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## DRYING AND ISOTHERMS OF SUGAR CANE BAGASSE

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### ABSTRACT

Sugarcane is nowadays considered an important source of energy. One of its products is sugarcane bagasse. Bagasse is largely used as a boiler fuel. The goal of this work was to study bagasse drying in a fixed bed and its desorption isotherm. Air was used as drying agent at 40, 50 and 60 °C at flow rate of 0.9 m s<sup>-1</sup>. Desorption isotherms were also obtained at 40 and 50 °C. Several models from literature were tested with regards to their fit to fixed bed drying and desorption isotherm data. The best adjustments were obtained with Modified Page 2 model for drying kinetics and both the Jaafar and Michalowski model and modified Henderson 2 model for the desorption isotherm.

**Keywords:** biomass, drying, energy

### RESUMO

#### SECAGEM E ISOTERMAS DE BAGAÇO DE CANA DE AÇÚCAR

A cana de açúcar é considerada, hoje em dia, como uma importante fonte de energia. Um de seus produtos é o bagaço de cana. O bagaço é muito utilizado como combustível para caldeiras. O objetivo deste trabalho foi o estudo da secagem de bagaço de cana em um leito fixo e de sua isoterma de desorção. O ar foi utilizado como agente de secagem a 40, 50 e 60 °C e 0,9 m s<sup>-1</sup>. As isotermas de desorção foram também obtidas a 40 e 50 °C. Vários modelos da literatura foram testados para o ajuste da secagem em leito fixo e para os dados de isoterma. Os melhores ajustes foram obtidos com uma modificação do modelo de Page (*modified Page 2*), para cinética de secagem e com os modelos de Jaafar e Michalowski e uma modificação do modelo de Henderson (*modified Henderson II*) para as isotermas de desorção.

**Palavras-chave:** biomassa, secagem, energia.

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## INTRODUCTION

Bagasse is the fibrous residue of sugarcane and is often used as a fuel in sugar and alcohol factories (LORA; ANDRADE, 2009; PALACIOS-BERECHE *et al.*, 2013) and for co-generation of electric energy (RÍPOLI *et al.*, 2000). However, it can also be used in paper production (JAIN *et al.*, 2009) as well as for bioethanol (DIAS *et al.*, 2009; NGUYEN *et al.*, 2009; PALACIOS-BERECHE *et al.*, 2013), as substrate for plantlet production (MORGADO *et al.*, 2000), for compost formulations (MODA *et al.*, 2005; SIQUEIRA *et al.*, 2009) and animal feed (ROCHA *et al.*, 2004; PEREIRA *et al.*, 2008).

Whatever the final use, the majority of moisture content should be removed before further processing (KROKIDA *et al.*, 2002; DOYMAZ *et al.*, 2004). Although the most common industrial dryer for sugarcane bagasse is the pneumatic type (SOSA-ARNAO *et al.*, 2006, BELTING ; SEMRAU, 2009), academic works have also address pneumatic (NEBRA ; MACEDO, 1988; ALARCÓN ; JÚSTIZ, 1993) cyclonic (CORRÊA *et al.*, 2004, DE OLIVEIRA *et al.*, 2011), fixed bed (VIJAYARAJ *et al.*, 2007) and vacuum drying (PURANIK ; YARNAL, 2009).

Sorption isotherms relate the moisture content to the relative humidity for a product at a constant temperature. This relation depends on factors like physical structure, affinity of the material with water, the amount of water-soluble solutes and the growth rate of the process microorganism in the fermented sugarcane bagasse (KUROZAWA *et al.*, 2005; FURMANIAK *et al.*, 2009; MAZUTTI *et al.*, 2010). Sorption isotherms are necessary to model drying and moisture uptake, as well as to design equipment and extend the product useful life (De TERMMERMAN *et al.*, 2008).

The goal of this work was to study sugarcane bagasse drying in a fixed bed and its desorption isotherm. Fixed bed drying was performed at 40, 50 and 60 °C and the desorption isotherms, at 40 and 50 °C. Mathematical models from literature were tested for both the desorption isotherm and

fixed bed drying.

## MATERIALS AND METHODS

Sugarcane [*Saccharum officinarum* L.] bagasse was provided by the Junqueira sugar company (COSAN), located in Iguarapava, São Paulo, Brazil, and by Ester sugar company, Cosmópolis, São Paulo, Brazil. These factories extract juice from the sugarcane by milling.

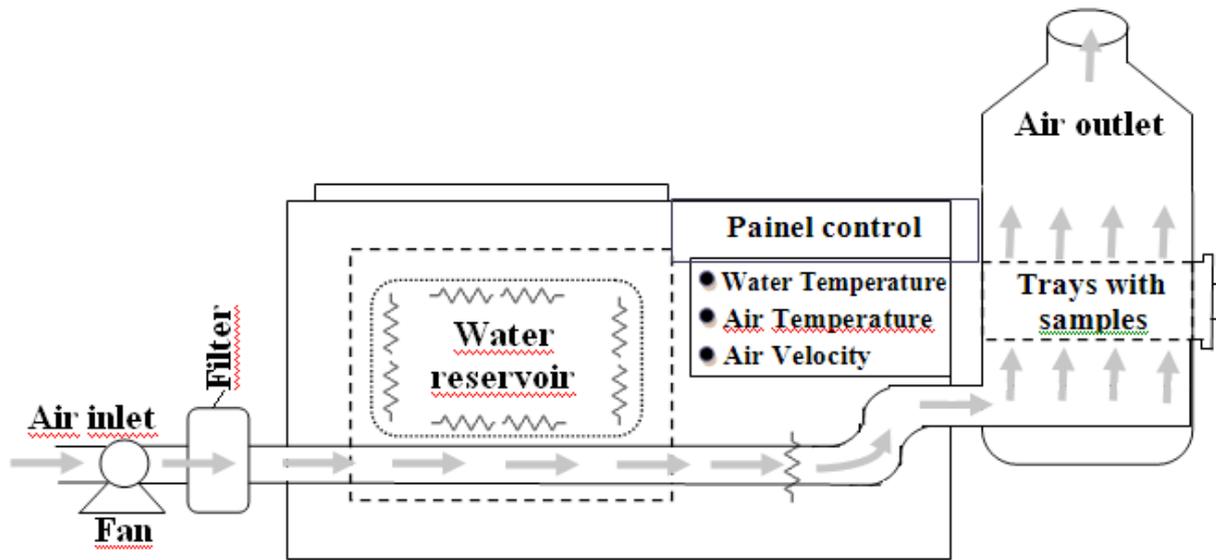
The experiments were performed at the Federal University of Lavras, in the Department of Food Science and the Department of Agricultural Engineering.

The bagasse from both sources was characterized via sieve analysis with a set of standardized sieves (Tyler series: 4, 8, 14, 28, 35 and 48). The sieves were agitated for 20 minutes. This agitation time was established by verifying that additional time did not affect the mass fraction of product on each sieve.

Determination of the total moisture content was determined by the oven drying method at 105 °C for 24 h (AOAC, 1990), as described by Rasul *et al.* (1999).

The fixed bed drying and desorption isotherm experiments were performed using a dryer with a laboratory air conditioning unit (Figure 1), produced by Consciente Ltda, Belo Horizonte, Minas Gerais, Brazil.

This device permits defining the relative humidity and air velocity. Air velocity was measured using a digital anemometer and was set to an experimentally determined velocity that would maintain the bagasse in the fixed bed for both the drying and isotherm experiments and would prevent material loss during the experiments. The range of velocities used was selected based on the terminal velocity of the smallest particles, according to the study of Nebra and Macedo (1988). Because of the diversity of particle shapes and sizes in the bagasse, the experiments were carried out only with particles from sieves 4, 8, 14, and 28 of the complete sieve analysis (Tyler series sieves 4, 8, 14, 28, 35 and 48).



**Figure 1.** Dryer with Laboratory Air Conditioning Unit (setup).

The drying experiments were performed with samples obtained after milling with moisture content of 71.0 % w.b., from the Junqueira sugar company (COSAN).

The experiments consisted of the passage of heated air (relative humidity of 25 % and temperature of 40, 50 and 60 °C) across the sample through a deep tray with a perforated screen. The wet bagasse layer had a volume of  $1.984 \times 10^{-3} \text{ m}^3$ , a mass of  $1000 \times 10^{-3} \text{ kg}$  and a thickness of approximately  $3.5 \times 10^{-2} \text{ m}$ . The air velocity was approximately  $0.9 \text{ m s}^{-1}$ . The material was weighed on a scale with a resolution of  $0.0001 \times 10^{-3} \text{ kg}$  until the mass variations were less than  $0.02 \times 10^{-3} \text{ kg}$ . Curves of the drying kinetics were obtained for all of the operational conditions considered in this work.

The desorption isotherm experiments were carried out on bagasse samples, which were obtained from the Ester sugar company and had a moisture content (w.b.) of 46 % after milling. These samples were packaged in hermetic bags and refrigerated (6 °C) until performing the laboratory experiments, which were performed two days after milling.

The direct method was used to determine the isotherms, with heated air at predefined values of

relative humidity (25, 35, 45, 55, 65 and 75 %), temperature (40 and 50 °C) and velocity ( $0.9 \text{ m s}^{-1}$ ), and a mass of wet sugarcane bagasse equal to  $1.35 \times 10^{-1} \text{ kg}$ .

The conditions used were the same as in the drying tests, with a wet bagasse layer presenting a volume of  $1.984 \times 10^{-3} \text{ m}^3$ , mass of  $100 \times 10^{-3} \text{ kg}$  and thickness of approximately  $3.5 \times 10^{-2} \text{ m}$ .

Mathematical models to describe the drying kinetics and isotherms are shown below. It is important to note that predictions for the drying experiments and desorption isotherms were performed with a quasi-Newton estimation method, with a convergence criterion of  $1.00 \times 10^{-4}$ , an initial value of 0.10 and an initial estimate of 0.50, for all of the model parameters.

The drying data was fitted with thirteen semi-theoretical fixed bed drying models (Table 1), where  $M_r$  for each model was obtained using equation 1:

$$M_r = \frac{X_t - X_q}{X_i - X_q} \quad (1)$$

In this series of equations,  $M_r$  is defined as the moisture ratio,  $X_t$  is the moisture content at time  $t$

(w.b.) [kg kg<sup>-1</sup>], X<sub>i</sub> is the moisture content at time 0 (w.b.) [kg kg<sup>-1</sup>], X<sub>eq</sub> is the equilibrium moisture content (w.b.) [kg kg<sup>-1</sup>], t is time [min] and k, k<sub>0</sub>, and k<sub>1</sub> are the drying constants [min<sup>-1</sup>].

The desorption data was fitted to thirteen sorption isotherm models by a non-linear regression. The mathematical models were of two types: those not considering temperature and/or vapor pressure as variables (Table 2) and those considering temperature and/or vapor pressure as variables (Table 3).

Fit was determined using the coefficient of determination (R<sup>2</sup>) and the estimated standard error (SE), calculated by:

$$R^2 = \frac{\sum_{i=1}^n (\text{PRED} - \overline{\text{OBS}})^2}{\sum_{i=1}^n (\text{OBS} - \overline{\text{OBS}})^2} \quad (2)$$

$$SE = \sqrt{\frac{\sum_{i=1}^n (\text{OBS} - \text{PRED})^2}{n}} \quad (3)$$

where OBS corresponds to observed value,  $\overline{\text{OBS}}$  corresponds to the average value of all observed values, PRED is the predicted value and n is the number of observations (JAAFAR; MICHALOWSKI, 1990).

**Table 1.** Mathematical models used to describe the fixed bed drying of sugarcane bagasse.

Model	Equation	Reference
Newton	$M_r = e^{-kt}$	Ayensu, 1997, Shi et al., 2008
Page	$M_r = e^{-k^n}$	Page (1949)
Modified Page 1	$M_r = e^{(-k^n)}$	Sobukola et al., 2008
Modified Page 2	$M_r = e^{(-kt)^n}$	Overhults et al., 1973
Henderson and Pabis	$M_r = a^{(-kt)}$	Henderson and Pabis (1961)
Logarithmic	$M_r = a^{(-kt)} + c$	Doymaz, 2008, 2006
Two term	$M_r = a^{(k_0 t)} + b^{(k_1 t)}$	Madhiyanon et al., 2009
Two term exponential	$M_r = a^{(-kt)} + (1 - a)e^{(-kat)}$	Sharafeldeen et al., 1980
Wang and Singh	$M_r = 1 + a + b^2$	Wang and Singh, (1978)
Approximation of diffusion	$M_r = a^{(-kt)} + (1 - a)e^{(-kbt)}$	Yaldiz and Ertekin, 2001
Verma	$M_r = a^{(-kt)} + (1 - a)e^{(-k_1 t)}$	Verma and Shukla (2000)
Modified Henderson and Pabis	$M_r = a^{(-k)} + b^{(k_0 t)} + c^{(k_1 t)}$	Madhiyanon et al., 2009
Midilli	$M_r = a^{(k^n)} + b$	Midilli et al., (2002)

**Table 2.** Mathematical models that were used to describe the desorption isotherm of sugarcane bagasse not considering temperature and vapor pressure of saturation as a variable.

Model	Equation	Reference
Jaafar and Michalowski	$X = \frac{S_1 S_2}{(1 - S_3 \phi)[1 + (S_2 S_3) \phi]}$	Jaafar and Michalowski (1990)
Hailwood and Horrobin	$\frac{\partial}{\partial X} = S_1 S_2 S_3 \phi^2$	Hailwood and Horrobin (1946)
Anderson and Hall	$X = \frac{S_1 S_2 S_3 \phi}{(1 - S_4 S_3 \phi)[1 + (S_2 - S_4) S_3 \phi]}$	Anderson and Hall (1948)
Peleg	$X = s_1 \exp(s_2 h \phi) + s_3 \phi^{s_4}$	Peleg (1993)
Huttig and Theimer	$\frac{X}{S_1} = \frac{\phi S_2}{1 + \phi S_2}$	Huttig and Theimer (1950)
Caurie	$h X = \ln(S_1) - \phi S_2$	Caurie (1970)
Kühn	$X = \frac{S_1}{h \phi} + S_2$	Kühn (1964)
5 <sup>th</sup> degree polynomial	$\phi = S_1 + S_2 X + S_3 X^2 + S_4 X^3 + S_5 X^4$	(Pakowski, 1995)
Harkins and Jura	$h \phi = S_1 - \frac{S_2}{X^2}$	Harkins and Jura (1944)
Halsey	$\phi = \frac{S_1}{e^{S_2 X^{S_3}}}$	Halsey (1983)

**Table 3.** Mathematical models used to describe the desorption isotherm of sugarcane bagasse considering temperature and vapor pressure of saturation as a variable.

Model	Equation	Reference
Modification Henderson I	$h(1 - \phi) = -s_1 T + s_2 X^{s_3}$	(Pakowski, 1995)
Modification Henderson II	$\phi = s_3 \left( 1 - \exp(-s_1 X^{s_2}) \right)$	(Pakowski, 1995)
Modification Henderson III	$\phi = 1 - \exp[-s_1 (s_2 + T) X^{s_3}]$	(Madamba et al., 1995)

**RESULTS AND DISCUSSION**

Figures 2 and 3 show the particle size distribution characterized by sieve analysis, with Figure 2 showing the size distributions of sugarcane bagasse from the Junqueira sugar company (COSAN) and Figure 3 showing the size distribution of bagasse from the Ester sugar company.

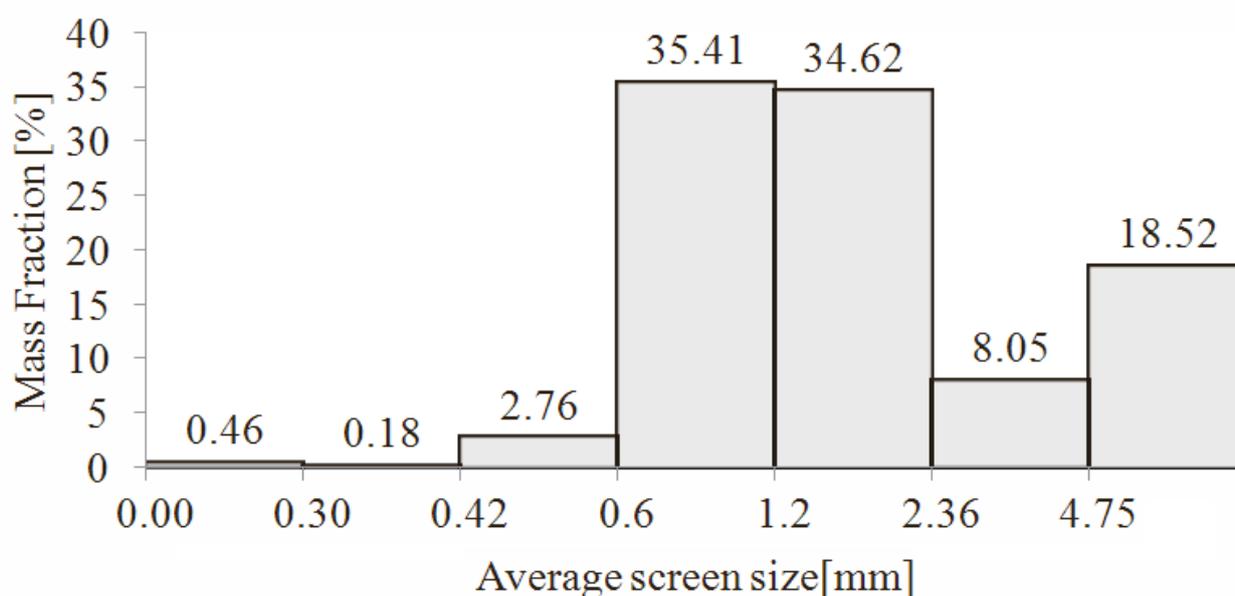
Sugarcane bagasse contains diverse particle sizes and shapes. The difference between size distributions shown in Figure 2 and 3 is mainly related to the moisture content of the samples. Because bagasse from the Junqueira sugar company presents higher moisture content, the smaller particles of this bagasse tend to agglomerate.

Figure 4 shows the predicted drying results obtained with the Modified Page 2 model. If considering agreement based on the R<sup>2</sup> and standard error (SE), this model provided the best agreement with the experimental data for all

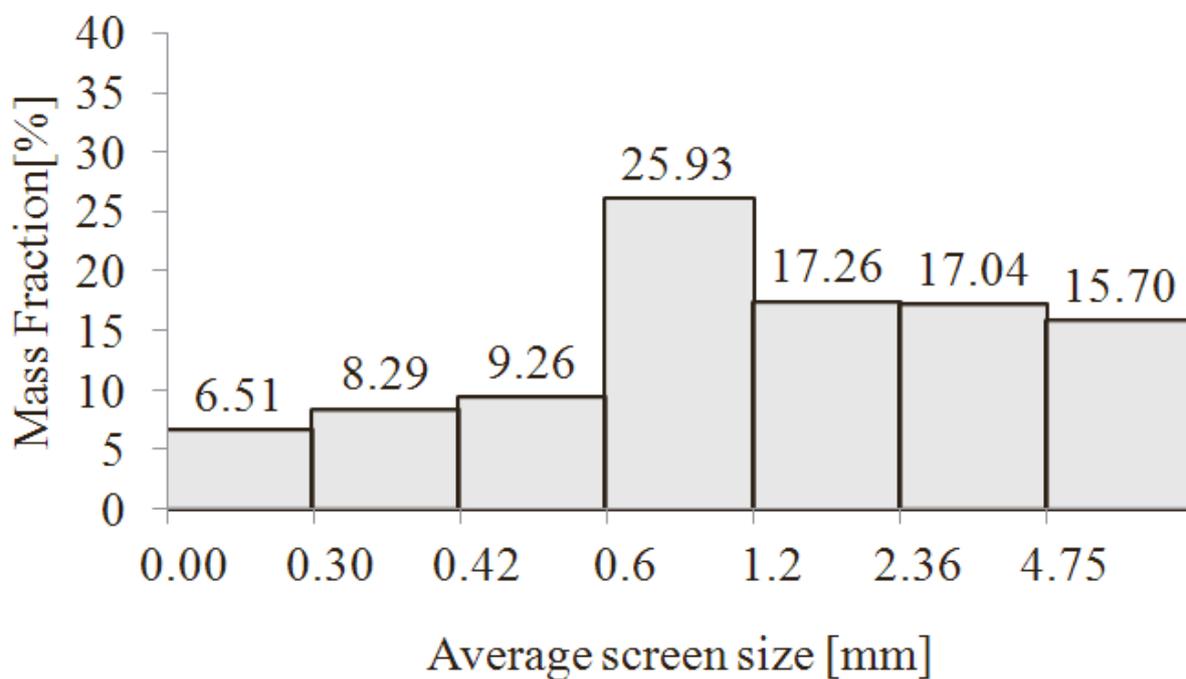
studied temperatures. This is an empirical model that is traditionally applied to predict drying of diverse agricultural products (DOYMAZ, 2004; GUNHAN *et al.*, 2005; CAI; CHEN, 2008). It was observed (Figure 4) that the drying rate is directly proportional to the temperature, corroborating innumerable drying results from literature, such as the works of Gunhan *et al.* (2005), Hossain *et al.* (2007); Shi *et al.* (2008) and Sobukola *et al.* (2008).

It was observed that for all three temperatures used in the drying process, the R<sup>2</sup> values describing the agreement of most of the mathematical models presented with the experimental data (Table 4) were close to 0.9000, indicating a satisfactory representation of the drying process. The exception to this was the Modified Page 1 model which showed no agreement.

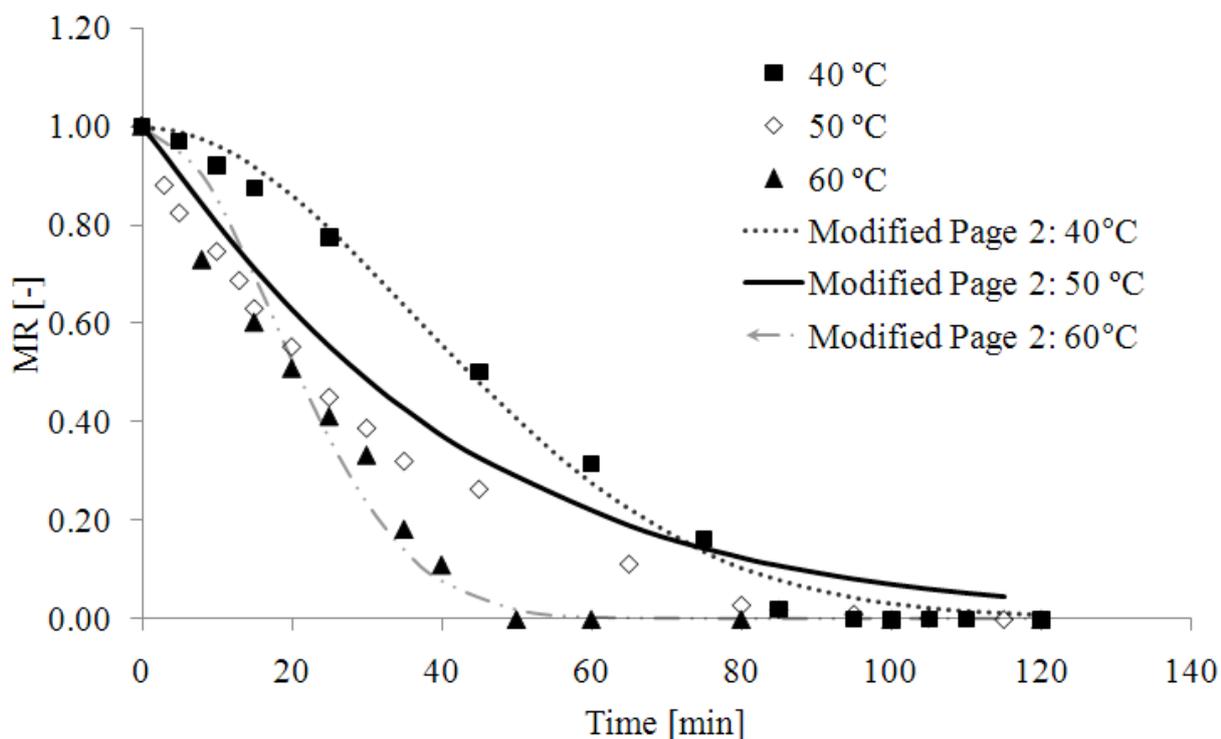
Table 5 and 6 show the parameters that were obtained when the mathematical models were compared to the experimental sugarcane bagasse desorption isotherms at 40 and 50 °C, respectively.



**Figure 2.** Particle size distribution, determined by sieve analysis, of bagasse (the Junqueira sugar company) with a moisture content of 71.0 % (w.b.).



**Figure 3.** Particle size distribution, determined by sieve analysis, of bagasse (Ester sugar company) with a moisture content of 8.0 % (w.b.).



**Figure 4.** Drying kinetics of sugarcane bagasse at different temperatures and comparison with the Modified Page 2 model.

**Table 4.** Agreement of mathematical models with the experimental sugarcane bagasse drying results at the temperatures of 50, 60 and 70 °C.

Equation	Constants	50 °C	60 °C	70 °C
Newton (Ayensu, 1997; Shi et al., 2008)	k	0.084785	0.099209	0.138714
	R <sup>2</sup>	0.92273	0.99988	0.92639
	SE	0.00461	0.00448	0.00437
Page (1949)	k	0.012002	0.014503	0.017706
	n	1.755319	1.779354	1.960761
	R <sup>2</sup>	0.99611	0.99999	0.99865
	SE	0.00232	0.00210	0.00008
* Modified Page 1 (Sobukola, et al. 2008)	-----	-----	-----	-----
* Modified Page 2 (Overhults et al., 1973)	k	0.080491	0.09262	1.01E-05
	n	1.755319	1.77935	5.18E-10
	R <sup>2</sup>	0.99999	0.99655	-----
	SE	0.00232	0.00210	0.06026
Henderson and Pabis (1961)	a	1.170492	1.17534	1.193599
	k	0.098122	0.11437	0.160387
	R <sup>2</sup>	0.95056	0.9524	0.95220
	SE	0.00295	0.00290	0.00284
Logarithmic (Doymaz, 2006, 2008)	a	1.523805	1.35218	1.247573
	k	0.049851	0.07269	0.132021
	c	-0.43327	-0.24005	-0.0849
	R <sup>2</sup>	0.98881	0.98155	0.96605
	SE	0.00067	0.00112	0.00202

**Table 5.** Parameters of the desorption isotherms model and agreements for sugarcane bagasse at 40 °C, not considering temperature and vapor pressure of saturation as a variable.

Models	Constants						
	S <sub>1</sub>	S <sub>2</sub>	S <sub>3</sub>	S <sub>4</sub>	S <sub>5</sub>	R <sup>2</sup>	SE
Jaafar and Michalowski (1990)	0.031	92849	1.12057	-----	-----	0.9604	0.0097
Hailwood and Horrobin (1946)	-556	1781.7	-1379.7	-----	-----	-----	0.0525
Anderson and Hall (1948)	0.031	118.96	26.5359	0.0422	-----	0.9603	0.0098
Peleg (1993)	0.137	1.7407	0.13755	1.7407	-----	0.7547	0.0243
Huttig and Theimer (1950)	305.8	0.0004	-----	-----	-----	0.7466	0.0248
Caurie (1970)	0.014	-3.345	-----	-----	-----	0.8535	0.0188
Kühn (1964)	-0.05	0.0050	-----	-----	-----	0.9090	0.0149
Polinômio de 5° (Pakowski, 1995)	-12.0	541.28	-8510.0	56975	-13224	0.9090	0.0074
Harkins and Jura (1944)	-0.17	0.0030	-----	-----	-----	0.9438	0.0405
Halsey (1983)	0.799	0.0006	2.5575		-----	0.9662	0.0314

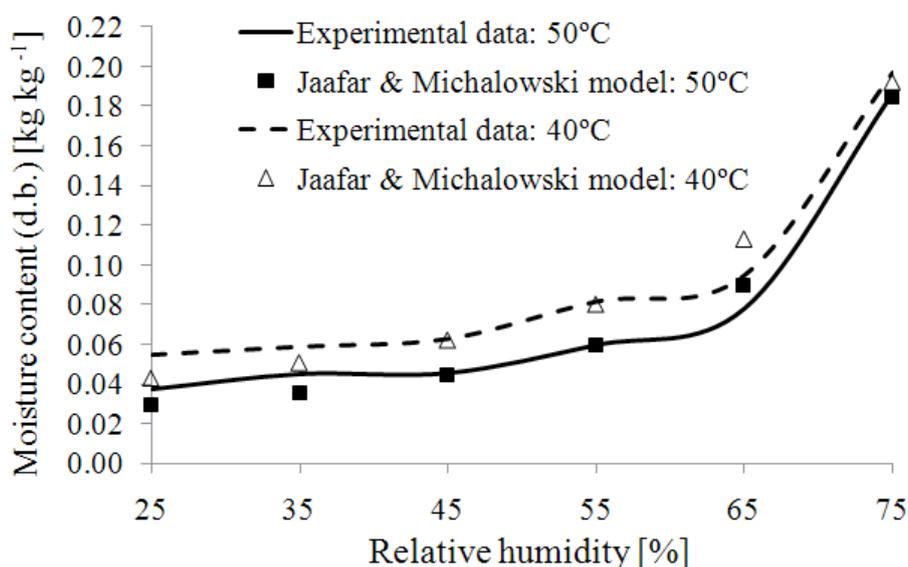
**Table 6.** Parameters of the desorption isotherm models and agreements for sugarcane bagasse at 50 °C, not considering temperature and vapor pressure of saturation as a variable.

Models	Constants					R <sup>2</sup>	SE
	S <sub>1</sub>	S <sub>2</sub>	S <sub>3</sub>	S <sub>4</sub>	S <sub>5</sub>		
Jaafar and Michalowski (1990)	0.0207	33498	1.1835	-----	-----	0.9809	0.0071
Hailwood and Horrobin (1946)	-658	2114.9	-1643	-----	-----	0.3968	0.0398
Anderson and Hall (1948)	0.0207	9901.3	4.1298	0.2866	-----	0.9808	0.0072
Peleg (1993)	0.1837	2.7756	0.18367	2.7756	-----	0.7988	0.0229
Huttig and Theimer (1950)	375.64	0.0003	-----	-----	-----	0.6864	0.0287
Caurie (1970)	0.0052	-4.662	-----	-----	-----	0.8774	0.0179
Kühn (1964)	-0.051	-0.014	-----	-----	-----	0.8929	0.0168
Polinômio de 5° (Pakowski, 1995)	-2.014	112.46	-1844.6	13437	-34084	0.9753	0.0268
Harkins and Jura (1944)	-0.216	0.0015	-----	-----	-----	0.9620	0.0333
Halsey (1983)	0.7671	0.0004	2.3423	-----	-----	0.9551	0.0362

Regarding the equations that do not consider temperature and vapor pressure of saturation as a variable, the best values of  $R^2$  were obtained with the equation of Jaafar and Michalowski (1990) for both tested temperatures (40 and 50 °C). This result is in agreement with the work of Nascimento *et al.* (2008), in which the authors compared 41 mathematical models of sorption isotherms for 53 food products and found that the best agreement was obtained with the model of Jaafar and Michalowski (1990). A comparison between the experimental data and the data predicted by the Jaafar and Michalowski model for temperatures of 40 and 50 °C are shown

in Figure 5. Table 7 shows the parameters obtained by comparing the mathematical models, in which temperature was a variable, with the sugarcane bagasse desorption isotherms.

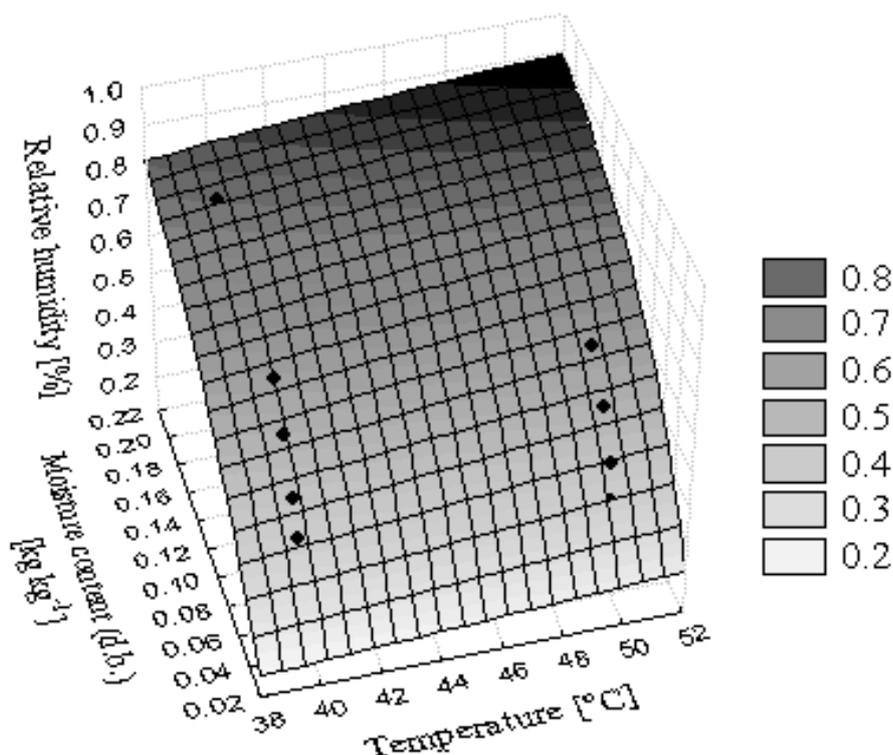
With respect to the equations that consider temperature and vapor pressure of saturation as a variable, the best agreement with the experimental data for the two temperatures was obtained with the modified Henderson II model (PAKOWSKI, 1995), due to the higher  $R^2$  value (0.89090) and lower SE value (0.07980). A comparison between the experimental data and the data predicted using the modified Henderson II model is shown in Figure 6.



**Figure 5.** Desorption isotherm of sugar cane bagasse compared to the Jaafar and Michalowski model at 40 and 50 °C.

**Table 7.** Parameters of the desorption isotherm models and agreements for sugarcane considering temperature and vapor pressure of saturation as a variable.

Models	Constants				
	$S_1$	$S_2$	$S_3$	$R^2$	SE
Modification Henderson I (Pakowski, 1995)	0.0016	-7.287	0.9446	0.7552	0.1195
Modification Henderson II (Pakowski, 1995)	0.7600	2.9944	1.7771	0.8909	0.0798
Modification Henderson III (Madamba et al., 1995)	0.1921	-3.502	0.92697	0.8000	0.1080



**Figure 6.** Comparison of experimental data for the sugarcane bagasse isotherm with the isotherm predicted by the Modified Henderson II model.

**CONCLUSIONS**

- Of the 13 mathematical models tested, the best prediction of the kinetics of fixed bed drying of sugarcane bagasse at 40, 50 and 60 °C was obtained with the Modified Page 2 model;
- Among the mathematical models in which temperature is not considered a variable, the model of Jaafar and Michalowski (1990) provided the best agreement with experimental data at 40 and 50 °C for the sugarcane bagasse desorption isotherms. Of those in which temperature is considered a variable, the best agreement with experimental data was obtained with the modified Henderson II equation.

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