Acta Scientiarum 22(5):1229-1233, 2000.
ISSN 1415-6814.

Generalized drying rate curves in conductive/convective paper drying

Oswaldo Curty da Motta Lima*, Nehemias Curvelo Pereira and Marlon Alessandro Lincoln dos Santos Machado

*Departamento de Engenharia Química, Universidade Estadual de Maringá, Av. Colombo, 5790, 87020-900, Maringá-Paraná, Brazil. *Author for correspondence. e-mail: oswaldo@deq.uem.br*

ABSTRACT. The drying of paper (cellulose) sheets over heated surfaces, under natural and forced air conditions is studied. Samples were placed over the upper surface of a metallic box heated by a thermostatic bath. The system is exposed to ambient air under two different conditions: natural convection and forced convection provided by an adjustable blower. Samples consisted of pure eucalyptus pressed cellulose (about 1 mm thick). Moisture content of sheets (dry basis, d.b.) was determined from their constant weight in an oven at a temperature of 105°C. The influence of initial paper moisture content, drying (heated surface) temperature and air velocity on the drying rate curves behavior was analyzed under different drying conditions and studied through generalized drying rate curves. A model was then successfully employed to fit them.

Key words: drying, paper drying, generalized drying rates.

RESUMO. Taxas de secagem generalizadas na secagem condutiva/convectiva de papel. Este trabalho teve como objetivo estudar alguns aspectos relacionados à secagem de folhas de papel (celulose) sobre superfícies aquecidas, em regime de convecção natural e forçada. Os experimentos foram realizados com folhas de celulose de eucalipto prensadas colocadas sobre a face superior de uma caixa metálica aquecida por um banho termostático, submetida, ou não, a uma corrente de ar fornecida por um soprador. O conteúdo de umidade (base seca, b.s.) das amostras era determinado a partir de seu peso seco em estufa a 105ºC. A influência da umidade inicial das amostras, da temperatura de secagem (placa aquecida) e da velocidade do ar no comportamento das curvas de taxa de secagem foi observada para diferentes condições de secagem, sendo posteriormente estudada a partir de uma proposta de curvas de taxa de secagem generalizadas. Em seguida, os resultados obtidos foram adequadamente ajustados por um modelo.

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

This work presents a study related to some aspects in the conductive/convective drying of paper (cellulose) sheets over heated surfaces under natural and forced air conditions developed at the Separation Processes Laboratory (DEQ/UEM). Its aim is to analyze the contact drying of paper and the influence of the samples' initial moisture content, drying (heated surface) temperature and air velocity in the behavior of the drying curves under different operational conditions.

It was verified whether Hodges (1982) generalized (normalized) drying rate curves theory may be applied to drying results. Generalized drying rate curves are analyzed individually for each air condition mentioned above. Verification of Hodges's (1982) proposed model will also be undertaken to see if it fits them.

Material and methods

Material. Individual handsheets (15 x 10 cm) of short-fiber cellulose (eucalyptus), approximately 1 mm thick (basis weight: 876 g/m^2), with no filler, and ambient moisture content ranging from 7 to 10% (db) were used. The sheets' moisture content (d.b.) was determined by their constant dry weight in an oven at a temperature of 105°C.

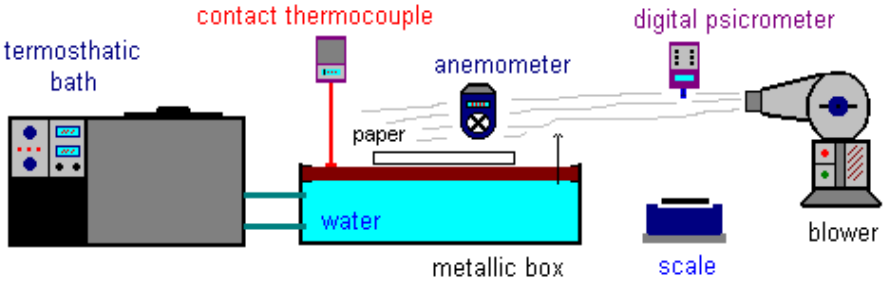


Figure 1. Experimental apparatus

Experimental apparatus. The experimental apparatus, Figure 1, consists of a metallic box with an upper surface heated by water from a thermostatic bath. Paper samples are placed on the surface. The system is submitted to ambient air under two different conditions: natural convection and forced convection provide by an adjustable blower. Heating surface temperatures were adjusted and periodically verified with a contact thermocouple; air velocities over samples surfaces were measured with a portable anemometer (forced convection); and samples were periodically weighed in an analytical scale for their water content.

Drying rate curves. Drying process was carried out for both as follow:

- natural convection: initial moisture content of paper sheets ranging from 1.3 to 1.7 (kg water / kg dry solid) and drying (heated surface) temperature from 60 to 90 °C.
- forced convection: initial moisture content of about 150 % (db), drying temperature (heated surface) ranging from 60 to 90 °C and drying air velocity from 2 to 6 m/s.

Drying rate curves were built by drying curves derivation (finite differences), Motta Lima *et al.* (2000). Details about experimental apparatus and drying curves construction are found elsewhere in the works of Motta Lima *et al.* (1998) and Motta Lima *et al.* (1999).

Results and discussion

Drying rate curves. Drying rate curves for the conditions at the experimental heading are shown in Figures 2 to 5 (natural convection) and Figures 6 to 9 (forced convection), and are found elsewhere in the works of Motta Lima *et al.* (2000a) and Motta Lima *et al.* (2000b), respectively.

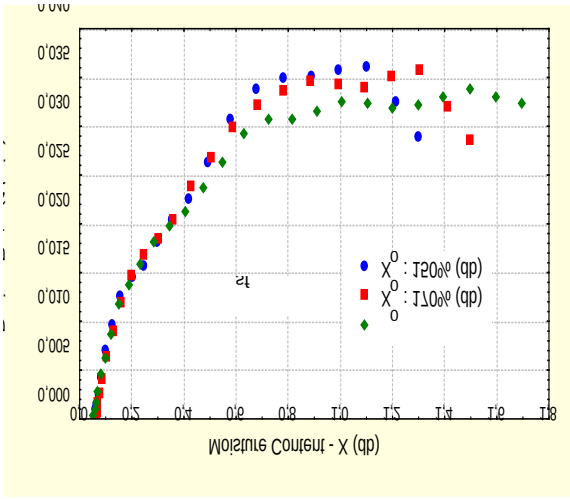


Figure 2. Drying rates - Natural convection – 60 °C

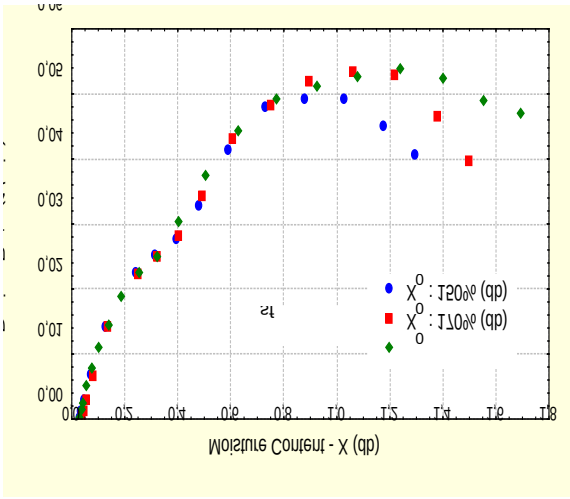


Figure 3. Drying rates - Natural convection – 70 °C

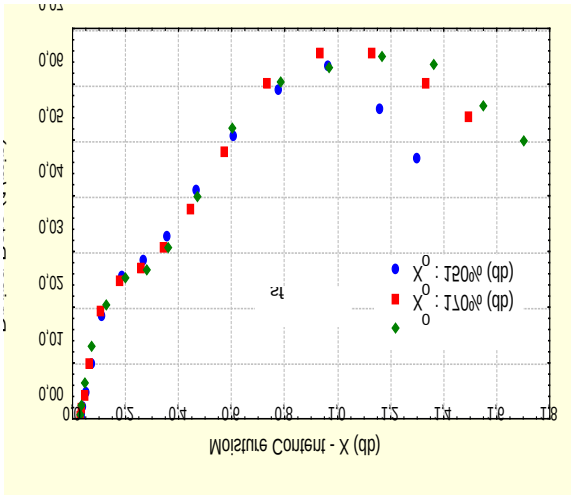


Figure 4. Drying rates - Natural convection – 80 ºC

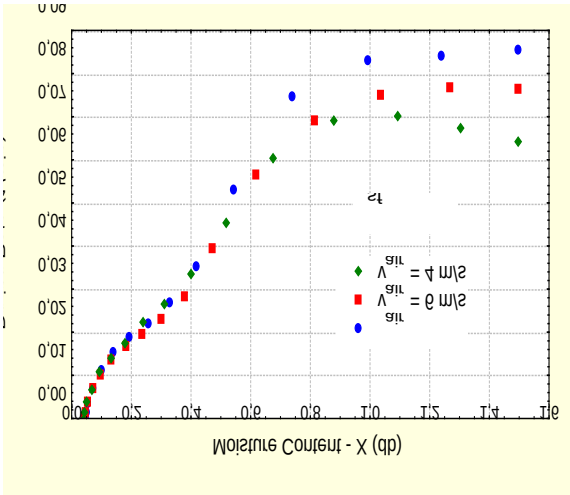


Figure 7. Drying rates - Forced convection – 70 ºC

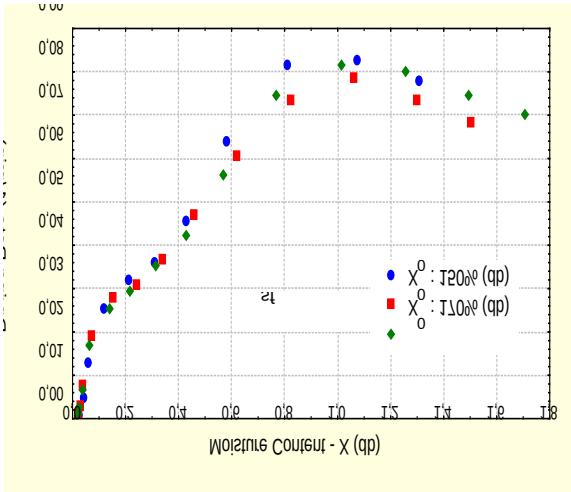
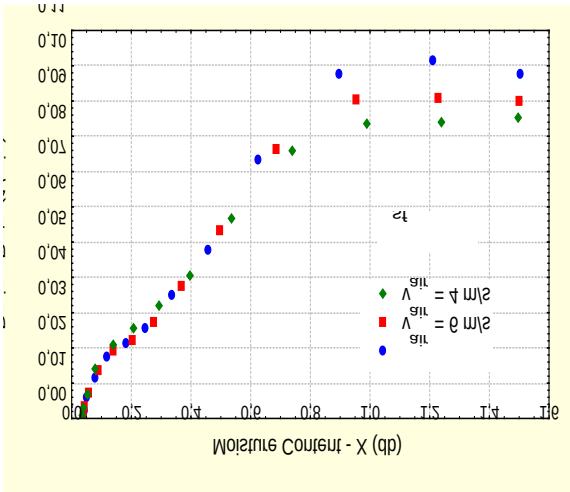
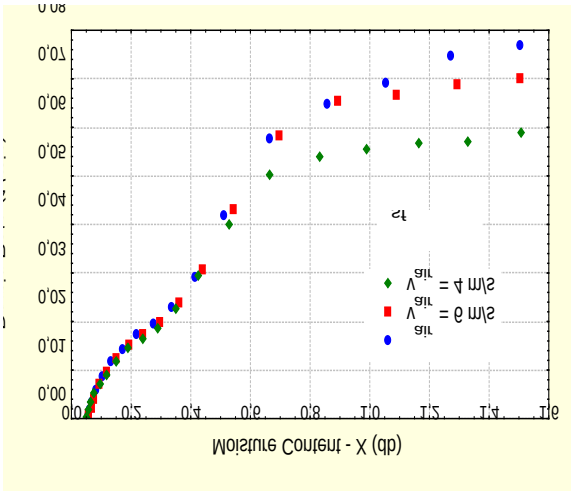


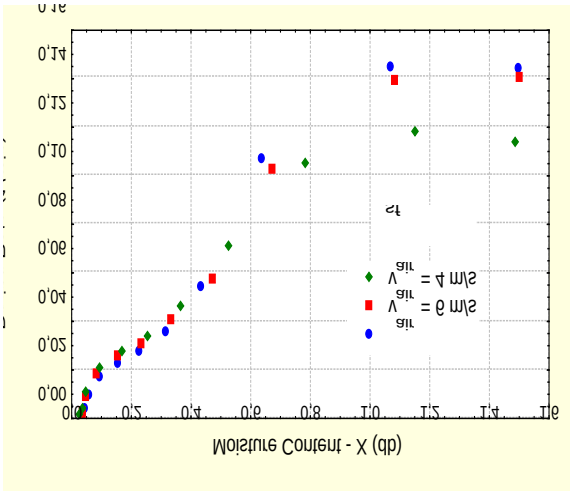
Figure 5. Drying rates - Natural convection – 90 ºC



Figures 8. Drying rates - Forced convection – 80 ºC



Figures 6. Drying rates - Forced convection – 60 ºC



Figures 9. Drying rates - Forced convection – 90 ºC

Generalized drying rate curves. The methodology of generalized drying rate curves discussed by Hodges (1982) is applied to the drying rate results. Thus, a normalized (dimensionless) drying rate (NDR), defined by the ratio (N/N_C), is correlated to the sheet moisture content (X). Results are shown in Figures 10 and 11, with values for N_C obtained from the experimental drying curves presented in Tables 1 and 2, respectively, for the natural and forced convection experiments.

Table 1. Constant drying rate - Natural convection

T_{sf} (°C)		60			70	
N_C (kg/m^{2}s) (x 10^3)	0.511	0.496	0.467	0.686	0.730	0.745
T_{sf} (°C)		80			90	
N_C (kg/m^{2}s) (x 10^3)	0.847	0.920	0.905	1.183	1.080	1.124

Table 2. Constant drying rate - Forced convection

T_{sf} (°C)		60			70	
v_{air} (m/s)	2.0	4.0	6.0	2.0	4.0	6.0
N_C (kg/m^{2}s) (x 10^3)	0.818	0.964	1.022	1.007	1.080	1.197
T_{sf} (°C)		80			90	
v_{air} (m/s)	2.0	4.0	6.0	2.0	4.0	6.0
N_C (kg/m^{2}s) (x 10^3)	1.212	1.299	1.445	1.650	1.986	2.102

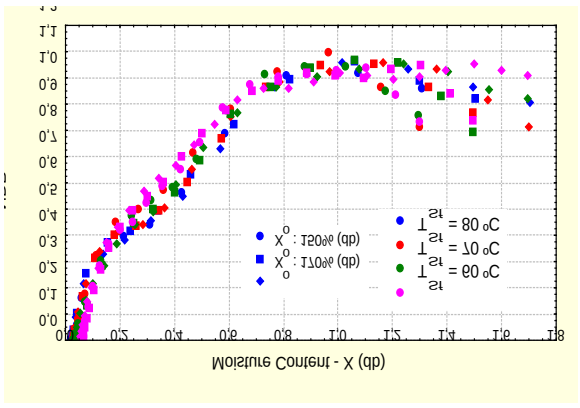


Figure 10. Generalized drying rate - Natural convection

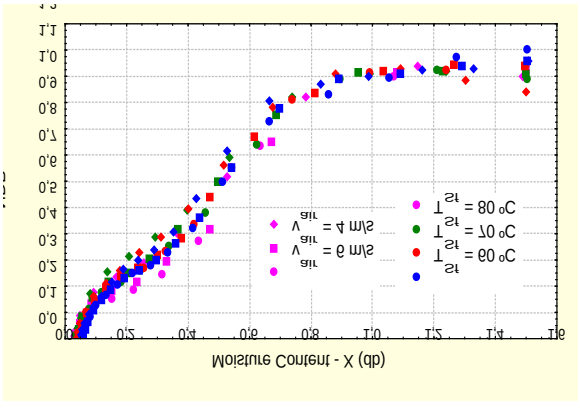


Figure 11. Generalized drying rates - Forced convection

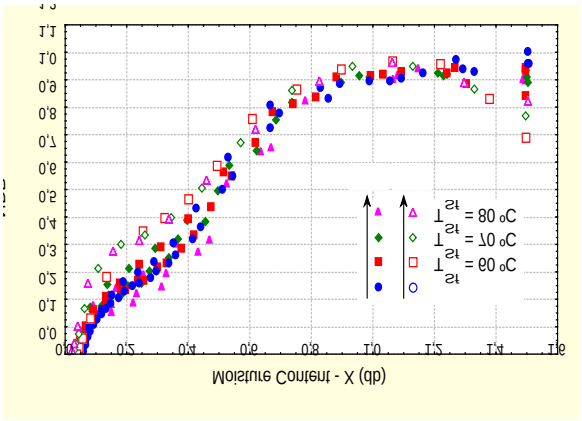


Figure 12. Generalized drying rate - Natural and forced convection

Generalized drying rate curves modeling. Equation 1, suggested by Hodges (1982), was used to model the generalized drying rate curves for natural and forced convection combined (Figure 12). Results are shown below (Equation 2) and in Figure 13.

$$NDR = 1 - \exp[-(X/a)^{(b)}], \quad (1)$$

where: $NDR = (N/N_C)$.

$$NDR = 1 - \exp[-(X/0.48)^{(1,52)}], \quad (2)$$

where: $R^2 = 0.9848$ and $F = 68.3$.

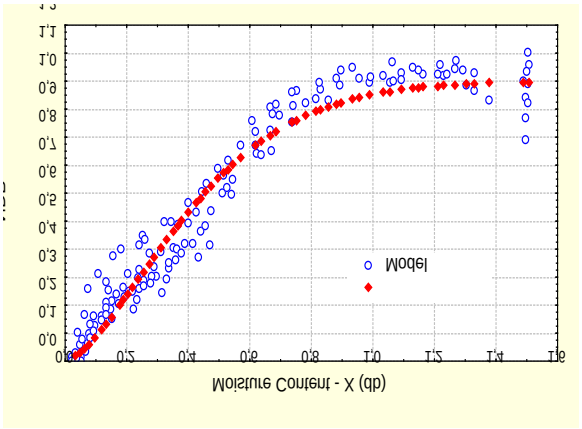


Figure 13. Generalized drying rate modeling - Natural and forced convection

The generalized drying rate curve results confirm that the suggestion is a very interesting tool for the study of conductive/convective drying processes. More specifically, it has been shown that the influence of the three operational variables here studied (initial moisture content, surface temperature and air velocity) on paper drying rates may be analyzed by this methodology and that

Hodges's (1982) equation has a good performance. Its use for modeling this curve is thus recommended.

Constant rate drying dependence on temperature and air velocity. The dependence of first period constant rate drying (N_C' [min^{-1}]), upon surface temperature (T_{sf} [ºC]), for natural convection, and upon temperature and air velocity (v_{air} [m/s]), for forced convection, was analyzed, resulting into the following expressions, respectively:

$$N_C' = (-0.0516) + (1.43 \times 10^{-3})\, T_{sf} \quad (3)$$

($R^2 = 0.9898$; $F = 627.5$)

$$N_C' = \exp(-15.2 + T_{sf}^{0.56}) + \ln(1.038\, v_{air}^{0.017}) \quad (4)$$

($R^2 = 0.9906$; $F = 662.9$)

Notation

a, b	parameters of equation 1	[-]
db	dry basis ($kg_{WATER}/kg_{DRY\ SOLID}$)	[-]
F	F statistics, ≡ ratio between the mean of the square of the predicted values and the mean of the square of estimated residuals	[-]
N	drying rate	[M/L^2T]
N_C	constant drying rate	[M/L^2T]
N_C'	constant drying rate	[1/T]
NDR	normalized drying rate	[-]
R^2	correlation coefficient	[-]
t	drying time	[T]
T_{sf}	heating surface temperature (drying temperature)	[θ]
v_{air}	drying air velocity	[L/T]
X	moisture content (db)	[-]
X_0	initial moisture content (db)	[-]
X_e	equilibrium moisture content (db)	[-]

References

Hodges, C.R. Laboratory drying study and applications for paper machine drying. *Drying'82*. Hemisphere, 1982. p. 99-105.

Motta Lima, O.C.; Machado, M.A.L.S.; Oliveira, V.M. Estudo sobre a secagem de papel V: secagem condutiva/convectiva com ar ambiente. In: COBRASP, 25, 1997, São Carlos-SP. *Proceedings*... São Carlos: DEQ/CCET-UFSCar, 1998. 2: p.647-653.

Motta Lima, O.C.; Massarani, G.; Pereira, N.C.; Machado, M.A.L.S. Estudo sobre a secagem de papel VI: secagem condutiva/convectiva com ar ambiente em convecção forçada. In: COBRASP, 26, 1998, Teresópolis-RJ. *Proceedings...* Teresópolis*:* DTQ/IT-UFRRJ, 1999. 2: p.429-436.

Motta Lima, O.C.; Massarani, G.; Pereira, N.C.; Machado, M.A.L.S. Drying rate analysis in conductive/convective paper drying. In: COBEQ 2000, 2000, Águas de São Pedro-SP. *Proceedings...* Águas de São Pedro. 2000a. CD-ROM.

Motta Lima, O.C.; Massarani, G.; Pereira, N.C.; Machado, M.A.L.S. Taxas de secagem na secagem condutiva/ /convectiva de papel com ar ambiente em convecção forçada. In: COBRASP, 27, 2000, Campos de Jordão-SP. *Proceedings...* Campos de Jordão: DEQ-EPUSP, 2000b. p.525-532.

Received on September 22, 2000.
Accepted on November 24, 2000.