XVIIth World Congress of the International Commission of Agricultural and Biosystems Engineering (CIGR)

Hosted by the Canadian Society for Bioengineering (CSBE/SCGAB)
Québec City, Canada June 13-17, 2010

THIN-LAYER DRYING BEHAVIOUR OF COFFEE BERRIES

A.L.D. GONELI[1], P.C. CORRÊA[2], G.H.H. OLIVEIRA[3*], F.M. BOTELHO[4], E.S. SANTOS[5]

[1]Federal University of Grande Dourados, UFGD Campus, P.O. Box 533, Dourados-MS, Brazil.
[2]Federal University of Viçosa, UFV Campus s/n, P.O. Box 270, Viçosa-MG, Brazil.
[3]Federal University of Viçosa, UFV Campus s/n, P.O. Box 270, Viçosa-MG, Brazil, gabriel_ufv@yahoo.com.br*Corresponding author
[4]Federal University of Viçosa, UFV Campus s/n, P.O. Box 270, Viçosa-MG, Brazil.
[5]Federal University of Viçosa, UFV Campus s/n, P.O. Box 270, Viçosa-MG, Brazil.

CSBE101103 – Presented at Section VI: Postharvest Technology, Food and Process Engineering Conference

ABSTRACT Mathematical modeling of thin layer drying is important to optimize operating parameters and performance improvements of drying systems. The ease of use is the main advantage of empirical or semi-empirical models in drying simulations. Many mathematical models have been used to describe the drying process, and thin-layer drying models have been widely used. Thus, the objective of this work was to study and compare the thin-layer drying characteristics of coffee berries (*Coffea arabica* L.) and to include the experimental data obtained to semi-theoretical models widely used to describe thin-layer drying behavior of agricultural products. The effect of drying air temperature was evaluated. Drying kinetics of coffee berries in a thin-layer dryer was investigated within a temperature range of 40–60 °C. The time required to dry coffee from an initial moisture content of around 1.10 dry basis to the final moisture content of around 0.13 dry basis was 97.67, 40.92 and 17.98 at 40, 50, and 60 °C of drying air temperature respectively. Six mathematical thin layer equations (Page, Diffusion approach, Midilli, Modified Henderson and Pabis, Thompson and Two-term) were used to fit the drying data. Precision of these models was based on the coefficient of determination (R^2), standard error of the estimate (SEE) and mean relative error (MRE). The Page equation was the most adequate in describing thin layer drying tests. Temperature dependence of the model parameter k was well documented by Arrhenius-type relationship. The activation energy for k parameter during drying was found to be 43.2589 kJ mol^{-1}.

Keywords: moisture ratio, mathematical modeling, Page model, activation energy

INTRODUCTION Coffee is considered to be one of the most important agricultural products in Brazil, due to the income generated by exportation and industrialization and also due to the number of employments related to its agribusiness. In order to consolidate its economic success and sustainability, a technological model of production is crucial to improve its quality.

Drying is the most used commercial process for preserving quality of agricultural products. It consists on removing part of the initial water content just after the physiological maturity has being achieved. The final moisture content is the maximum level in which it can be stored for long periods without any significant quality loss. The moisture decreasing prevents the growth and the reproduction of microorganisms and minimizes many of the moisture-related deteriorative reactions.

Drying of food depends on the heat and mass transfer characteristics within the product. The knowledge of temperature and moisture distribution in the product is essential for equipment and process design and quality control. Many mathematical models have been used to describe the drying process such as the widely used thin-layer drying models. A thin-layer drying is defined as a given layer thickness that represents one layer of the products.

Mathematical modeling of thin-layer drying is important for optimization of operating parameters and performance improvements of the drying systems. The implementation of empirical or semi-empirical models for drying simulations is straightforward and it is its major advantage. Several models have been proposed to describe the rate of moisture loss during thin-layer drying of biological materials (Jayas et al., 1991). These studies are fundamental in developing mathematical and computer simulation drying models. An equation describing the thin-layer drying rate is required for simulation of deep bed drying, since simulation models are usually based on the assumption that the deep bed is composed of several of thin-layers of product (Kashaninejad et al., 2007).

Semi-theoretical models are ease to implement and they are restricted to a given range of temperature, relative humidity, air velocity and moisture content. Among the thin-layer drying models, the Henderson and Pabis model, the Two-term model, the Diffusion approach model, the Page’s model, the Thomson model and the Midilli model are frequently used (Mohapatra and Rao, 2005).

The objective of this work is to study and to compare the thin-layer drying characteristics of coffee berries (*Coffea arabica* L.) and to fit the experimental data obtained to semi-theoretical models used to describe the thin-layer drying behavior of agricultural products.

MATERIAL AND METHODS: The present work was carried on the laboratory for the physical properties and quality evaluation of agricultural products of national grain storage training center – centreinar, located at the Federal University of Viçosa, brazil.

The “Catuaí vermelho” variety of coffee was used in the experiment. The coffee berries was manually harvested at a moisture content of 1.10 dry basis, measured by applying the oven method at 105 ± 1 ºC, for a period of 24 hours in duplicate, according to the of Seeds Analysis Standard of Brazil (Brazil, 1992).

Drying experiments were performed in a controlled temperature chamber under temperatures of 40, 50 and 60°C, and relative humidity of 22, 14 and 7, respectively. The drying was proceeded until the product reaches the final moisture content of around 0.13 dry basis.

The moisture ratio (MR) was determined for the coffee berries drying under different temperatures using the following expression

$$MR = \frac{M_\theta - M_e}{M_i - M_e} \qquad (1)$$

where:

MR : moisture ratio, dimensionless;
$M\theta$: moisture content at time θ (kg water/kg dry mater);
Mi : initial moisture content, (kg water/kg dry mater); and,
Me : equilibrium moisture content, (kg water/kg dry mater).

The drying curves were adjusted from the experimental data using empiric and semi-empiric models reported in the literature, presented in Table 1 (Madamba et al, 1996; Doymaz, 2004; Mohapatra and Rao, 2005; Akpinar, 2006).

Table 1. Mathematical models used to describe the drying kinetics.

Model designation	Model	
Page	$MR = \exp\left(-kt^{n}\right)$	(2)
Midilli	$MR = a\exp\left(-kt^{n}\right) + bt$	(3)
Modified Henderson and Pabis	$MR = a\exp\left(-k\,.\,t\right)$	(4)
Diffusion approach	$MR = a\exp\left(-kt\right) + \left(1 - a\right)\exp\left(-kbt\right)$	(5)
Two-term	$MR = a\exp\left(-k_1 t\right) + b\exp\left(-k_2 t\right)$	(6)
Thompson	$MR = \exp\left(\frac{-a - (a^2 + 4bt)^{0,5}}{2b}\right)$	(7)

where:

t : drying time (h);
k, k_1, k_2 : empirical coefficients in the drying models (h-1); and,
a, b, c, n : empirical constants in drying model.

A regression analysis was performed using the mathematical models of drying and the experimental data. The experimental data were interpreted by means of non-linear regression analysis using the Quasi-Newton method implemented in a computer program STATISTICA 6.0®. The drying models were selected based on the mean relative error (MRE), the standard error of estimate (SEE) and the determination coefficient (R^2). The mean relative error and the standard error of estimate were calculated for each model by the following expressions (Madamba et al., 1996, Mohapatra and Rao, 2005):

$$\mathrm{MRE} = \frac{100}{n} \sum_{i=1}^{n} \left(\frac{\left| M_{exp} - M_{pre} \right|}{M_{exp}} \right) \tag{8}$$

$$\mathrm{SEE} = \sqrt{\frac{\sum_{i=1}^{n} \left(M_{exp} - M_{pre} \right)^2}{D_f}} \tag{9}$$

where:

n : number of observations;
M_{exp} : experimental observed values;
M_{pre} : estimated values by the model; and,
D_f : degrees of freedom of the model.

RESULTS AND DISCUSSION: The calculated determination coefficient (R^2), standard error of estimate (SEE) and mean relative error (MRE) for the models presented in table 1 for all drying temperature are presented in table 2.

According to the results presented in table 2, all models achieve a R^2 greater than 0.99 which is acceptable according to Madamba et al. (1996), for all the drying temperatures. In addition, all models used also presented values of MRE below 10%. The values of this parameter indicates the deviation of the observed data in relation to the estimated curve by the model (Kashaninejad et al., 2007). According to Mohapatra and Rao (2005), values below 10% are recommended to the models selection. Besides the determination coefficient and mean relative error, the standard error of estimate was also obtained (Table 2). According to Draper and Smith (1998), the capacity of the model to describe satisfactory a determined physical process is inversely proportional to the values of SEE. Thus, lower values of SEE indicate a higher quality of the model adjustment to the observed data. However, this statistical tool by itself cannot be used to decide which model represents the best the phenomenon in scope, requiring analyzing this along with other statistical parameters (MRE and R^2).

Dessa forma, levando-se em conta que todos os modelos (table 2) apresentaram ajustes estatísticos satisfatórios, os modelos de Page, Midilli, Modified Henderson and Pabis, Diffusion approach, Two-term and Thompson são recomendados para representar o fenômeno da secagem em camada fina dos frutos de café, para as temperaturas de 40, 50 e 60°C. Dentre estes modelos, o tradicional modelo de Page é o mais simples, apresentando um menor número de parâmetros, tornando mais simples sua aplicação e uso em simulações de secagem. Dessa forma, nas condições em que este trabalho foi realizado, o modelo de Page foi selecionado para representar a cinética de secagem dos frutos de café em camada fina. Similar findings were reported by Madamba et al. (1996) for garlic slices, and by Doymaz and Pala (2002) for red pepper drying. A mean relative error (MRE) lower then 10 was for a given model (Mohapatra & Rao, 2005).

Table 2. Statistical analysis for the models using experimental data thin-layer drying of coffee berries.

40°C

Model	**R^2**	**SEE**	**MRE (%)**
Page	0.9988	0.0118	4.4164
Two-terms	0.9993	0.0098	1.2557
Thompson	0.9991	0.0102	1.6949
Diffusion approach	0.9991	0.0107	1.5185
Modified Henderson and Pabis	0.9995	0.0090	1.1879
Midilli	0.9994	0.0092	1.4917

50°C

Model	**R^2**	**SEE**	**MRE (%)**
Page	0.9995	0.0078	2.9995
Two-terms	0.9996	0.0085	2.3876
Thompson	0.9986	0.0135	3.9634
Diffusion approach	0.9996	0.0078	2.3818
Modified Henderson and Pabis	0.9996	0.0102	2.6310
Midilli	0.9996	0.0083	3.1224

60°C

Model	**R^2**	**SEE**	**MRE (%)**
Page	0.9995	0.0083	5.2562
Two-terms	0.9999	0.0039	1.3602
Thompson	0.9997	0.0070	4.2152
Diffusion approach	0.9999	0.0035	1.3761
Modified Henderson and Pabis	0.9999	0.0052	1.1189
Midilli	0.9999	0.0042	1.3075

The observed and estimated data are represented in Figure 1 as a function of the drying time for each temperature. Figure 1 shows good adjustment for the Page model to the experimental data.

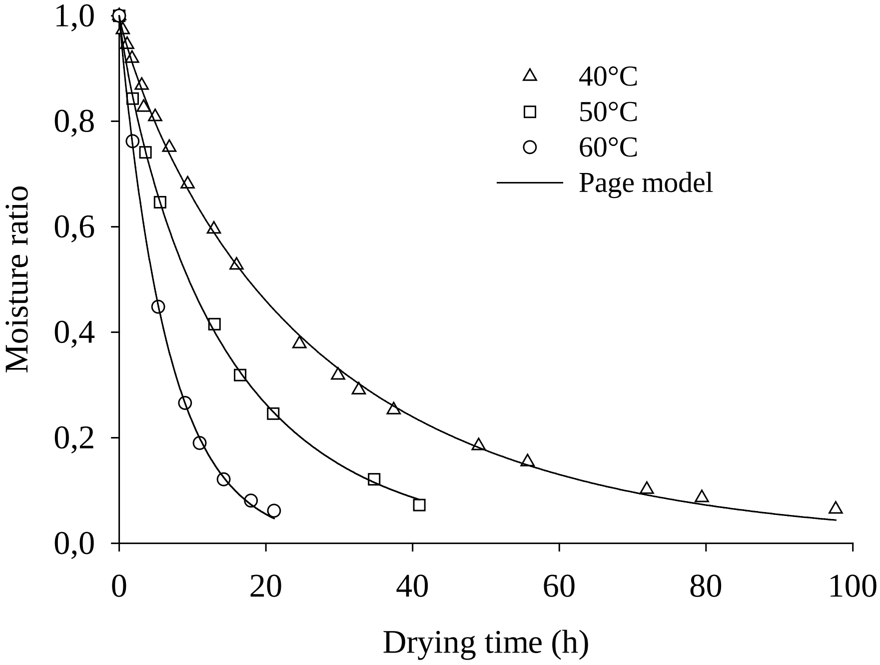

Figure 1. Experimental and predicted moisture ratio obtained using the Page model.

The time required to dry coffee from an initial moisture content of around 1.10 dry basis to the final moisture content of around 0.13 dry basis was 97.67, 40.92 and 17.98 at 40, 50, and 60 °C of drying air temperature respectively. It can be verified in Figure 1 that higher temperatures allow faster evaporation rates. Therefore, the drying time to achieve given moisture content decreases as expected, resulting in a faster dehydration process.

Table 3 shows the coefficients of the Page model (Equation 2) fitted to the observed data of thin layer drying kinetics of coffee fruits to the different air conditions used.

Tabela 3. Parameters of the Page model to different drying conditions of coffee fruits.

Temperature (°C)	k	n
40	0.0560	0.8779
50	0.0970	0.8746
60	0.1552	0.9771

It can be observed from Table 3 that the drying constant (k), which represents the effect of the external drying conditions, increased with temperature increase. According to Madamba et al. (1996) and Babalis and Belessiotis (2004), the drying constant (k) can be used as an approximation to characterize the temperature effect and it is related to the effective diffusivity of the drying process in the falling period and to the liquid diffusivity that controls the process. These results indicate that the drying rate increases with temperature increase. The n coefficient from the Page model, which reflects the internal resistance of the product to drying, did not presented a defined tendency of its values in relation to temperature.

The temperature dependence of the drying coefficient k (Table 3) may be represented by an Arrhenius-like relationship (Madamba et al., 1996; Babalis and Belessiotis, 2004), as follows

$$k = k_o \exp\left(\frac{E_a}{RT_a}\right) \tag{10}$$

where k_0 is the pre-exponential factor of the Arrhenius equation, E_a is the activation energy (kJ mol^{-1}), R is the universal gas constant (kJ $kmol^{-1}$ K^{-1}), and T is the absolute temperature (k). The logarithm of K as a function of the inverse of the temperature was plotted in Figure 3, where a linear relationship for the Arrhenius equation can be verified.

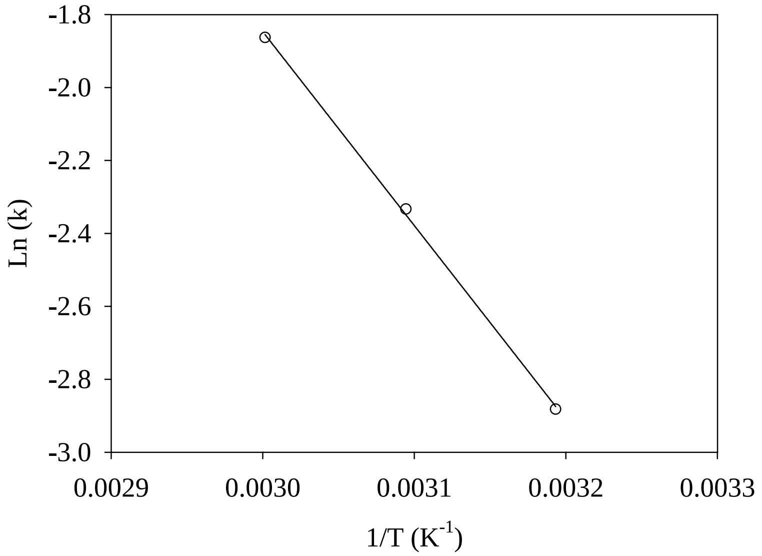

Figure 3. Arrhenius-like relationship between drying coefficient (*K*) and temperature.

Equation 11 shows the effect of temperature on drying coefficient *K* of coffee berries with the following coefficients:

$$k = 1.34 \times 10^6 \exp\left(-\frac{43258.9078}{RT_a} \right) \qquad (11)$$

The activation energy was 43.26 kJ mol^{-1} (Equation 13). This value is higher than that corresponding to vegetable waste drying (19.82 kJ mol^{-1}) reported by Lopez et al. (2000) and for corn drying (29.56 kJ mol^{-1}) presented by Doymaz and Pala (2003), but lower than the value obtained for garlic drying (54.9 kJ mol^{-1}) reported by Madamba et al. (1996).

CONCLUSIONS: From the results presented in this work it was possible to conclude that higher temperatures allows faster drying rates, resulting in faster dehydration processes, which is of importance in order to reduce costs associate to coffee berries drying operation. It was verified that Page model gave good fitting to the experimental data for coffee berries, being the most adequate to describe the thin-layer drying tests. Temperature dependence of the model parameter K was verified by Arrhenius-type relationship. The activation energy for the K parameter at the drying was found as 43.26 kJ mol^{-1}.

REFERENCES

Akipinar, E. K. 2006. Mathematical modeling of thin layer drying process under sun of some aromatic plants. Journal of Food Engineering. 77(4): 864-870.

Babalis, S.J. and V.G. Belessiotis. 2004. Influence of the drying conditions on the drying constants and moisture diffusivity during the thin-layer drying of figs. Journal of Food Engineering. 65(4): 449-458, 2004.

Brazil (1992). Regra para análise de sementes [Seeds Analysis Standard], Ministério da Agricultura e Reforma Agrária, Brasília. 365 p.

Doymaz I. Drying kinetics of white mulberry. 2004. Journal of Food Engineering. 61(3): 341-346.

Doymaz, I., and M. Pala. 2002. Hot-air drying characteristics of red pepper. Journal of Food Engineering. 55(4): 331-335.

Draper, N. R. and H. Smith. 1998. Applied regression analysis. 3rd ed. New York: John Wiley & Sons.

Doymaz, I., and M. Pala. 2003. The thin-layer drying characteristics of corn. Journal of Food Engineering. 60(2): 125–130.

Jayas, D. S., S. Cenkowski, S. Pabis and W. Muir. 1991. Review of thin-layer drying and wetting equations. Drying Technology. 9(3): 551-588.

Kashaninejad, M., A. Mortazavi, A. Safekordi and L. G. Tabil. 2007. Thin-layer drying characteristics and modeling of pistachio nuts. Journal of Food Engineering. 78(1): 98-108.

Lopez, A., A. Iguaz, A. Esnoz and P. Virseda. 2000. Thin layer drying behaviour of vegetable wastes from wholesale market. Drying Technology. 18(4, 5): 995–1006.

Madamba, P. S., R. H. Driscoll and K. A. Buckle. (1996). The thin-layer drying characteristics of garlic slices. Journal of Food Engineering. 29(1): 75–97.

Mohapatra, D. and P. S. Rao. 2005. A thin layer drying model of parboiled wheat. Journal of Food Engineering. 66(4): 513-518.