MOTTA LIMA et al., 2003) e Motta Lima et al. (2002) e aos modelos propostos por Hogdes (1982) e Toffoli (2005 apud SANTOS et al., 2008), respectivamente. Outros modelos matemáticos também foram ajustados para cada secagem, tais como: Exponencial Simples, Page, Henderson e Pabis, Logaritmo, Exponencial de Dois Termos e Wang e Singh. O melhor modelo entre os estudados foi obtido analisando-se os maiores valores do R^2 e Teste F e a menor raiz do erro médio.

Palavras-chave: secagem convectiva, curvas de secagem, ajuste de modelos matemáticos.

Introduction

The passion fruit comes from the Tropical America and there are more than 150 species of *Passifloraceas* used for the human consumption. The most cultivated species in Brazil and worldwide are: the yellow passion fruit (*Passiflora edulis f. flavicarpa*), purple passion fruit (*Passiflora edulis*) and the Fragrant Granadilla (*Passiflora alata*).

The yellow passion fruit is the most cultivated in the world, and Brazil is responsible for more than 95% of the world production.

One byproduct of the industry of passion-fruit juice with lower added value is the bagasse from humid passion fruit, composed mainly of flavedo (colored portion) and albedo (white portion).

The drying of passion fruit bagasse reduces volume and weight, easing the storage and transport, thereby allowing adding value and developing other applications for this low-cost industrial waste (DOYMAZ, 2005).

The drying of any solid material involves simultaneously the transference of heat and mass (CORRÊA et al., 2006; MWITHIGA; OLWAL, 2005), and its behavior is characterized by the analysis of the humidity changes over time.

Through the drying process one may determine the drying kinetics, which attempts to determine the solid material behavior which is being dried, being represented by the curves of drying and of drying rate. The behavior of a curve of drying a humid solid before a gas flow at a certain temperature is always the same, according to Foust et al. (1980). In turn the curve of drying rate is obtained by deriving the humidity data as a function of the drying time.

The drying kinetics of many products can also be described by semi-empirical or purely empirical mathematical models (MADAMBA, 2003). The semi-empirical models are based on the analogy with the Newton's Law for cooling, applied to the mass transference, while the empirical models have an association between the average humidity content and the drying time, and consider as the major mechanism, the diffusion based on the second Law of Fick (ZANOELO et al., 2007).

Given the above, the present study aimed: (i) to analyze the convective drying behavior of the yellow passion fruit bagasse under four temperatures and three gas flow speeds; (ii) to apply mathematical models from literature for the experimental data; and (iii) to select the model which best represents the experimental data.

Material and methods

Material

The yellow passion fruit bagasse was provided by a fruit juice industry, located in Japurá, Paraná State. After collecting the raw material, it was crushed in a blender and separated into samples of approximately 500 g. Each sample was placed in sealed plastic bags. These bags were freezer-stored at -15 ± 2°C.

Experiments of drying

First, the initial humidity of the passion fruit bagasse was determined in an oven at 105 ± 3°C for 24 hours.

In order to collect the kinetic data for the study on the convective drying of the yellow passion fruit bagasse, it was used a convective bench dryer with transverse flow, as shown in the Figure 1.

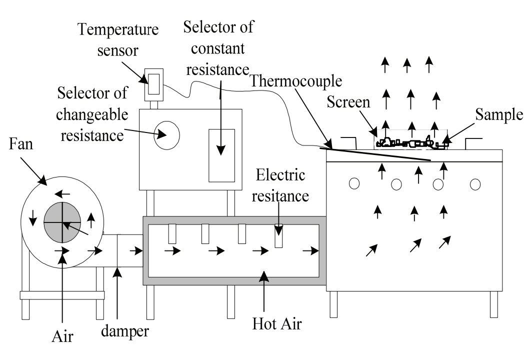

Figure 1. Experimental module, convective system (PACHECO et al., 2011).

The air flow used in the drying is from a blower, where the air flow rate can be adjusted through a butterfly valve, being the gas flow speed measurement made by a portable digital anemometer (Model HH-F10 – accurate to 0.1 m s^{-1}) placed immediately above the dryer tray, and the room humidity was measured with the aid of a digital psychrometer (Model THWD – 1 – accurate to 1.0°C – temperature; 3% – humidity).

After established the gas flow speed, the temperature was manipulated from electrical resistances arranged in a heater in which the air passes before come into contact with the raw material. These resistances are triggered, alone or simultaneously, until reach the desired temperature.

The experiments were performed in duplicate, by varying the gas flow speed (0.8; 1.0 and 1.3 m s^{-1}) and temperature (35, 45, 55 and 65°C).

In the first 30 minutes, the tray was weighed in a digital scale (GEHAKA Line Bg 4000 – accurate 0.01 g) with intervals of 2 minutes, and then, up to 1h, the interval lasted 5 minutes, and from 1 to 1h 30 min., the interval was 10 minutes, then the interval extended to 15 minutes until the drying end, i.e., until achieving a constant mass.

With these data, we constructed the curves of drying and of drying rate. The first was obtained by a graph of humidity over time. The humidity for every instant was obtained from the Equation 1.

$$X\left(d.b\right)=\frac{M_{humid}-M_{dry}}{M_{dry}} \tag{1}$$

where:

X (d.b) is the ratio between the mass of water present in the sample (M_{humid} – M_{dry}) and the mass of solid exempt from this humidity (M_{dry}), at a particular time (d.b). M_{humid} is the sample mass before the oven (g) and M_{dry} is the dry mass obtained in oven (g).

The drying rate curves were obtained from the respective drying curves derivation by the numerical method $(\Delta X/\Delta t)$, obtaining the humidity value in the points originally used in constructing the drying curves, according to Motta Lima et al. (2002).

The calculation procedure for the drying rate in the point i is detailed below in the Equation 2.

$$\begin{aligned}
&(\Delta X/\Delta t)_{i-}\ (between\ \ i-1\ and\ \ i)\ and\\
&(\Delta X/\Delta t)_{i+}\ (between\ \ i\ and\ \ i+1)\\
&(\Delta X/\Delta t)_i=\left[(\Delta X/\Delta t)_{i-}+(\Delta X/\Delta t)_{i+}\right]/2\\
&in\ X_0=(\Delta X/\Delta t)_{0+}\ or\ (\Delta X/\Delta t)_{i+}\\
&in\ X_C=(\Delta X/\Delta t)_{X_e^-}
\end{aligned} \tag{2}$$

Modeling the drying process

The generalized drying curves are other way to evaluate the humidity of a sample. These are curves relating the non-dimensional humidity of a sample to a dimensionless time variable.

Some authors proposed generalized equations for the drying process. Page (1949 apud MOTTA LIMA et al., 2003) proposed the following model given by the Equation 3.

$$X_{ad} = exp(-K_1 t^{a_1}) \quad (3)$$

Subsequently, Motta Lima et al. (2002) modified the Equation 3 obtaining the Equation 4.

$$X_{ad} = exp(-K_2 t_{ad}^{(a_2 t_{ad} + b_2)}) + 0.01 \quad (4)$$

For the two equations presented there is $X_{ad}=X/X_0$, where X is the humidity at a given moment and $X_0$is the initial humidity of the passion fruit bagasse; $t_{ad} = t.\frac{N_c}{X_0}$, where t_{ad} is the dimensionless time, t is the time, N_c is the constant drying rate; k_1, k_2, a_1, a_2, $b_2$are equations parameters.

For the generalized drying rate curves, Hogdes (1982) proposed:

$$NDR = \frac{N_T}{N_{max}} = 1 - exp\left(-\left(\frac{X}{a_3}\right)^{b_3}\right) \quad (5)$$

Based on the equation of Hogdes (1982), Toffoli (2005 apud SANTOS et al., 2008) developed a variation for the exponent, linearly with the humidity, obtaining the Equation 6.

$$NDR = \frac{N_T}{N_{max}} = 1 - exp\left(-\left(\frac{X}{a_4}\right)^{(b_4 X + c_4)}\right) \quad (6)$$

For the two equations presented there is:

X is the humidity at a given time;

t_{ad}= $t.N_c/X_0$, where t_{ad} is the dimensionless time, t is the time, N_c is the constant drying rate;

NDR is the normalized drying rate (N_T/N_{max}), N_T is the instantaneous drying rate and N_{max} is the maximum drying rate;

a_3, a_4, b_3, b_4, and c_4 are the equations parameters.

The convective drying kinetics can also be characterized from the dimensionless humidity data (AD) as a function of the process time. The models listed in Table 1 were used for fitting the experimental data.

The kinetic models parameters and the generalization were obtained by nonlinear regression (Quasi-Newton), convergence criterion of 0.0001, using the software Statistica 6.0®.

Table 1. Mathematical models for the drying kinetics

Model	Equation	References
Simple Exponential	$AD = \exp(-kt)$	Abe and Afzal (1997)
Page	$AD = \exp(-kt^v)$	Karathanos and Belessiotis (1999)
Henderson and Pabis	$AD = A\exp(-kt)$	Henderson and Pabis (1961)
Logarithm	$AD = B\exp(-kt) + c$	Yaldiz et al. (2001)
Two-term Exponential	$AD = C\exp(-k_0 t) + D\exp(-k_1 t)$	Ozdemir and Devres (1999)
Wang and Singh	$AD = 1 + Et + Ft^2$	Wang and Singh (1978)

Where: k, v, A, B, C, D, E, F, k_0 and $k_1$are models constants; t is the drying time (s).

The criterion used to choose the best model for the generalizations was based on the highest values of the determination coefficient (R^2) and the F-Test. As for the kinetic models, the choice was based on the highest values of R^2 and the F-test, and on the lowest value of the root mean square error (RMSE). The RMSE values and the F-Test were calculated as showed in Equations 7 and 8.

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(X_{exp i} - X_{pred i}\right)^2\right]^{1/2} \quad (7)$$

$$F - Test = \frac{\sum \bar{X}^2_{pred}}{\sum \bar{X}^2_{resid}} \quad (8)$$

where:

$X_{\exp,i}$ is the humidity experimentally obtained;

$X_{pred,i}$, the humidity predicted by the model;

$X_{resid,i}$, the residual humidity, defined as the difference between $X_{\exp,i}$,and $X_{pred,i}$ and N, the number of experiments.

Results and dicussion

The initial humidity of the passion fruit bagasse was obtained in an oven at 105 ± 3°C for 24 hours, in which the bagasse reached its equilibrium humidity in approximately 3 hours, showing, thus, a fast drying, typical of materials with a lot of free water. In this stage, the water in the raw material represented 90.44% of its total mass.

With the curves of drying and of drying rates, it was possible to observe the influence of the gas flow speed and temperature on the drying of the yellow passion fruit bagasse. The Figure 2 shows the drying curves obtained for the gas flow speed at 1.3 m s^{-1}.

The Figure 2 indicated that the higher the temperature, the shorter the drying time, once with the gas flow speed at 1.3 m s^{-1} and the temperature of 35°C, the sample took 225 minutes to reach the equilibrium humidity, while at 65°C, the drying time lasted 120 minutes.

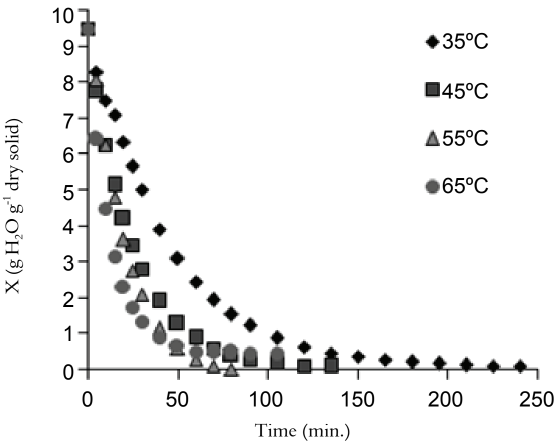

Figure 2. Drying curves for gas flow speed at 1.3 m s^{-1}.

Below are presented the drying rate curves (R) for assessing the influence of temperature in the process, obtained from the humidity data derivation (X) over time.

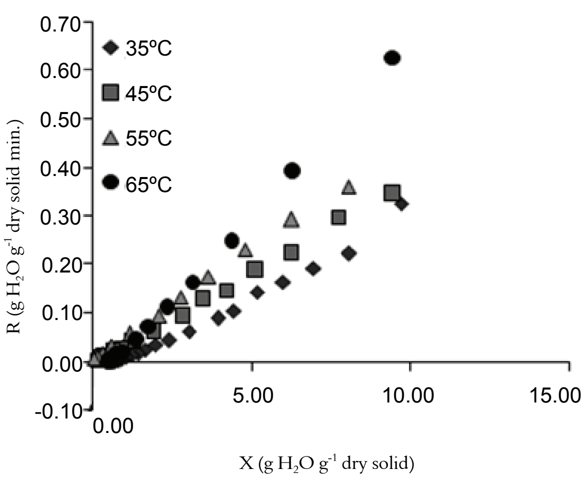

Figure 3. Drying rate curves for the gas flow speed at 1.3 m s^{-1}.

The drying rate curves did not present the initial period for the material conditioning to the process nor the period with constant rate, but only the period of decreasing rate until reach the equilibrium humidity, which is typical of each material (Figure 3). This shows that diffusion is the dominant physical mechanism governing the humidity movement in the samples.

Similar results were obtained by Gogus and Maskan (1999) for the okra drying and Gupta et al. (2002) for the red bell pepper drying.

Moreover, with increasing temperature, the drying rate also increases, as verified for the dryings at 35 and 65ºC and gas flow speed at 1.3 m s^{-1}, in which the rates were 0.33 and 0.62 min.$^{-1}$, respectively.

The Figure 4 represents the same type of graph, but for the test at 55ºC and variable gas flow speeds.

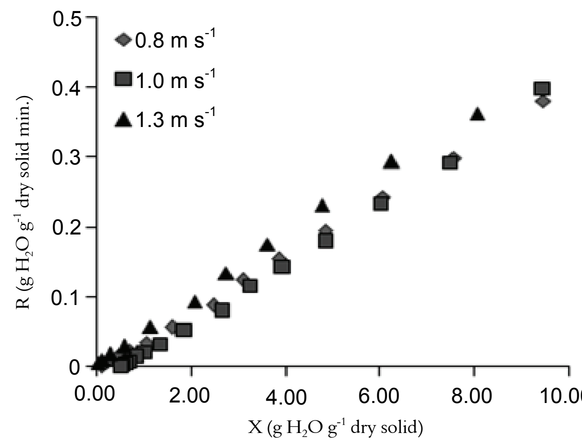

Figure 4. Yellow passion fruit bagasse drying rate as a function of the humidity at 55°C.

Having the Figure 4, the gas flow speed had no significant influence on the passion fruit bagasse drying, unlike the temperature, because the higher the temperature, the higher the heat transferred to the material, and consequently, the water present in the passion fruit bagasse migrates most easily to the surface, easing the evaporation.

In order to determine the best working condition, it was analyzed each drying condition. The temperatures of 35 and 45ºC presented the highest final humidity and the longest drying time in all speeds of the gas flow, around 4h and 3h, respectively.

As for the temperatures of 55 and 65ºC, the lowest final humidity and the shortest drying time was verified, and for both temperatures, the humidity becomes constant around 80 minutes, completing the process in 120 minutes for a gas flow speed at 1.3 m s^{-1}, but at 55ºC there was a lower energy expenditure (7700 W) than at 65ºC (8500 W).

On this basis, searching to achieve the equilibrium humidity with time and energy savings, the best drying condition for the yellow passion fruit bagasse in fixed bed was at the temperature of 55°C and the gas flow speed of 1.3 m s^{-1}.

Similar results were verified by Fiorentin et al. (2012) for the orange bagasse drying in fixed bed, where the temperature used was between 30 and 90ºC. The best drying condition obtained was for the temperature of 45ºC and gas flow speed of 1.3 m s^{-1}.

The generalizations of the drying curves of yellow passion fruit bagasse for the temperature interval from 35 to 65°C and gas flow speeds of 0.8, 1.0 and 1.3 m s^{-1} were made through the Equations 3, 4, 5 and 6, previously presented.

Thus, the Figures 5 and 7 present the generalized drying curves according to the models proposed by Page (1949 apud MOTTA LIMA et al., 2003) and Motta Lima et al. (2002). The Figures 6 and 8 present the respective residues.

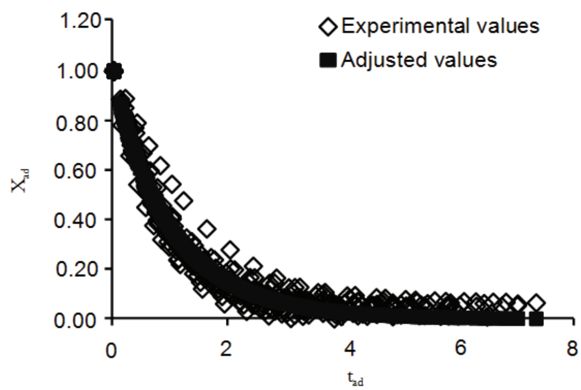

Figure 5. Drying curve Generalized by the model of Page (1949 apud MOTTA LIMA et al., 2003).

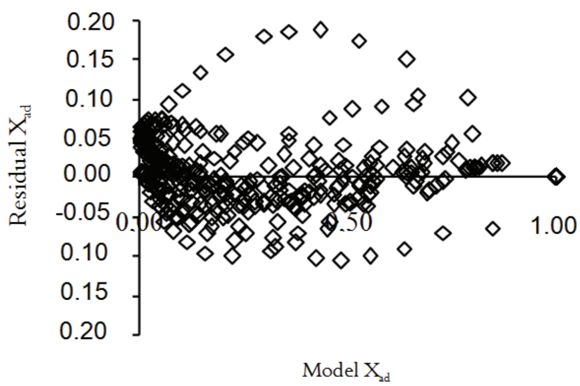

Figure 6. Residuals graph for the model of Page (1949 apud MOTTA LIMA et al., 2003).

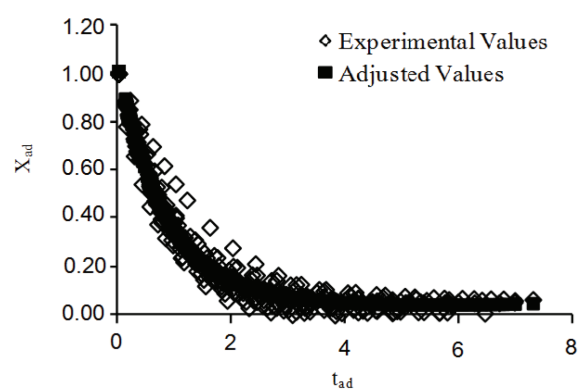

Figure 7. Drying curve generalized by the model of Motta Lima et al. (2002).

The models adopted fitted well to the drying data for the bagasse of yellow passion fruit (Figures 5 and 7).

The residuals had a good random distribution around zero, being verified a greater amount of dots close to the equilibrium humidity (Figures 6 and 8). This because the humidity difference between the material and the environment, in this region, is very small, which makes the residuals more expressive, not interfering, in this way, in the quality of the adjustment, according to Motta Lima (2002).

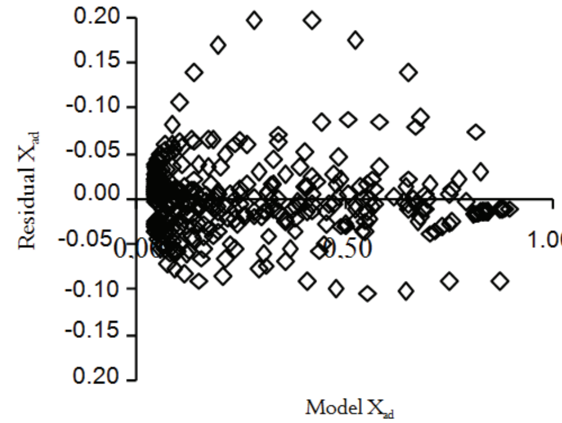

Figure 8. Residuals graph for the model of Motta Lima et al. (2002).

The maximum and minimum residual values were 0.1865 and-0.1049 for the model of Page (1949 apud MOTTA LIMA et al., 2003) and 0.2010 e -0.1029 for the model of Motta Lima et al. (2002).

The generalizations for the drying rate curves were performed according to the models proposed by Hogdes (1982) and Toffoli (2005 apud SANTOS et al., 2008) presented in Figures 9 and 11, and the respective residuals are shown in Figures 10 and 12, respectively.

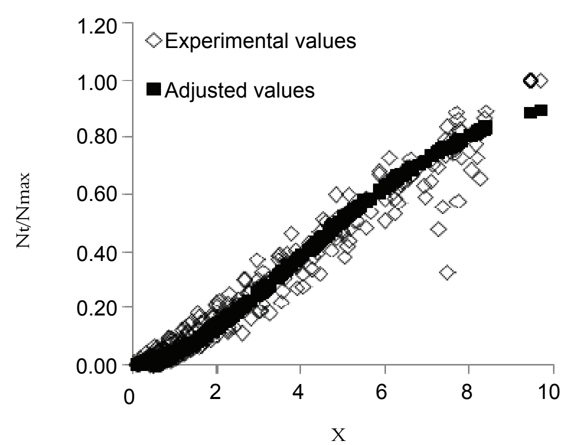

Figure 9. Drying rate curve generalized by the model of Hogdes (1982).

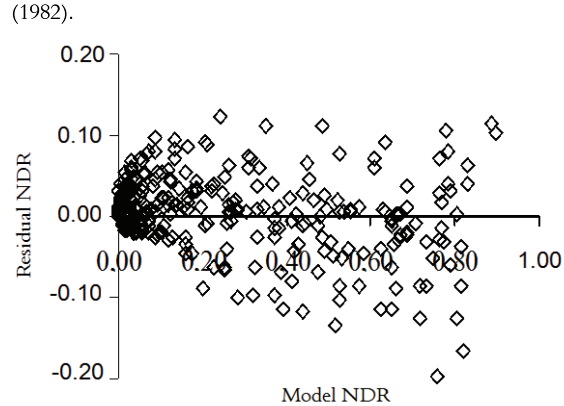

Figure 10. Residuals graph for the model of Hogdes (1982).

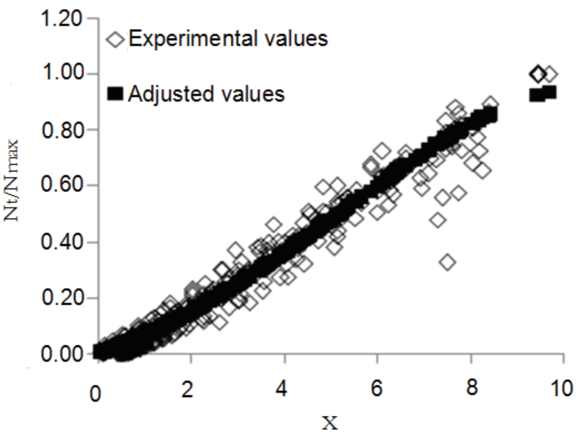

Figure 11. Drying rate curve generalized by the model of Toffoli (2005 apud SANTOS et al., 2008).

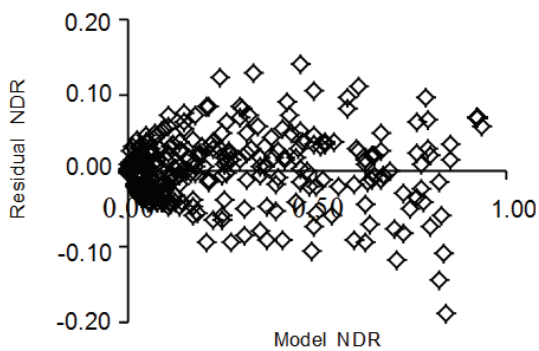

Figure 12. Residuals graph for the model of Toffoli (2005 apud SANTOS et al., 2008).

Both models used for generalizing the drying rate curves were well fitted to the experimental data (Figures 9 and 11).

The residuals had a good random distribution around zero, without any specific tendency, in which the maximum and minimum residual values were0.1407 and -0.1878 for the model of Toffoli (2005 apud SANTOS et al., 2008) (Figures 10 and 12).

The R^2 values, F-Test and the parameters obtained for the studied models are listed in the Table 2.

The model of Motta Lima et al. (2002) reached a better adjustment to the experimental data, presenting R^2 and F-Test values higher than the model of Page (1949 apud MOTTA LIMA et al., 2003)(Table 2). The same behavior was observed for the model of Toffoli (2005 apud SANTOS et al., 2008) in relation to the model of Hogdes (1982).

The results obtained are in accordance with Fiorentin et al. (2012) who also applied these models of generalized curves of drying and of drying rates in the drying kinetics analysis of the orange bagasse.

The application of the mathematical models for the drying kinetics presented in the Table 1 was performed for each drying condition. The Figure 13 presents the behavior of the mathematical models based on the experimental data for the drying at 55°C and gas flow speed of 1.3 m s^{-1}.

Table 2. Parameters obtained in the generalization of the curves of drying and of drying rates, values of R^2 and F-Test.

Model	Parameter	Value
Page	R^2	0.977
	F-Test	90.362
	k_1	1.022
	a_1	0.910
Motta Lima et al. (2002)	R^2	0.981
	F-Test	110.192
	k_2	1.094
	a_2	-0.065
	b_2	1.021
Hogdes	R^2	0.963
	F-Test	46.499
	a_3	6.080
	b_3	1.760
Toffoli	R^2	0.969
	F-Test	55.015
	a_4	6.270
	b_4	0.101
	c_4	0.104

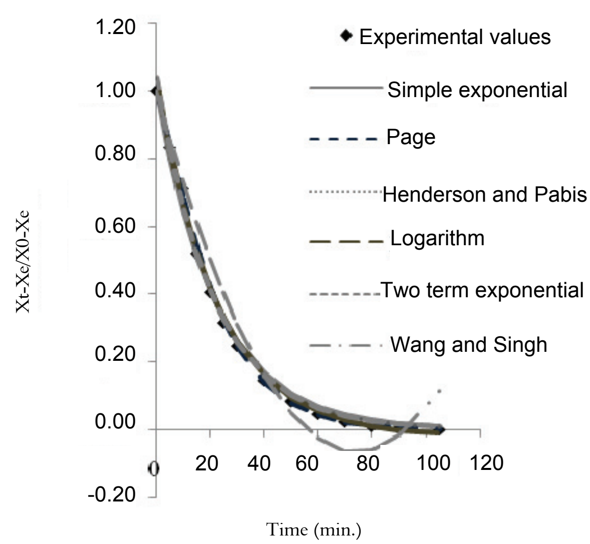

Figura 13. Fit of models

The Figure 13 indicates that, except for the Wang and Singh (1978) model, the models presented a good relationship with the experimental data, not being possible to determine the best model, only observing the graph. This result was also obtained in the other tests. Thus, the best model was chosen based on the highest values for the determination coefficient (R^2) and F-Test, and on the lowest value of the root mean square error (RMSE).

The R^2 values, F-Test and RMSE for the drying at 55°C and gas flow speed of 1.3 m s^{-1} are presented in Table 3.

Through the results of the Table 3, it can be observed that the model of Page presented the highest R^2 and F-Test values and the lowest RMSE value, evidencing, thus, its high potential for the experimental data representation in all the drying conditions. The Two-Term Exponential Model and The Henderson and Pabis Model presented the same tendency in relation to the values of F-Test, RMSE and R^2.

The results obtained are in line with Orikasa et al. (2008); Kingsly and Singh (2007); Martinazzo et al. (2007); Mwithiga and Olwal (2005); Doymaz (2005), that evaluated the drying process of food stuffs along time and had similar results.

Table 3. Comparison of models and parameters obtained by the fit of mathematical models for the drying kinetics of the yellow passion fruit bagasse

Model	Parameter	Value
Simple Exponential	R^2	0.9936
	F-Test	287.620
	RMSE	0.0258
	k	0.0447
Page	R^2	0.9986
	F-Test	1396.841
	RMSE	0.0120
	k	0.0260
	v	1.1723
Henderson and Pabis	R^2	0.9952
	F-Test	405.545
	RMSE	0.0223
	k	0.0466
	a	1.0385
Logarithm	R^2	0.9961
	F-Test	493.612
	RMSE	0.0202
	a	1.0519
	k	0.0442
	c	-0.0200
Two-term Exponential	R^2	0.9952
	F-Test	405.545
	RMSE	0.0223
	a	0.5192
	k_0	0.0466
	b	0.5193
	k_1	0.0466
Wang and Singh	R^2	0.9546
	F-Test	48.336
	RMSE	0.0689
	a	-0.028661
	b	0.000193

Conclusion

Regarding the bagasse drying process, at the temperature of 55°C and air speed of 1.3 m s^{-1}, the equilibrium humidity was reached more rapidly, with time and energy savings, in comparison with other conditions studied, being the best drying condition.

The number of parameters involved with the dryer project requires an even empirical modeling in order to reduce the engineering work with the dimensioning of the processing units. The generalized drying curves obtained at the temperature range of 35 and 65 ± 1°C showed that the model of Motta Lima et al. (2002) presented the best fit to the experimental data, based on the values of R^2 and F-Test. For the generalized drying rate curves, the model of Toffoli (2005 apud SANTOS et al., 2008) was the best in describing the experimental data.

The application of the mathematical models Two-Term Exponential, Simple Exponential, Page, Henderson and Pabis, Logarithm, and Wang and Singh to the experimental data of drying, pointed out that the model of Page (1949 apud MOTTA LIMA et al., 2003) was the best in representing the experimental data under all study conditions.

Acknowledgements

The authors thank CNPq for the financial support.

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Received on May 29, 2010.
Accepted on April 25, 2012.