The methodology of generalized drying curves applied to paper drying

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ABSTRACT. Aspects in the drying of paper (cellulose) sheets over a heated surface under natural convection condition inside an oven are provided. Three different operational situations are carried out: (1) for initial paper moisture contents: sheets of only one hand sheet of paper, drying temperature of 100 ºC and initial moisture content from 130 to 180% (dry basis - d.b.); (2) for drying temperature: sheets of only one hand sheet of paper, initial moisture content of about 150% (d.b.) and drying temperature from 50 to 110 ºC; (3) for sheet thickness: drying temperature of 100 ºC, initial moisture content of about 150% (d.b.) and multi-layer sheets of one to five hand sheets of paper. The influence of these variables in drying curves behavior is studied through the theory of generalized drying curves, analyzed individually for each effect and for all together. Finally, the possibility of fitting them is discussed.

Key words*: drying, paper drying, generalized drying curves.*

RESUMO. Aplicação da metodologia de curvas generalizadas à secagem de papel. Este trabalho tem como objetivo estudar alguns aspectos relacionados à secagem de folhas de papel (celulose) sobre uma superfície aquecida e regime de convecção natural no interior de uma estufa. Foram analisadas três situações: - para a umidade inicial: amostras de 1 folha de papel, temperatura de secagem de 100 ºC e umidade inicial de 130 a 180% (b.s.); - para a temperatura de secagem: amostras de 1 folha de papel, umidade inicial de 150% (b.s.) e temperatura de 50 a 110 ºC;- para a espessura das amostras: temperatura de 100 ºC; umidade inicial de 150% (b.s.) e amostras com de 1 a 5 folhas de papel. A influência destas variáveis no comportamento da secagem foi estudada a partir de uma proposta de curvas de secagem generalizadas, analisadas individualmente e para os três efeitos em conjunto, sendo proposto um modelo para ajustá-las.

Palavras-chave: secagem, secagem de papel, curvas de secagem generalizadas.

This work presents some aspects in the drying of paper (cellulose) sheets over heated surfaces, initially developed in the Laboratory of Particulate Systems of PEQ/Coppe - UFRJ and, nowadays, in the Separation Processes Laboratory of DEQ/UEM.

The main objective of this work is to verify the influences of some variables upon contact paper drying. Hence, the influences of initial paper moisture content, drying (heated surface) temperature and sheet thickness were taken into account in the behavior of the drying curves under different operational situations and natural convection conditions inside an oven.

Next, due to its simplicity and work facility, it was verified whether a theory of generalized drying curves could be applied to drying results,

individually for each effect and for all together. Finally, the possibility of fitting these curves was discussed.

Generalized drying curves - a brief review

Brunello (1992) presented a compilation of papers in which the drying of grains is successfully analyzed under a generalized point of view. In these works reduced moisture, defined as the ratio of moisture content (X) and the initial one (X_0), or to the initial unbounded moisture content ($X_0 - X_e$), was correlated to a reduced time, defined as the ratio between the product of the drying rate (dX/dt) at $t = 0$ and the time, and the initial moisture content (X_0), or ($X_0 - X_e$).

Günther *et al*. (1984) and Brunello *et al*. (1992) studied the behavior of fixed bed drying of cellulose pulp at different operational conditions of temperature, humidity and velocity of the drying air, and for different bed thickness and initial moisture content (but with the same dry basis mass of pulp). They verified that there was no influence of the initial moisture content of the samples. They thus suggested a modification of the dimensionless time, now defined as a ratio of the product of the drying rate (dX/dt) at t = 0 and the time, to the initial mass water content, to eliminate the bed thickness influence. Brunello *et al*. (1992), also analyzing and suggesting a set of equations to correlate the air temperature and velocity effects in the initial rate of drying, obtained good results.

Krasnikov (1980) and Ciesielczyk (1996) brought a discussion on the methods of drying curves generalization based upon the regularity of moisture transfer during drying processes. Based on this work, Ciesielczyk (1996) suggested a universal drying curve relating the same dimensionless moisture (X/X_0) but with the first period constant drying rate (N_C) and X_0 in the dimensionless time. It was successfully tested against the experimental results of the drying of ammonium sulfate, silica-gel and sand in a batch fluidized drier.

Material and methods

Material. The material used in the experiments consisted of individual hand sheets of short-fiber cellulose (eucalyptus) approximately 1 mm thick, with no filler, and environment moisture content of 7 to 10% (d.b.). The sheets' moisture content (d.b.) was determined by the method of drying in an oven at 105 °C, until constant weight.

Drying schematic model. The hypothesis used in this study is based on the simplification of the industrial cylindrical geometry as a flat (rectangular) one, since the cylinder radius is much bigger than the thickness of the sheets. Figure 1 shows the model.

Drying curves. Drying process was carried out in an oven with no air circulation (natural convection regime), as shown in Figure 2. The heating surface temperature was controlled by a thermocouple. Samples dimensions were (15 x 10) cm and they were periodically weighted in a analytical scale to measure their moisture content.
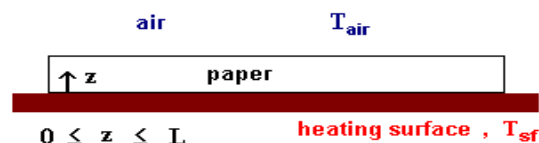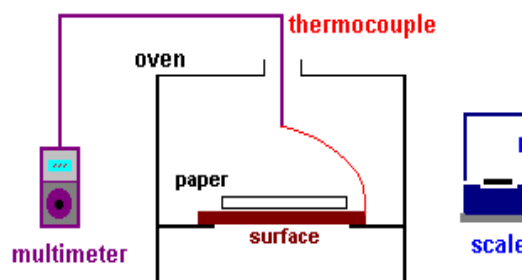

Figure 1. Drying scheme model

Figure 2. Drying inside oven – Experimental setup

The drying curves were built for different operational conditions according to the variables (effect) studied:
- initial paper moisture effect: sheets of only one hand sheet of paper, drying temperature of 100 ºC and initial moisture content from 130 to 180% (d.b.);
- drying temperature effect: sheets of only one hand sheet of paper, initial moisture content of about 150% (d.b.) and drying temperature from 50 to 110 ºC;
- sheet thickness effect: drying temperature of 100 ºC, initial moisture content of about 150% (d.b.) and multilayer sheets of one to five hand sheets of paper.

Details about drying curves construction can be seen in Motta Lima and Massarani (1996a,b,c) and Motta Lima *et al*. (1998).

Results and discussion

Drying curves. Drying curves obtained for conditions at the experimental heading are presented in Figures 3, 4 and 5 and show the effects of initial moisture content, drying temperature and sheet thickness (based upon the number of individual hand sheets of the sample - NS), respectively.

These results show (Motta Lima and Massarani, 1996 a,b,c and Motta Lima *et al*., 1998):
- the weak influence of initial moisture content in the kinetics (drying rates) of the process, as may be noted from the parallel shape of the curves during the constant rate periods (from t = 0 to about 24 min) and from their mutual convergence at the falling rate ones;

- the strong dependence of drying process time and kinetics upon drying (heated surface) temperature;
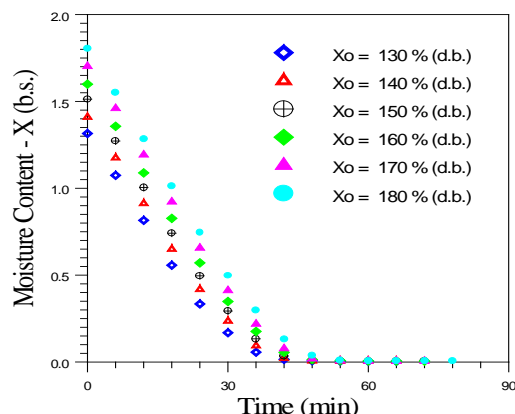- the negative effects of incoming sheet thickness on drying process time and drying rates.

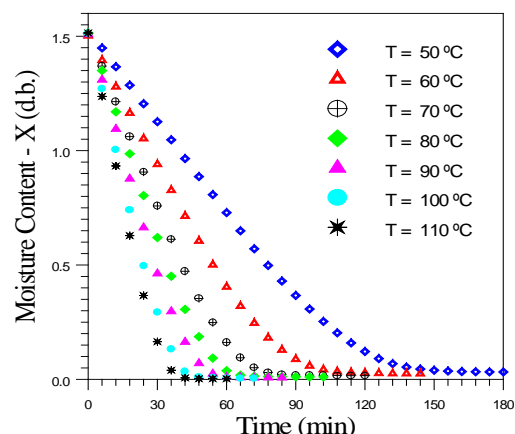**Figure 3.** Drying curves - Initial moisture content

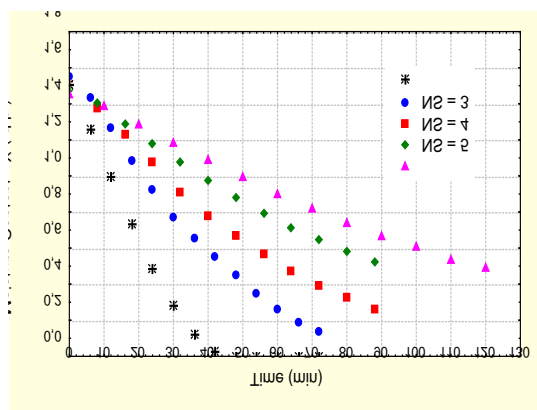**Figure 4.** Drying curves - Drying temperature

Figure 5. Drying curves - Sheet thickness

Generalized drying curves. To verify whether the methodology of generalized drying curves might be

applied to drying results, a method similar to that discussed in the work of Ciesielczyk (1996) was elaborated in which a dimensionless moisture content (Y), defined by the ratio (X/X_0), is correlated to a dimensionless time variable (t_{Ad}), defined by drying time (t), constant drying rate (N_C) and initial moisture content (X_0), as $t_{Ad} = N_C t / X_0$.

Tables 1, 2 and 3 present the values of the constant drying rates (N_C) obtained from the experimental curves and their respective initial moisture content (X_0) (Motta Lima and Massarani, 1996b; Motta Lima *et al.*, 1998).

Table 1. Constant drying rate - Initial moisture content

X_0 (%)	130	140	150	160	170	180
X_0 (d.b.)	1.3151	1.4094	1.5129	1.5987	1.7014	1.8046
N_C (min^{-1})	0.0418	0.0418	0.0424	0.0427	0.0435	0.0436

Table 2. Constant drying rate - Drying temperature

T (°C)	50	60	70	80	90	100	110
X_0 (d.b.)	1.5131	1.5022	1.5102	1.5151	1.5081	1.5129	1.5145
N_C (min^{-1})	0.0131	0.0186	0.0250	0.0299	0.0352	0.0424	0.0487

Table 3. Constant drying rate - Sheet thickness

Thickness - NS	1	2	3	4	5
X_0 (d.b.)	1.5129	1.5577	1.5127	1.4891	1.4644
N_C (min^{-1})	0.0424	0.0267	0.0187	0.0128	0.0093

Figures 6 to 9 present the generalized drying curves for the three effects studied, individually and all together.

Results for the initial moisture content and drying temperature effects were convergent, but became worse when the sheet thickness effect was included (see Figure 9), albeit still accepted. These results show that the suggestion of generalized drying curves may be successfully applied in the analysis of the influence of these variables in the drying process.
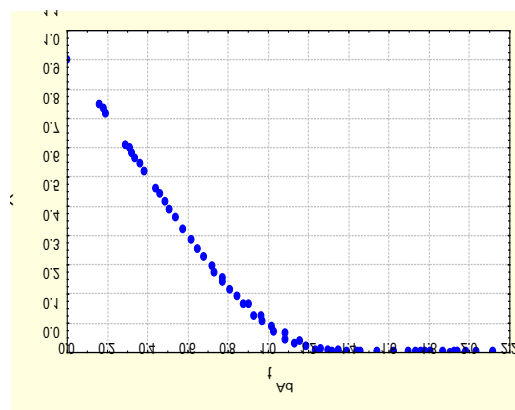

Figure 6. Generalized drying curve - Initial moisture content effect
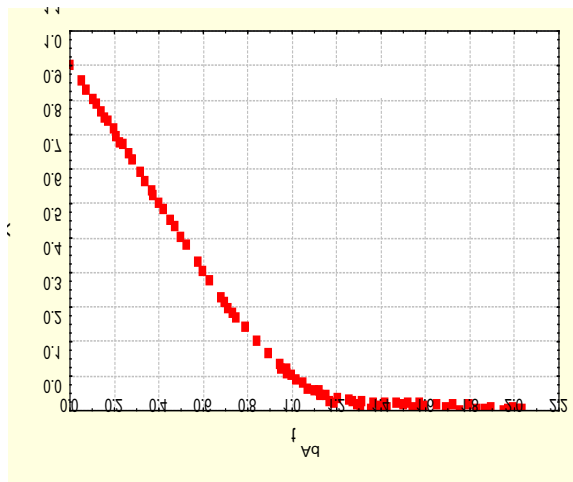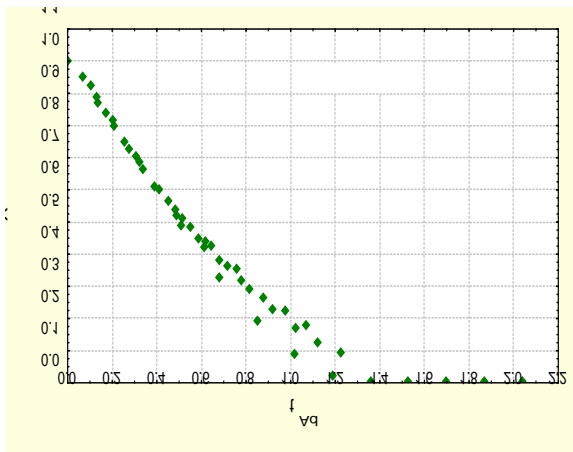
Figure 7. Generalized drying curve - Temperature effect

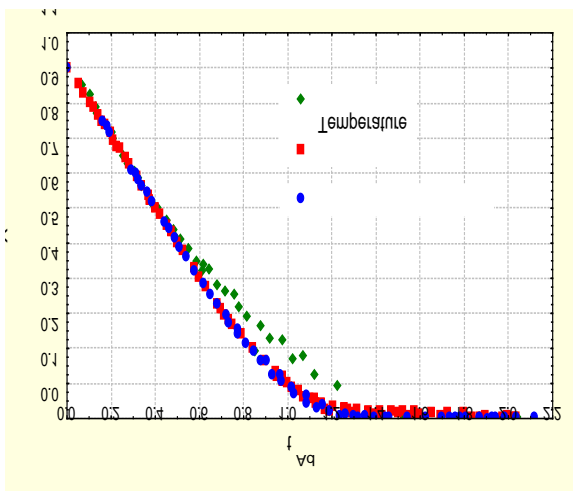**Figure 8.** Generalized drying curve - Sheet thickness effect

Figure 9. Generalized drying curve - General

Generalized drying curves modelling. Page (1949) equation (Equation 1) was used to fit the

generalized drying curves, initially for both initial moisture content and drying temperature, because of their better performance; later, for the three effects together. The fitting results, Equations 2 and 3, are shown, respectively, in Figures 10 and 11.

$$Y = \exp(-k \cdot t_{Ad}^{n}), \tag{1}$$

where $Y = X/X_0$ and $t_{Ad} = N_C \, t / X_0$.

- Considering only initial moisture content and drying temperature effects

$$Y = \exp[-(2,1719) \cdot t_{Ad}^{1,5733}], \tag{2}$$

With $R^2 = 0,9985$, $F = 588,2$.

- General, with the three effects:

$$Y = \exp[-(2,0504) \cdot t_{Ad}^{1,5306}], \tag{3}$$

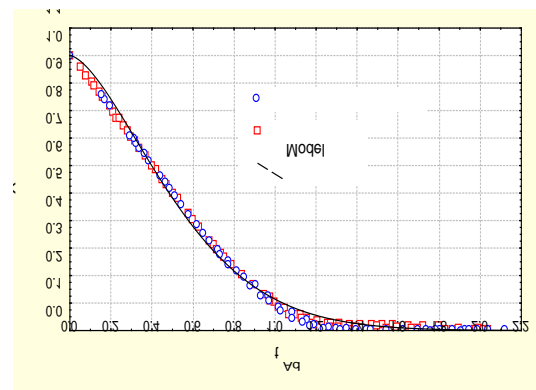With $R^2 = 0,9968$, $F = 322,1$.

Figure 10. Generalized drying curves fitting - Initial moisture content and temperature effects
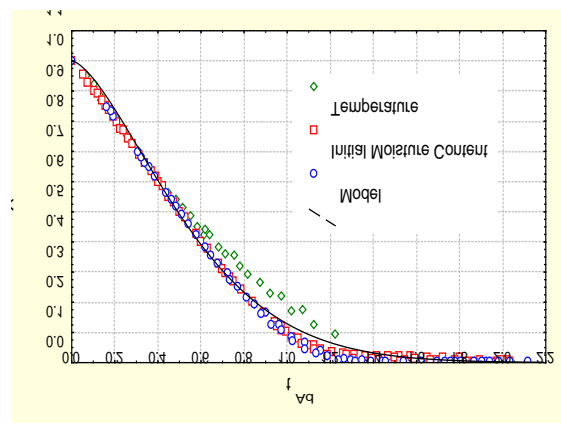

Figure 11. Generalized drying curves fitting - General

As one may see, fitting results show a very good performance, mainly in the case of adjusting only the initial moisture content and drying temperature

effects. This is confirmed by the greatest values obtained for R^2 and the F factor statistics.

Constant period drying rate dependence upon temperature and sheet thickness. The dependence of constant period drying rate (N_C, [min^{-1}]) upon temperature (T_{sf}, [^{o}C]) and sheet thickness (in NS basis) was previously analyzed, respectively, in the works of Motta Lima and Massarani (1996a,b) and Motta Lima *et al*. (1997). The authors suggested the follow expressions:

$$N_C = -0,017 + (5,94 \times 10^{-4}).T_{sf} \qquad (4)$$

$$N_C = (3,165 + NS)^{-2,21} \qquad (5)$$

Notation

d.b.	dry basis	[-]
F	F factor statistics, $\equiv$ ratio between the mean of the square of the predicted values and the mean of the square of the estimation residuals	[-]
k	"drying constant", Equation 1	[-]
n	parameter of Equation 1	[-]
N_C	constant drying rate	[1/T]
NS	number of individual hand sheets	[-]
t	drying time	[T]
t_{Ad}	dimensionless drying time ($= N_C t / X_0$)	[-]
T_{air}	drying air temperature	[θ]
T_{sf}	heating surface temperature (drying temperature)	[θ]
X	moisture content (d.b.)	[-]
X_0	initial moisture content (d.b.)	[-]
X_e	equilibrium moisture content (d.b.)	[-]
Y	dimensionless moisture content ($= X / X_0$)	[-]
z	spatial variable	[L]

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