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DRYING KINETICS OF PEELED COFFEE SUBMITTED TO DIFFERENT TEMPERATURES AND RELATIVE HUMIDITY OF THE AIR OF DRYING AFTER PARTIAL DRYING

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ABSTRACT

The mathematical modelling is fundamental for the understanding of the related processes the drying, that influences the quality of the coffee drink. The objective of this study was to evaluate the influence of different relative humidity of the drying air after partial drying on drying kinetics of peeled coffees. Coffee fruits were harvested in the cherry stage and processed by wet, resulting in the portion of peeled coffee. Eleven treatments of drying were accomplished, being nine results of the combination of three dry bulb temperatures and three dew point temperatures, more two treatments without the control of the dew point temperatures. The control of the relative humidity by the dew point temperature was made after the grains reached the partial drying. Among the studied models, those of Diffusion Approximation and Modified Midilli were the most adequate for describing the drying process of the first and second part of drying respectively. The effective diffusivity coefficient of water in coffee grains ranged from 0.81 x 10^{-11} to 1.84 x 10^{-11} m² .s^{-1} during the first part of the drying and ranged from 1.49 x 10^{-11} to 3.29 x 10^{-11} m² .s^{-1} during the second part of the drying, increasing significantly with the reduction of the dew point temperature and increase of the dry bulb temperature.

Palavras-chave:
coffea arabica L.
modelagem matemática
temperatura de pondo de orvalho
coeficiente de difusividade

CINÉTICA DE SECAGEM DE CAFÉ DESCASCADO SUBMETIDO A DIFERENTES TEMPERATURAS E UMIDADES RELATIVAS DO AR DE SECAGEM APÓS MEIA SECA

RESUMO

A modelagem matemática é fundamental para a compreensão dos processos relacionados à secagem, que por sua vez, influencia diretamente a qualidade da bebida do café. Assim, o objetivo deste trabalho foi estudar a influência que diferentes umidades relativas do ar de secagem após meia seca têm sobre a cinética de secagem dos cafés descascados. Os frutos de *Coffea arábica* L. foram colhidos no estádio de maturação cereja e processados por via úmida, resultando na porção de café descascado. Foram realizados onze tratamentos de secagem, sendo nove resultados da combinação de três temperaturas de bulbo seco e três temperaturas de ponto de orvalho, mais dois tratamentos sem o controle da temperatura de ponto de orvalho. O controle da temperatura de ponto de orvalho foi feito apenas após os grãos alcançarem a meia seca. Dentre os modelos estudados, os de Aproximação da Difusão e Midilli Modificado foram os que melhor se ajustaram aos dados experimentais referentes a primeira e segunda parte de secagem respectivamente. O coeficiente de difusividade efetivo da água em grãos de café variou de 0,81 x 10^{-11} a 1,84 x 10^{-11} m² s^{-1} durante a primeira parte da secagem e variou de 1,49 x 10^{-11} a 3,29 x 10^{-11} m² s^{-1} durante a segunda parte da secagem, aumentando significativamente com a redução da temperatura de ponto de orvalho e aumento da temperatura de bulbo seco.

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INTRODUCTION

Drying reduces risks with respiration, fermentation, oxidation and microorganisms development, directly influencing the final quality of the coffee drink. In addition, it is the stage of greatest energy demand, which results in high financial costs (BORÉM, 2008).

Therefore, the studies of drying kinetics have aroused the interest of several researchers, because, according to Resende *et al.* (2010), the mathematical simulation of drying is fundamental for the understanding of related processes. Thus, the use of some techniques, such as the adjustment of mathematical models, can bring some contributions (ALVES *et al.*, 2013; CORRÊA *et al.*, 2010b; ISQUIERDO *et al.*, 2013; SIQUEIRA *et al.*, 2013), as indicate the ideal time for changes in drying characteristics aiming at greater energy savings and shorter drying times.

Numerous models have been proposed to describe the rate of water reduction during thin layer drying of biological materials (ERBAY; ICIER, 2010). An equation describing the water reduction rate of a thin layer is necessary for thick layer drying simulation because simulation models are generally based on the assumption that the thick layer is composed of a series of thin layers (KASHANINEJAD *et al.*, 2007). The adjustment of mathematical models for the drying of agricultural products provides information of fundamental importance for the development of processes and for the dimensioning of equipment. Using this information, it is possible to estimate the drying time and, consequently, the energy expenditure that will reflect on the processing cost (SIQUEIRA *et al.,* 2013; VILELA; ARTUR, 2008).

There are three types of mathematical simulation models of the thin layer drying process, which aim to describe the drying kinetics of agricultural products. The semi-empirical and empirical models, which are generally based on conditions external to the product, such as temperature and relative humidity of the drying air; and the theoretical models, which normally consider not only external conditions, but also internal mechanisms of energy and mass transfer and their effects (BORÉM, 2008).

Most of the time, the empirical and semi-empirical models, due to their ease of use, have been shown as the best options to represent the drying process of agricultural products. However, their validity is restricted to the temperature, relative humidity and air velocity under which the experimental data were obtained (BROOKER *et al*., 1992; MOHAPATRA; RAO, 2005).

Depending on the conditions of the drying process, different models can be adjusted to adequately describe the drying kinetics of porous, hygroscopic hair products. The models of Midilli *et al.* (2002), Page, Logarithm, Henderson and Pabis, Modified Page, Two Terms, Exponential of Two Terms, Newton, Wang and Sing (AKPINAR, 2010; ANDRADE *et al*., 2006; CORRÊA *et al*., 2010b; ISQUIERDO *et al*., 2013; KAYACAN *et al*., 2018; SOUSA *et al*., 2011), among others, have been frequently adjusted to predict the drying process of agricultural products.

The objective of this study is, for peeled coffees, to evaluate the influence of different temperatures and relative humidity of the drying air on the drying kinetics after partial drying. This influence has not yet been studied or modeled. The knowledge and prediction of these conditions helps in making decisions regarding the equipment sizing and process variables that can result in lower costs and better quality of the final product.

MATERIAL AND METHODS

In the experiment, coffee fruits were used as raw material in the cherry ripening stage (*Coffea arabica* L. cv. Catuaí Vermelho), harvested at Sítio Vista Alegre, located in the municipality of Nepomuceno, MG (Latitude: 21 ° 12’19.5 ”S; Longitude: 45 ° 11’27.4” W; Altitude: 980 m), during the 2018 harvest.

The selective harvesting of coffee fruits was performed manually. After harvesting, the fruits were subjected to hydraulic separation to remove fruits of lower specific mass and to a new manual selection to remove remaining immature and overripe fruits.

Right after the manual selection, the coffee was wet processed, the peeled coffee portion was determined, with the exocarp and part of the mesocarp removed mechanically. The water content was 1.565 ± 0.065 db, determined according to the standard greenhouse method, 105 ± 3 ° C, for 24 hours, according to the Seed Analysis Rule (BRASIL, 2009).

Before the beginning of mechanical drying, the equivalent radius of the coffee grains was calculated, defined as the radius of a sphere with volume equivalent to the volume of the fruit. In order to calculate its volume, due to the greater uniformity of the grains, a sample of 25 grains was taken from each repetition, from all treatments, from which measures of length (a), width (b) and thickness (c) were taken using a digital caliper with 0.01 mm resolution, with the volume of coffee fruits (V) being calculated by Equation 1 (ISQUIERDO, 2011).

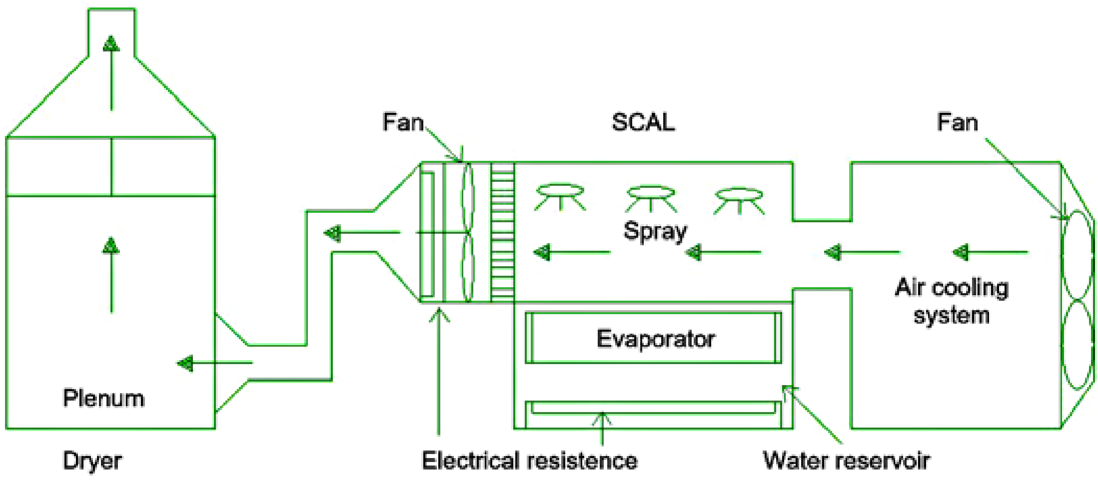
$$V = \frac{4}{3}\pi\, abc \tag{1}$$

Where,
V = grain volume, m^3;
a = length, m;
b = width, m; and
c = thickness, m.

The drying system was composed of an air conditioning system coupled to a fixed layer dryer (Figure 1). The air characteristics were controlled by a laboratory air conditioning system (SCAL), a model proposed by Fortes *et al.* (2006). This equipment allows the control of the flow, dry bulb temperature (T_{bd}), dew point temperature (T_{pd}) and the relative humidity (RH) of the drying air with precision. In order to obtain the lowest dew point temperatures and, consequently, the lowest relative humidity, before SCAL, the air was pre-conditioned by a refrigeration system composed of three air conditioning units.

The dryer consisted of four removable trays with a perforated bottom, of square section, with sides equal to 0.30 m and depth of 0.10 m, located on a plenum for uniform air flow. Air velocity was monitored using a paddle anemometer. The dew point temperature was measured inside the SCAL chamber and the drying air temperature was measured in the plenum, under the perforated bottom trays. The relative humidity of the drying air was measured by a psychrometer inserted inside the plenum (Assmann type psychrometer). The temperature of the coffee fruits was measured with mercury thermometers inserted in the center of the dough.

For the design of the coffee drying experiments, nine treatments in a 3x3 factorial scheme, with three dry bulb temperatures (40 °C; 40 °C - 35 °C and 35 °C; T_{bd}) and three point temperature dew (2.6 °C; 10.8 °C and 16.2 °C; T_{pd}) were performed. Two more treatments were performed without dew point temperature control, with two dry bulb temperatures (40 °C and 35 °C). For each treatment, four repetitions were performed. Depending on the combinations between dry bulb temperature and dew point temperature, different relative humidity (RH) of the drying air were obtained (Table 1).



Source: Alves *et al*., (2013)

Figure 1. Drying system used for the mechanical drying of coffee

Table 1. Dry bulb temperature, dew point temperature and relative humidity of the drying air for partial drying and complementing drying

Treatment	First Part (Partial Drying) Initial Water Content – 1.56±0.01 db Final Water Content – 0.42±0.01 db	Second Part (Complementing Drying) Initial Water Content – 0.42±0.01 db Final Water Content – 0.12±0.01 db		
	T_{bd} (°C)	T_{bd} (°C)	T_{pd} (°C)	RH (%)
1	40	40	2.6	10.0
2	40	40	10.8	17.5
3	40	40	16.2	25.0
4	40	35	2.6	13.1
5	40	35	10.8	23.0
6	40	35	16.2	32.7
7	35	35	2.6	13.1
8	35	35	10.8	23.0
9	35	35	16.2	32.7
10	40	40	-	-
11	35	35	-	-

The drying operation took place in two stages for treatments numbered from one to nine. The first stage started at the moment of the grain entering the dryer and its completion occurred when the product reached approximately 0.428 ± 0.01 db. During the first stage there was no control of T_{pd} and consequently of the RH of the drying air. The second stage started after the product reached 0.428 ± 0.01 db, with T_{pd} control and consequently of the UR. The T_{bd} were changed in relation to the first stage, only for treatments four, five and six, remaining unchanged until the grain mass reached a water content of 0.123 ± 0.006 db.

After processing, 1.2 kg of wet peeled coffee were deposited in each tray, promoting the complete filling of its bottom (0.30 x 0.30 m), corresponding to a thin layer of approximately 0.015 m in height. Knowing the mass and the initial water content of the fruits, the drying of the product was monitored using the gravimetric method (Equation 2). The trays containing the samples were removed from the dryer and weighed on a semi-analytical scale with a resolution of 0.01 g, every fifteen minutes in the first hour of drying, thirty minutes in the second hour, every hour until approximately 0.428 ± 0.01 db and every two hours until the coffee grains reached a water content of 0.123 ± 0.006 db. After each treatment, the water content of the endosperm of the grains was determined by the drying oven method, 105 ± 1 ° C, for 16 hours (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION - ISO, 1999). In order to minimize possible differences in temperature and air flow between the perforated bottom trays, a 90° rotation was made in the position of the trays at each weighing, as well as the turning of the grain mass.

$$U_t = \frac{m_{ai} - (m_{ti} - m_{tt})}{m_{ms}} \quad (2)$$

Where,

Ut = water content at time t, kg of water.kg of dry matter^{-1} (db);

m_{ai} = initial water mass, kg;

m_{ti} = initial total mass, kg;

m_{tt} = total mass at time t, kg; and

m_{ms} = dry matter mass, kg.

For all treatments, the drying air speed was kept constant at 0.33 m s^{-1}, corresponding to the flow of 20 m^3 min^{-1} m^{-2}. State points for the drying air from the relationship between dry bulb temperatures (T_{bd}) and dew point temperatures (T_{pd}) were experimentally obtained and these conditions were adopted during the drying of the grains.

In the analysis of drying data, the moisture ratio (RU) is essential to describe different models of thin layer drying. The moisture ratio during drying, as a function of the variables evaluated, was determined by Equation 3. At each drying time, a water content was correlated with the initial water content and the equilibrium water content, for specific conditions of drying. Thus, in all conditions tested, the models were adjusted to the values of moisture ratio as a function of drying time to describe the drying kinetics of coffee grains (Table 2).

$$RU = \frac{U - U_e}{U_i - U_e} \quad (3)$$

Where,
RU = moisture ratio, dimensionless;
U = water content of the product at time t, decimal (db);
Ue = equilibrium water content of the product, decimal (db); and
Ui = initial water content of the product, decimal, (db).

The hygroscopic equilibrium water content was calculated by Equation 4, for peeled coffee (AFONSO JÚNIOR, 2001).

$$U_e = (1.8062+0.0273*T -9.8728*RH^{7.0075})^{-2.4999} \quad (4)$$

Where:
U_e = equilibrium water content of the product (decimal, (db));
T = temperature of the drying air, (° C); and
RH = relative humidity of the drying air, (decimal).

Table 2. Mathematical models used to predict the drying phenomenon

Model Designation	Model	Equation
Diffusion Approximation 1	RU = (a(exp(-k t)))+(1-a)exp(-k b t)	(5)
Two Terms 2	RU = a exp(-k_0 t)+b exp(-k_1 t)	(6)
Exponential of two terms 3	RU = (a(exp(-k t)))+(1-a)exp(-k a t)	(7)
Henderson and Pabis 4	RU = a exp(-k t)	(8)
Henderson and Modified Pabis 5	RU = a exp(-k t)+b exp(-k_0 t)+c exp(-k_1 t)	(9)
Lewis 6	RU = exp(-k t)	(10)
Midilli 7	RU = a exp(-k t^n)+b t	(11)
Modified Midilli 8	RU = exp(-k t^n)+a t	(12)
Newton 9	RU = exp(-k t)	(13)
Page 10	RU = exp(-k t^n)	(14)
Thompson 11	RU = exp((-a-(((a^2)+(4 b t))$^{0.5}$))(2 b)$^{-1}$)	(15)
Valcam12	RU = a+b t+c $t^{1,5}$+d t^2	(16)
Verma 13	RU = -a exp(-k t)+(1-a)exp(-k_1 t)	(17)
Wang & Sing 14	RU = 1+a t+b t^2	(18)

[1]Kassem (1998); [2]Henderson (1974); [3]Sharaf-Eldee, Blaisdell and Hamdy (1980); [4]Henderson and Pabis (1961); [5]Karathanos (1999); [6]Lewis (1921); [7]Midilli *et al.* (2002), Kucuk and Yapar (2002); [8]Ghazanfari *et al.* (2006); [9]Callaghan *et al.* (1971); [10]Page (1949); [11]Thompson *et al.* (1968); [12]Siqueira *et al.* (2013); [13]Verma *et al.* (1985); [14]Wang and Singh (1978).

Where,
RU = moisture ratio;
t = drying time, h;
k, k_0, k_1 = drying constants; and
a, b, c, d, n = model coefficients.

To adjust the mathematical models, non-linear regression analyses by the Gauss-Newton method were performed using the STATISTICA 5.0® software (Statsoft, Tulsa, USA). The choice of the best model was based on the following statistical parameters: standard deviation of the estimate (SE), average relative error (P), coefficient of determination (R^2) and trend in the residues distribution. The standard deviation of the estimate and the average relative error were calculated, respectively, by Equations 19 and 20.

$$SE = \sqrt{\frac{\sum_{i=1}^{n}(Y-\hat{Y})^2}{GLR}} \quad (19)$$

$$P = \frac{100}{n}\sum_{i=1}^{n}\left(\frac{|Y-\hat{Y}|}{Y}\right) \quad (20)$$

Where,
SE = standard deviation of the estimate, decimal;
Y = value observed experimentally;
$\hat{Y}$ = value calculated by the model;
GLR = model degrees of freedom;
P = average relative error, %; and
n = number of observed data.

The effective diffusion coefficient for the drying conditions used in this study was calculated by adjusting the model based on the liquid diffusion theory (Equation 21) to the observed data, using non-linear regression, using the STATISTICA 5.0® software (Statsoft, Tulsa, USA). This equation (21) is the analytical solution for Fick's second law, considering the product's geometric shape as spherical, disregarding the volumetric contraction of the fruits and considering the contour condition of the water content known on the product surface (BROOKER *et al*., 1992).

$$RU = \frac{U-Ue}{Ui-Ue} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left[-\frac{n^2\,\pi^2\,D_{eff}}{R^2}\,t\right] \quad (21)$$

Where,
D_{eff} = effective diffusion coefficient, $m^2\ s^{-1}$;
R = equivalent radius of coffee fruits, m;
n = number of terms; and
t = time, s.

RESULTS AND DISCUSSION

The statistical parameters used for the comparison between the fourteen models used to describe the drying kinetics of peeled coffee grains (Table 2) are shown in Tables 3 and 4. The average initial water content was 1.565 ± 0.065 db, when subjected to dry bulb temperature and dew point temperature of the drying air used in this experiment, for the first and second part of drying. The values of the coefficients of determination (R^2), standard deviation of the estimate (SE), average relative error (P) and trend of the distribution of residues are also presented. The choice of a model to represent the drying phenomenon of an agricultural product is based on the joint analysis of these parameters presented, as well as the behavior of the error distribution, and the analysis of a single parameter is not a good tool for the selection non-linear models.

According to Kashaninejad *et al*. (2007) and Madamba *et al*. (1996), determination coefficients (R^2) greater than 95% indicate a satisfactory representation of the drying process. Draper and Smith (1998) state that the ability of a model to accurately describe a particular physical process is inversely proportional to the value of the standard deviation of the estimate (SE). Therefore, the lower the SE value, the better the model fits the experimental water content ratio data (SIQUEIRA *et al*., 2013). For the average relative error (P) that indicates the deviation of the values observed in relation to the curve estimated by the model (KASHANINEJAD *et al*., 2007) values below 10% are suggested for the model recommendation (MOHAPATRA; RAO, 2005).

Analyzing the first part of the drying of the coffee grains (Table 3), it can be seen that the Diffusion Approximation, Modified Midilli and Page models reached the desired requirements for the three statistical parameters analyzed. Among the models that met the three requirements, the

Table 3. Statistical parameters obtained for the drying models used to describe the drying kinetics of coffee grains, referring to the first part of drying

TR	M	R^2(%)	SE	P (%)	TE	M	R^2(%)	SE	P (%)	TE	M	R^2(%)	SE	P (%)	TE
1		99.98	0.010	0.84			99.98	0.006	0.85			67.02	0.380	28.68	
2		99.98	0.010	0.68			99.98	0.006	0.68			50.26	0.484	26.98	
3		99.33	0.062	2.48			78.90	0.201	21.15			73.81	0.388	25.89	
4		99.99	0.009	0.60			99.98	0.005	0.60			63.08	0.430	21.52	
5		99.28	0.066	2.57			99.33	0.037	2.59			52.17	0.533	25.18	
6	Diffusion Approximation	99.15	0.074	2.79	A	Two Terms	99.20	0.042	2.81	T	Exponential of two terms	38.85	0.632	36.07	T
7		99.49	0.053	2.21			75.82	0.211	12.62			38.40	0.584	27.99	
8		99.96	0.014	0.94			99.96	0.008	0.94			48.11	0.467	26.98	
9		99.93	0.016	1.02			99.93	0.009	1.02			39.86	0.474	28.05	
10		99.90	0.021	1.62			99.90	0.012	1.62			64.98	0.396	27.45	
11		99.97	0.011	0.78			99.97	0.007	0.77			47.93	0.475	28.38	
1		69.70	0.365	22.13			69.70	0.163	22.13			49.98	0.468	35.91	
2		67.10	0.394	15.61			67.10	0.176	15.61			27.07	0.586	33.58	
3		78.90	0.349	21.15			99.38	0.027	2.51			60.56	0.477	31.69	
4		75.65	0.349	13.71			75.65	0.156	13.71			47.62	0.512	25.64	
5		76.02	0.377	14.25			99.71	0.019	1.39			32.44	0.634	30.00	
6	Henderson and Pabis	73.19	0.419	15.40	T	Henderson and Pabis Modified	99.36	0.029	2.24	T	Lewis	13.90	0.751	43.62	T
7		75.82	0.366	12.62			99.70	0.018	1.23			14.99	0.686	32.47	
8		69.45	0.358	14.31			99.99	0.001	0.17			24.55	0.563	33.46	
9		68.47	0.344	12.85			68.47	0.154	12.85			11.75	0.575	34.55	
10		70.63	0.363	19.79			99.99	0.154	12.85			47.01	0.487	34.47	
11		68.83	0.368	15.06			100.00	0.000	0.06			24.87	0.571	35.17	
1		92.21	0.185	9.74			99.95	0.015	1.04			49.98	0.468	35.91	
2		99.73	0.036	2.30			99.98	0.004	0.17			27.07	0.586	33.58	
3		97.29	0.125	6.85			97.26	0.126	6.76			60.56	0.477	31.69	
4		68.29	0.399	31.46			99.93	0.019	0.92			47.62	0.512	25.64	
5		96.11	0.152	5.77			96.10	0.153	5.71			32.44	0.634	30.00	
6	Midilli	95.99	0.162	6.42	T	Midilli Modified	95.97	0.162	6.36	T	Newton	13.90	0.751	43.62	T
7		96.47	0.140	5.52			96.46	0.140	5.47			14.99	0.686	32.47	
8		99.99	0.005	0.22			99.99	0.005	0.22			24.55	0.563	33.46	
9		50.31	0.431	27.10			99.99	0.004	0.19			11.75	0.575	34.55	
10		90.23	0.209	8.15			99.90	0.022	1.43			47.01	0.487	34.47	
11		98.93	0.068	2.97			99.99	0.005	0.33			24.87	0.571	35.17	
1		99.64	0.040	3.42			94.11	0.161	11.82			96.00	0.076	9.80	
2		98.91	0.072	4.63			89.90	0.218	10.98			90.86	0.120	10.09	
3		96.33	0.145	6.94			95.52	0.161	9.74			96.51	0.082	8.95	
4		99.40	0.055	4.18			93.10	0.186	8.94			92.94	0.109	11.12	
5		96.09	0.153	5.67			91.67	0.223	9.60			91.34	0.131	9.87	
6	Page	95.94	0.163	6.05	T	Thompson	89.78	0.259	13.08	T	Valcam	89.69	0.150	12.04	T
7		96.37	0.142	6.11			89.86	0.237	10.22			89.77	0.137	10.33	
8		98.27	0.085	5.55			90.00	0.205	10.59			89.78	0.120	9.53	
9		97.79	0.091	5.68			89.11	0.202	10.70			88.77	0.118	11.14	
10		99.28	0.057	4.55			93.73	0.167	10.83			94.85	0.088	9.94	
11		98.11	0.090	6.04			89.60	0.212	11.16			88.86	0.127	10.32	
1		69.70	0.258	22.13			59.31	0.244	27.76						
2		67.10	0.278	15.61			39.61	0.308	27.15						
3		78.90	0.246	21.15			62.50	0.268	27.49						
4		75.65	0.247	13.71			52.89	0.280	21.95						
5		76.03	0.267	14.25			34.87	0.359	27.06						
6	Verma	73.19	0.296	15.40	T	Wang & Sing	20.12	0.417	35.51	T					
7		75.82	0.259	12.62			18.26	0.388	29.92						
8		69.45	0.253	14.31			36.72	0.298	27.18						
9		68.47	0.243	12.85			23.14	0.310	28.94						
10		70.63	0.256	19.79			57.51	0.252	26.63						
11		68.83	0.260	15.06			34.79	0.307	28.73						

TR= treatment; M= model; TE= trend; T= biased; A= random

Diffusion Approximation was the one with the highest values of R^2 ($R^2 \geq 99.15\%$) and lowest values of P ($P \leq 2.79\%$) and SE ($SE \leq 0.074$).

When more than one model satisfactorily represents the drying phenomenon, it becomes necessary to consider the complexity of each model, for its recommendation. The analysis of the distribution of error is another tool that has been constantly used in a complementary way to the statistical parameters in the choice of the model, because even though subjective, it provides a good indication of the model's adjustment to the experimental values. For Goneli *et al*. (2011), a model is considered random if the residual values are close to the horizontal range around zero and also do not form defined figures, indicating no bias in the results. If it presents a biased distribution, the model is considered inadequate to represent the phenomenon in question. Thus, among the models that met the statistical requirements, the Diffusion Approximation model was the only one that obtained a random error distribution.

When studying only the second part of drying (Table 4), we can note that all models used in this study meet the requirements of R^2, P and SE. All models showed a coefficient of determination (R^2) greater than 99.15%. When considering the criterion of the average relative error ($P < 10\%$) and the standard deviation of the estimate (SE) for an acceptable adjustment, all values are less than 6.75% and 0.0943 respectively. The Midilli and Modified Midilli models were the ones that resulted in the best adjustments, with the highest values of determination coefficient ($R^2 \geq 99.97\%$) and the lowest values of average relative error and standard deviation of the estimate ($P \leq 1.24\%$ and $SE \leq 0.020$). Regarding the trend of error distribution, the Midilli, Modified Midilli and Valcam models were the only ones to present randomness.

Among the models used in this experiment to describe the drying kinetics of the peeled coffee submitted to different combinations of T_{bd} and T_{pd}, the Diffusion Approximation was the one that presented the best adjustments for the first part of the drying, after a joint analysis of the coefficient of determination, average relative error, standard deviation of the estimate and trend of error distribution values. For the second part of the drying, the Midilli and Modified Midilli models were the ones that presented a more adequate fit. Therefore, the modified Midilli model is indicated due to its less complexity.

Isquierdo *et al*. (2013), studying the effect of different dry bulb temperatures and dew point on the drying kinetics of natural coffee, also indicated the Modified Midilli model as the one that best describes the process. The same result was verified by Corrêa *et al*. (2010b), who obtained a satisfactory fit of the Modified Midilli model to describe the drying of coffee fruits. Goneli *et al*. (2009) and Alves (2013), studied the drying kinetics of peeled and natural coffee respectively, and concluded that the Midilli model was the most suitable for representing the process.

In addition to coffee in its different forms of processing, the Midilli model is also recommended to predict the drying phenomenon of other agricultural products, such as red beans (CORRÊA *et al*. 2007), adzuki beans (RESENDE *et al*., 2010) and jatropha grains (SIQUEIRA *et al*., 2012).

The comparison between observed and estimated values of the moisture ratio by the Diffusion Approximation and Modified Midilli models, for the first and second drying periods, respectively, is showed in Figures 2 and 3. We can observe, in these figures, a high agreement between the moisture ratio values observed experimentally and the values estimated by the Diffusion Approximation and Modified Midilli models for all studied conditions, which confirms the satisfactory fit of these models to describe the kinetics drying of coffee grains, under the studied conditions.

In Tables 5 and 6 are shown the coefficients of the Diffusion Approximation models, for the first part of the drying of the peeled coffee, and the coefficients of the Modified Midilli model for the second part of the drying of the peeled coffee, adjusted to the observed data of thin layer drying kinetics, under the conditions considered in this experiment.

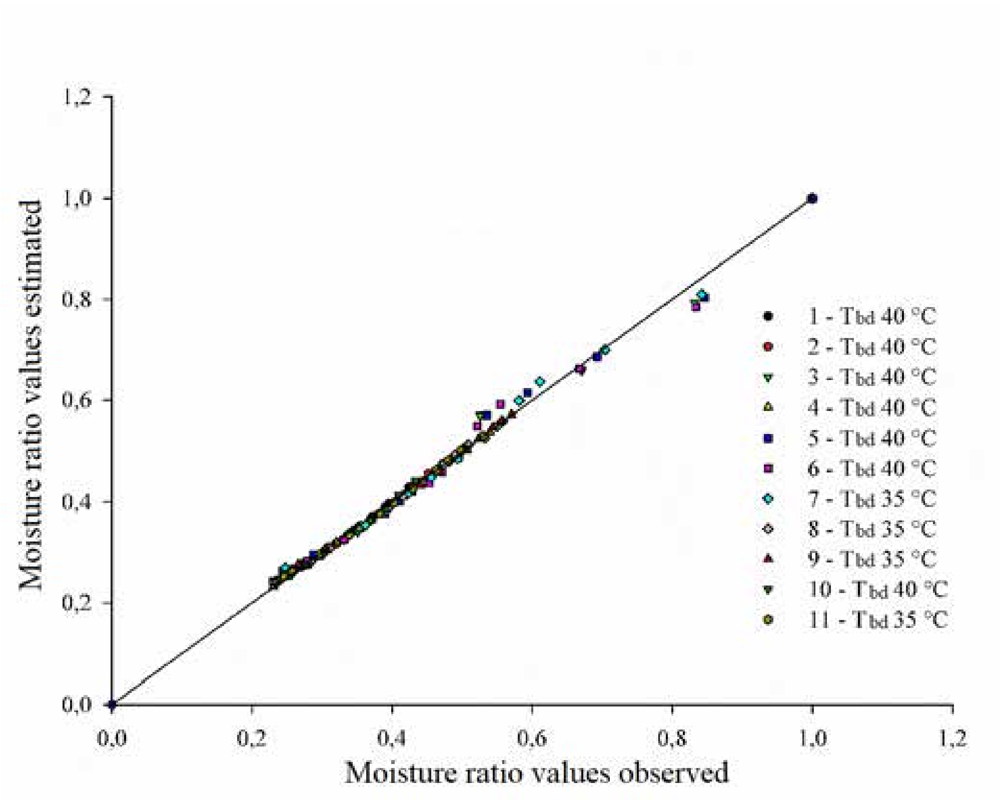


Figure 2. Moisture ratio values (dimensionless) observed (x-axis) and estimated (y-axis) by the Diffusion Approximation model for the first part of the drying of coffee grains

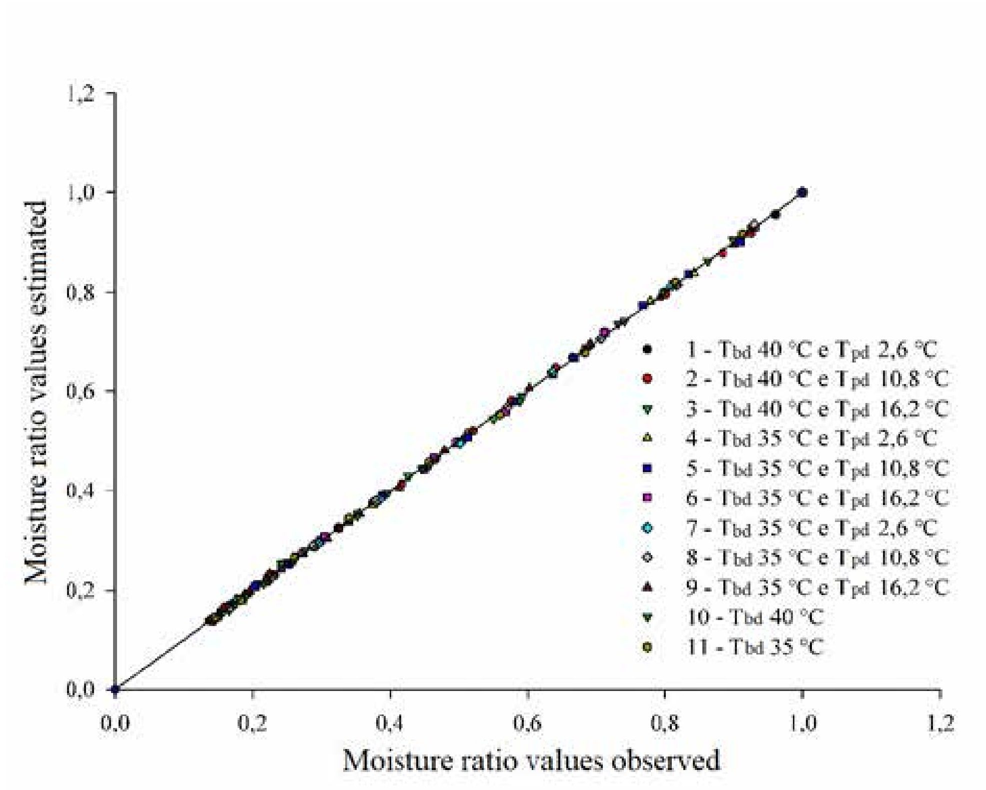


Figure 3. Moisture ratio values (dimensionless) observed (x-axis) and estimated (y-axis) by the Modified Midilli model for drying coffee grains after partial drying (second part of drying)

Table 4. Statistical parameters obtained for the drying models used to describe the drying kinetics of coffee grains, during the second part of drying (after partial drying)

TR	M	R^2(%)	SE	P (%)	TE	M	R^2(%)	SE	P (%)	TE	M	R^2(%)	SE	P (%)	TE
1		99.98	0.013	1.01			99.43	0.039	5.38			99.16	0.081	6.51	
2		99.96	0.022	1.25			99.70	0.035	3.47			99.96	0.023	1.32	
3		99.98	0.017	0.85			99.88	0.022	2.07			99.86	0.042	2.40	
4		99.56	0.073	4.88			99.27	0.054	6.60			99.23	0.098	6.75	
5		99.99	0.013	0.64			99.99	0.007	0.65			99.89	0.036	2.12	
6	Diffusion Approximation	99.98	0.014	0.82	T	Two Terms	99.93	0.017	1.88	T	Exponential of two terms	99.98	0.017	0.77	T
7		99.97	0.015	1.71			99.87	0.018	2.54			99.95	0.020	2.26	
8		99.99	0.011	0.67			99.98	0.009	1.38			99.98	0.014	1.17	
9		99.94	0.030	1.43			99.96	0.014	1.23			99.86	0.043	3.05	
10		99.65	0.055	5.30			99.56	0.036	5.48			99.48	0.068	5.58	
11		99.99	0.010	0.80			99.52	0.037	4.92			99.22	0.082	6.58	
1		99.43	0.067	5.38			99.43	0.030	5.38			99.16	0.081	6.51	
2		99.70	0.060	3.47			99.70	0.027	3.47			99.44	0.081	4.84	
3		99.88	0.038	2.07			99.88	0.017	2.07			99.86	0.042	2.40	
4		99.27	0.094	6.60			99.27	0.042	6.60			99.23	0.098	6.75	
5		99.78	0.050	2.29			99.99	0.006	0.65			99.52	0.074	4.11	
6	Henderson and Pabis	99.93	0.030	1.88	T	Henderson and Pabis Modified	99.99	0.005	0.58	T	Lewis	99.88	0.040	2.60	T
7		99.87	0.032	2.54			99.87	0.014	2.54			99.83	0.037	2.87	
8		99.98	0.015	1.38			99.98	0.007	1.38			99.98	0.015	1.37	
9		99.82	0.050	4.55			99.96	0.010	1.23			99.82	0.050	4.47	
10		99.56	0.062	5.48			99.56	0.028	5.48			99.48	0.068	5.58	
11		99.52	0.064	4.92			99.52	0.029	4.92			99.22	0.082	6.58	
1		100.00	0.006	0.34			100.00	0.006	0.37			99.16	0.081	6.51	
2		99.98	0.016	0.80			99.98	0.017	0.83			99.44	0.081	4.84	
3		99.99	0.013	0.72			99.99	0.014	0.73			99.86	0.042	2.40	
4		99.97	0.020	1.24			99.97	0.020	1.23			99.23	0.098	6.75	
5		99.98	0.016	0.83			99.98	0.016	0.81			99.52	0.074	4.11	
6	Midilli	99.99	0.013	0.69	A	Midilli Modified	99.99	0.013	0.68	A	Newton	99.88	0.040	2.60	T
7		99.99	0.011	1.08			99.99	0.011	1.08			99.83	0.037	2.87	
8		99.99	0.008	0.40			99.99	0.008	0.38			99.98	0.015	1.37	
9		99.98	0.015	0.81			99.98	0.015	0.80			99.82	0.050	4.47	
10		99.97	0.016	1.17			99.97	0.017	1.19			99.48	0.068	5.58	
11		99.99	0.010	0.65			99.99	0.011	0.68			99.22	0.082	6.58	
1		99.98	0.013	1.06			99.93	0.024	1.27			99.98	0.007	0.84	
2		99.96	0.022	1.33			99.94	0.026	0.86			99.95	0.014	1.09	
3		99.96	0.023	1.20			99.99	0.014	0.73			99.99	0.006	0.55	
4		99.48	0.080	5.30			99.76	0.055	3.07			99.97	0.011	1.21	
5		99.97	0.020	1.08			99.90	0.036	2.10			99.97	0.011	0.98	
6	Page	99.99	0.013	0.69	T	Thompson	99.98	0.017	0.77	T	Valcam	99.99	0.007	0.58	A
7		99.96	0.018	2.07			99.92	0.025	2.68			99.99	0.004	0.49	
8		99.98	0.015	1.35			99.98	0.014	1.19			99.98	0.007	1.10	
9		99.83	0.048	4.00			99.86	0.044	3.14			99.95	0.016	1.62	
10		99.56	0.063	5.88			99.49	0.067	5.72			99.94	0.013	2.02	
11		99.98	0.013	1.16			99.82	0.039	2.96			99.98	0.007	1.10	
1		99.43	0.047	5.38			99.96	0.011	0.71						
2		99.70	0.042	3.47			99.94	0.016	1.41						
3		99.88	0.027	2.07			99.89	0.021	1.75						
4		99.27	0.067	6.60			99.62	0.040	3.67						
5		99.78	0.035	2.29			98.69	0.071	6.85						
6	Verma	99.93	0.021	1.88	T	Wang & Sing	99.47	0.047	5.47	T					
7		99.87	0.022	2.54			99.98	0.007	1.05						
8		99.98	0.011	1.38			99.80	0.025	3.79						
9		99.82	0.035	4.55			99.74	0.034	4.75						
10		99.56	0.044	5.48			99.91	0.016	2.13						
11		99.52	0.045	4.92			99.93	0.014	1.50						

TR= treatment; M= model; TE= trend; T= biased; A= random

Table 5. Coefficients of the Two Terms model adjusted to the observed drying kinetics data throughout the drying of the peeled coffee grains

Treatment	T_{bd} (°C)	RH^{+} (%)	Diffusion Approximation model * RU = (a(exp(-k t)))+(1-a)exp(-k b t)		
			a	k	b
1	40	18.2	0.517696	2.862447	0.025116
2	40	20.9	0.493553	4.367485	0.011951
3	40	20.6	0.445483	0.044927	29.85704
4	40	20.1	0.482458	2.362937	0.020341
5	40	22.3	0.458232	2.142943	0.021837
6	40	21.4	0.467904	2.364888	0.020773
7	35	32.2	0.419978	2.321288	0.016976
8	35	24.2	0.438156	3.841785	0.010160
9	35	28.5	0.402894	7.609619	0.005629
10	40	18.4	0.496737	2.933963	0.022305
11	35	26.0	0.447693	6.398029	0.006362

+Average relative humidity of the drying air, obtained according to the ambient air conditions. *Kassem (1998)

Table 6. Coefficients of the modified Midilli model adjusted to the observed drying kinetics data after partial drying (second part of drying) of the peeled coffee grains

Treatment	T_{bd} (°C)	T_{pd} (°C)	RH (%)	Modified Midilli Model* RU = exp(-k t^n)+a t		
				k	n	a
1	40	2.6	10.0	0.096869	1.148387	-0.003380
2	40	10.8	17.5	0.081624	1.088685	-0.002150
3	40	16.2	25.0	0.072000	1.001071	-0.001998
4	35	2.6	13.1	0.072791	0.806539	-0.014063
5	35	10.8	23.0	0.097202	0.874404	-0.000845
6	35	16.2	32.7	0.072015	0.951352	0.000126
7	35	2.6	13.1	0.061757	1.121226	0.001283
8	35	10.8	23.0	0.066940	1.034742	0.000913
9	35	16.2	32.7	0.053817	1.093632	0.001860
10	40	-	18.4+	0.075456	1.239908	0.006055
11	35	-	26.0+	0.038652	1.192088	0.000578

+Average relative humidity of the drying air, obtained according to the ambient air conditions. *Ghazanfari *et al.* (2006)

In Table 5 no trends in relation to the constant “k” and the coefficients “a” and “b” is observed. In Table 6 we can verify that the magnitude of the drying constant “k”, which represents the effect of external drying conditions (GONELI *et al*., 2009) increased with the increase in the drying temperature (T_{bd}), which indicates that the rate of water reduction rises with increasing temperature. According to Babalis and Belessiotis (2004) and Madamba *et al.* (1996), Driscoll and Buckle (1996), the drying constant “k” is related to the effective diffusivity in the drying process for the decreasing period. Regarding the “n” and “a” coefficients of the Modified Midilli model, no definite trend in their values as a function of the temperature and relative humidity of the drying air was observed.

In Figures 4 and 5 are shown the behavior of the moisture ratio of the coffee grains, estimated by the Diffusion Approximation and Modified Midilli models for all studied conditions. A high agreement between the moisture ratio values observed experimentally and the values estimated by the models was observed, which confirms the satisfactory fit of these models to describe the kinetics for each studied condition.

In Figure 4 we can also observe that the start of drying, referring to the first minutes, occurred under a constant rate period, due to the high water content of the grains. After the first minutes, drying took place under a decreasing rate period. During this period, resistances to water and energy transfers are found essentially inside the grains, making the rate of surface evaporation higher than the rate of displacement of water from the interior to the product surface (BROOKER *et al*., 1992).

In the graph of the first part of drying (FIGURE 4), we can observe that the treatments that started drying with T_{bd} of 40 °C obtained greater water loss in the first hours of drying. However, some treatments that after partial drying presented T_{bd} of 35 °C (second part of drying), had total drying times higher than the times of some treatments that started and ended drying with T_{bd} of 35 °C. This result can be observed for treatment 5 (first part T_{bd} 40 °C - second part T_{bd} 35 °C and T_{pd} 10.8 °C), which despite starting the process with 40 °C T_{bd}, obtained a total time of drying equal to treatment 7 (first part T_{bd} 35 °C - second part T_{bd} 35 °C and T_{pd} 2.6 °C), which started the process with 35 °C T_{bd}. The same result occurred for treatment 6 (first part T_{bd} 40 °C - second part T_{bd} 35 °C and T_{pd} 16.2 °C), which obtained a total drying time greater than treatments 7 and equal to treatment 8 (first part T_{bd} 35 °C - second part T_{bd} 35 °C and T_{pd} 10.8 °C). In these cases, the lower T_{pd}, promotes higher rates of water reduction at the end of drying, when the removal of water becomes more difficult due to the internal mechanisms of the grains, making the process faster. Thus, for these conditions, the effect of T_{pd} at the end of drying becomes greater when compared to the effect of T_{bd} at the beginning of drying.

Analyzing Figure 5, referring to the second part of drying, drying under conditions, T_{bd} of 40 °C without T_{pd} control (treatment 10, average RH monitored of 18.4%) and T_{bd} of 40 °C and T_{pd} of 10.8

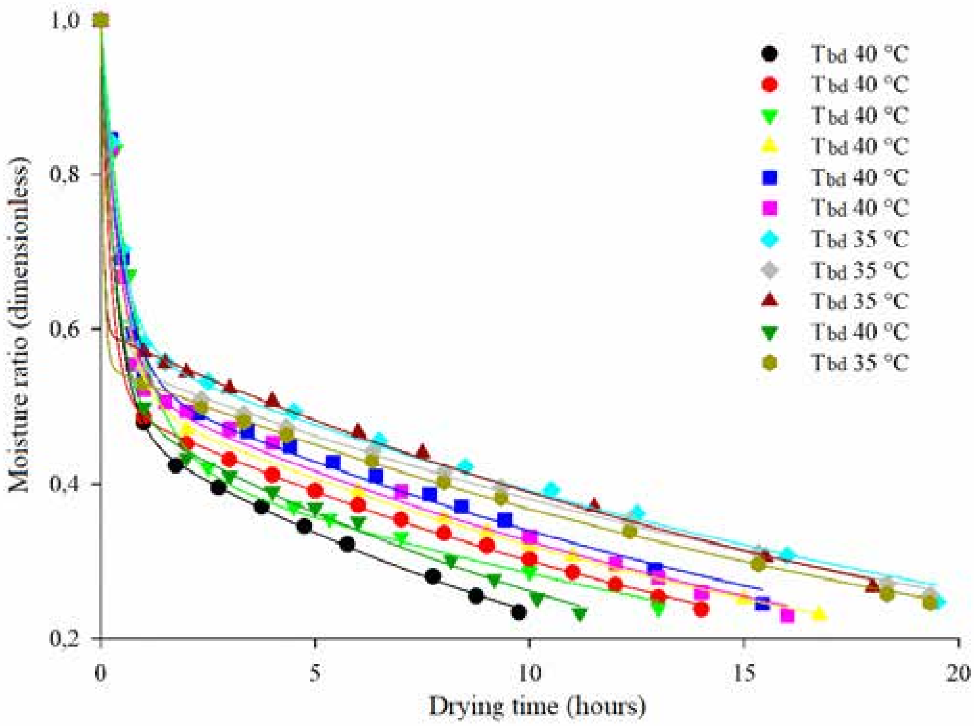


Figure 4. Moisture ratio values observed and estimated (y-axis) by the Diffusion Approximation model for the first part of the drying of the peeled coffee, as a function of the drying time (x-axis)

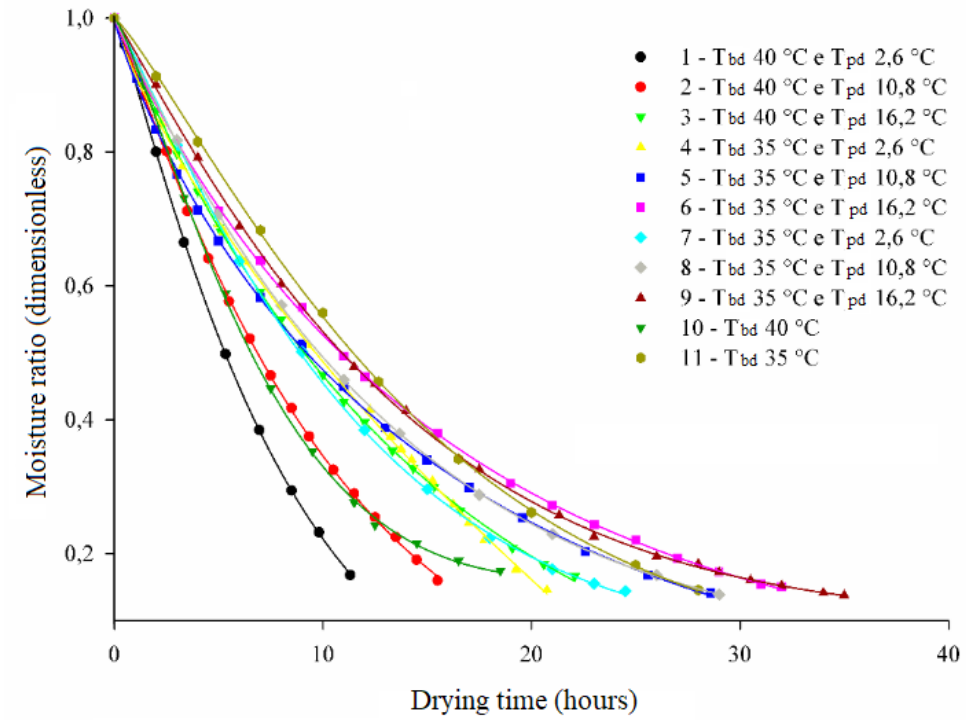


Figure 5. Moisture ratio values observed and estimated (y-axis) by the Modified Midilli model for the second part of the drying of the peeled coffee, as a function of the drying time (x-axis)

°C (treatment 2, 17.5% RH), occurred similarly during the end of drying. However, around 0.24 moisture ratio, the treatment without T_{pd} control (treatment 10) started to have lower rates of water reduction, probably due to greater oscillations in the RH of the drying air, resulting in a total drying time greater than the treatment with T_{pd} of 10.8 °C (treatment 2). When we analyze the treatments 5 and 8, both submitted to T_{bd} of 35 ° C and T_{pd} of 10.8 °C (UR of 23.0%), plus its equivalent without T_{pd} control (treatment 11; average RH monitored of 26.0%), we noticed that the oscillations between the water reduction rates were smaller during the final part, resulting in drying times practically equal.

The average values of the equivalent radius and the effective diffusion coefficients obtained for drying coffee grains, for the different combinations of dry bulb temperature and dew point temperature used in this experimente are shown in Table 7.

The results provided by the analysis of variance showed that the temperature of the drying air and the dew point temperature and, consequently, the relative humidity of the air had a significant effect both on the effective diffusivity coefficient of the first part of drying and on the coefficient of effective diffusivity of the second part of drying.

In Table 7 we can verify that for the first part of the drying of the peeled coffee grains, the effective diffusivity coefficient was higher for the treatments that started the process with higher T_{bd}. Analyzing only the second part of the drying (after partial drying), the increase in the dry bulb temperature and the reduction in the dew point temperature of the drying air to the same dry bulb temperature, increased the effective diffusion coefficient. However, greater differences between the coefficients obtained by each T_{pd}, were observed when using T_{bd} of 40 °C. Furthermore, we can observe a linear increase in the diffusion coefficient due to the reduction in T_{pd}, with values obtained in the range of 1.80 to 3.29 x10^{-11} m^2 s^{-1} for T_{bd} of 40 °C and from 1.69 to 2.14 x 10^{-11} m^2 s^{-1} for T_{bd} of 35 °C.

The pattern seen in the behavior of the diffusion coefficient is determined by some factors and

Table 7. Values of equivalent radius (R_{eq}) and effective diffusion coefficient (D_{eff}) of the peeled coffee grains, as a function of the combinations of dry bulb temperature (T_{bd}) and dew point temperature (T_{pd}) of the drying air, for first and second part of drying

Treatment	R_{eq} x 10^{-3} (m)	First Part			Second Part			
		T_{bd} (°C)	RH^{+} (%)	D_{eff} x 10^{-11} ($m^2.s^{-1}$)*	T_{bd} (°C)	T_{pd} (°C)	RH (%)	D_{eff} x 10^{-11} ($m^2.s^{-1}$)*
1	6.89	40	18.2	1.8459	40	2.6	10.0	3.2973
2	6.77	40	20.9	1.1556	40	10.8	17.5	2.3963
3	6.88	40	20.6	1.4740	40	16.2	25.0	1.8004
4	6.97	40	20.1	0.9883	35	2.6	13.1	1.9592
5	6.99	40	22.3	1.1189	35	10.8	23.0	1.8158
6	7.03	40	21.4	1.2575	35	16.2	32.7	1.6932
7	6.89	35	32.2	0.8401	35	2.6	13.1	2.1459
8	6.94	35	24.2	0.8198	35	10.8	23.0	1.7543
9	6.94	35	28.5	0.8859	35	16.2	32.7	1.7059
10	6.83	40	18.4	1.5002	40	-	18.4^{+}	2.6755
11	6.90	35	26.0	0.8631	35	-	26.0^{+}	1.4934
CV				19.16%				18.07%

$^{+}$Average relative humidity of the drying air, obtained according to the ambient air conditions. * Significant at 5% by the F test

explained by other authors. Corrêa *et al*. (2010a), state that the increase in temperature reduces the viscosity of water, directly influencing the resistance of the fluid to flow and facilitating the diffusion of water molecules in the product's capillaries. Another factor that can be attributed to this increase in the effective diffusion coefficient is that, with the increase in temperature, the level of vibration of water molecules increases, which also contributes to faster diffusion (GONELI *et al*., 2009).

The effect of the dew point temperature, consequently of the relative humidity of the drying air on the diffusion coefficient can also be explained by the internal vapor diffusion mechanism, due to the higher partial vapor pressure gradient (BROOKER *et al*., 1992). The values obtained in this study show the same pattern as those obtained by Isquierdo *et al*. (2013), working with natural coffee, which also observed higher coefficient values for higher T_{bd} and lower T_{pd}, consequently lower relative humidity. Alves *et al*. (2013), working with low relative humidity and different drying air temperatures, obtained coefficients of 1.908 x 10^{-11} m^2 s^{-1} for combination of T_{bd}-T_{pd} of 35 °C - 2.6 °C; 2.456 x 10^{-11} m^2 s^{-1} for T_{bd}-T_{pd} of 40 °C - 2.6 °C and 3.721 x 10^{-11} m^2 s^{-1} for combination of T_{bd}-T_{pd} of 45 °C - 2.6 °C.

The values of the effective diffusion coefficient obtained in this experiment, are in agreement with the values found for agricultural products, which according to Madamba *et al*. (1996), range from 10^{-11} to 10^{-9} m^2 s^{-1}. Corrêa *et al*. (2010b) studied the drying kinetics of coffee fruits at temperatures of 35, 45 and 55 °C and obtained effective diffusion coefficients of 2.99 x 10^{-11}, 2.39 x 10^{-11} and 5.98 x 10^{-11} m^2 s^{-1} respectively. The effective diffusivity of pigeon pea grains ranged from 2.1 x 10^{-10} to 6.8 x 10^{-10} m^2 s^{-1}, for the temperature range of 40 to 70 ° C, in a study performed by Silva *et al*. (2014). For *Jatropha curcas*, according to Siqueira *et al*. (2012), higher temperatures resulted in higher diffusion coefficients, ranging between 9.29 x 10^{-10} and 41.48 x 10^{-10} m^2 s^{-1} for grains and between 16.20 x 10^{-10} and 68.11 x 10^{-10} m^2 s^{-1} for fruits.

CONCLUSION

- In the conditions in which the present study was performed, we can conclude that the reduction of the dew point temperature and, consequently, of the relative humidity after the partial drying, increases the water reduction rate and reduces the drying time of the coffee grains.

- Among the tested models, the Diffusion Approximation and Modified Midilli models were the ones that best fit the experimental data regarding the first and second drying stages of coffee grains (*Coffea arabica* L.), respectively. The effective diffusivity coefficient of coffee grains ranged from 0.81 x 10^{-11} to 1.84 x 10^{-11} m^2 s^{-1} during the first part of drying and from 1.49 x 10^{-11} to 3.29 x 10^{-11} m^2 s^{-1} during the second part of drying, increasing significantly with a reduction in the dew point temperature and an increase in the dry bulb temperature.

REFERENCES

AFONSO JÚNIOR, P. C. **Aspectos físicos, fisiológicos e da qualidade do café em função da secagem e do armazenamento**. 373 p. Tese (Doutorado em Engenharia Agrícola) - Universidade Federal de Viçosa, Viçosa, 2001.

AKPINAR, E. K. Determination of suitable thin layer drying curve model for some vegetables. **Food Engineering**, Dordrecht, v. 3, n. 3, p. 103-108, 2010.

ALVES, G. E. **Cinética de secagem e qualidade do café para diferentes temperaturas e fluxos de ar**. 131 p. Dissertação (Mestrado em Engenharia Agrícolas) – Universidade Federal de Lavras, Lavras, 2013.

ALVES, G. E.; ISQUIERDO, E. P.; BORÉM, F. M.; SIQUEIRA, V. C.; OLIVEIRA, P. D.; ANDRADE, E. T. Cinética de secagem de café natural para diferentes temperaturas e baixa umidade relativa. **Coffee Science**, Lavras, v. 8, n. 2, p. 238-247, 2013.

ANDRADE, E. T.; CORREA, P. C.; TEIXEIRA, L. P.; PEREIRA, R. G.; CALOMENI, J. F. Cinética de secagem e qualidade de sementes de feijão. **Engevista, Niterói**, v. 8, n. 2, p. 83-95, 2006.

BABALIS, S. J.; BELESSIOTIS, V. G. Influence of the drying conditions on the drying constants and moisture diffusivity during the thin-layer drying of figs. **Journal of Food Engineering**, Essex, v. 65, n. 3, p. 449-458, 2004.

BORÉM, F. M. Pós-colheita do café. Lavras: UFLA, 2008.

BRASIL. Ministério da Agricultura, Pecuária e Abastecimento. Regras para análise de sementes. Secretaria de Defesa Agropecuária. Brasília, 399 p, 2009. <http://www.agricultura.gov.br/assuntos/insumos-agropecuarios/arquivos-publicacoes-insumos/2946_regras_analise__sementes.pdf > Acesso em: 12 jan. 2019.

BROOKER, D. B.; BAKER-ARKEMA, F. W.; HALL, C. W. Drying and storage of grains and oilseeds. Westport: AVI Plublishing, 1992.

CALLAGHAN, J. R. O.; MENZIES, D. J.; BAILEY, P. H. Digital simulation of agricultural drier performance. **Journal of Agricultural Engineering Research**, London, v. 16, n. 3, p. 223-244, 1971.

CORRÊA, J. L. G.; PEREIRA, L. M.; VIEIRA, G. V.; HUBINGER, M. D. Mass transfer kinetics of pulsed vacuum osmotic dehydration of guavas. **Jounal of Food Engineering**, Essex, v. 96, n. 4, p. 498- 504, 2010a.

CORRÊA, P. C. OLIVEIRA, G. H. H.; BOTELHO, F. M.; GONELI, A. L. D.; CARVALHO, F. M. Modelagem matemática e determinação das propriedades termodinâmicas do café (*Coffea arabica* L.) durante o processo de secagem. **Revista Ceres**, Viçosa, MG, v. 57, n. 5, p. 595-601, 2010b.

CORRÊA, P. C.; RESENDE, O.; MARTINAZZO, A. P.; GONELI, A. L. D.; BOTELHO, F. M. Modelagem matemática para a descrição do processo de secagem do feijão (*Phaseolus vulgaris* L.) em camadas delgadas. **Engenharia Agrícola**, Jaboticabal, v. 27, n. 2, p. 501-510, 2007.

DRAPER, N. R.; SMITH, H. Applied regression analysis. New York: J. Wiley, 1998.

ERBAY, Z.; ICIER, F. A review of thin layer drying of foods: theory, modeling, and experimental results. **Critical Reviews in Food Science and Nutrition**, Cleveland, v. 50, n. 5, p. 441-464, 2010.

GHAZANFARI, A.; EMAMI, S.; TABIL, L. G.; PANIGRAHI, S. Thin-layer drying of flax fiber: II., modeling drying process using semi-theoretical and empirical models. **Drying Technology**, New York, v. 24, n. 12, p. 1637-1642, 2006.

GONELI, A. L. D.; CORRÊA, P. C.; JÚNIOR, P. C. A.; OLIVEIRA, G. H. H. Cinética de secagem dos grãos de café descascados em camada delgada. **Revista Brasileira de Armazenamento**, Viçosa, MG, n. 11, p. 64-73, 2009.

GONELI, A. L. D.; CORRÊA, P. C.; MAGALHÃES, F. E. A.; BAPTESTINI, F. M. Contração volumétrica e forma dos frutos de mamona durante a secagem. **Acta Scientiarum Agronomy**, Londrina, v. 33, n. 1, p. 1-8, 2011.

HENDERSON, S. M. Progress in developing the thin layer drying equation. **Transactions of the ASAE**, Saint Joseph, v. 17, n. 6, p. 1167-1168, 1974.

HENDERSON, S. M.; PABIS, S. Grain drying theory: temperature effect on drying coefficient. **Journal of Agricultural Engineering Research**, London, v. 6, n. 3, p. 169-174, 1961.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. Green coffee: determination of loss mass at 105 °C: ISO 6673. New York: ISO, 1999.

ISQUIERDO, E. P. **Cinética de secagem de café natural e suas relações com a qualidade para diferentes temperaturas e umidades relativas do ar**. 157 p. Tese (Doutorado em Ciência dos Alimentos) – Universidade Federal de Lavras, Lavras, 2011.

ISQUIERDO, E. P. BORÉM, F. M.; ANDRADE, E. T.; CORRÊA, J. L. G.; OLIVEIRA, P. D.; ALVES, G. E. Drying kinetics and quality of natural coffee. **Transactions of the ASAE**, Saint Joseph, v. 53, n. 3, p. 1003-1010, 2013.

KARATHANOS, V. T. Determination of water content of dried fruits by drying kinetics. **Journal of Food Engineering**, Essex, v. 39, n. 4, p. 337-344, 1999.

KASHANINEJAD, M. *et al*. Thin-layer drying characteristics and modeling of pistachio nuts. **Journal of Food Engineering**, Essex, v. 78, n. 1, p. 98-108, 2007.

KASSEM, A. S. Comparative studies on thin layer drying models for wheat. In: INTERNATIONAL CONGRESS ON AGRICULTURAL MECHANIZATION AND ENERDY, 13., 1998, Morocco. **Proceedings**… Morocco, 1998. Disponível em: <http://www.sciepub.com/reference/161007>. Acesso em: 10 mar. 2017.

KAYACAN, S.; SAGDIC, O.; DOYMAZ, I. Effects of hot-air and vacuum drying on drying kinetics, bioactive compounds and color of bee pollen. **Journal of Food Measurement and Characterization**, v. 1, n. 2, p. 1-10, 2018.

LEWIS, W. K. The rate of drying of solid materials. **Journal of Industrial and Engineering Chemistry**, v. 13, n. 5, p. 427-432, 1921.

MADAMBA, P. S.; DRISCOLL, R. H.; BUCKLE, K. A. The thin layer drying characteristic of garlic slices. **Journal of Food Engineering**, Essex, v. 29, n. 1, p. 75-97, 1996.

MIDILLI, A.; KUCUK, H.; YAPAR, Z. A. A new model for single-layer drying. **Drying Technology**, New York, v. 20, n. 7, p. 1503-1513, 2002.

MOHAPATRA, D.; RAO, P. S. A thin layer drying model of parboiled wheat. **Journal of Food Engineering**, Essex, v. 66, n. 4, p. 513-518, 2005.

PAGE, C. **Factors influencing the maximum rates of air drying of shelled corn in thin layers**. Thesis (Ph.D.) - Purdue University, Lafayette, 1949.

RESENDE, O.; SIQUEIRA, V. C.; CORRÊA, P. C.; JUNIOR, P. C. A. Modelagem matemática da secagem do café (*Coffea canephora* Pierre) em terreiros de concreto e híbrido. **Revista Brasileira de Armazenamento**, Viçosa, MG, v. 35, n. 2, p. 153-160, 2010.

SHARAF-ELDEEN, Y. I.; BLAISDELL, J. L.; HAMDY, M. Y. A model for ear corn drying. **Transactions of the ASAE**, v.23, p.1.261-1.265, 1980.

SILVA, P. A.; RABELO V. M.; CALIXTO J. M. R.; COELHO P. O.; GORSKI I. C. Quality assessment of coffee grown in Campos Gerais, Minas Gerais State, Brazil. **Acta Scientiarum.** Technology, Maringá, v. 36, n. 4, p. 739-744, 2014.

SIQUEIRA, V. C.; RESENDE, O.; CHAVES, T. H. Mathematical modelling of the drying of jatropha fruit: an empirical comparison. **Revista Ciência Agronômica**, Fortaleza, v. 44, n. 2, p. 278-285, 2013.

SIQUEIRA, V. C.; RESENDE, O.; CHAVES, T. H. Drying kinetics of Jatropha seeds. **Revista Ceres**, Viçosa, v. 59, n. 2, p. 171-177, 2012.

SOUSA, K. A.; RESENDE, O.; CHAVES, T. H.; COSTA, L. M. Cinética de secagem do nabo forrageiro (*Raphanus sativus* L.). **Revista Ciência Agronômica**, Fortaleza, v. 42, n. 4, p. 883-892, 2011.

THOMPSON, T. L.; PEARTT, R. M.; FOSTER, G. H. Mathematical simulation of corn drying: a new model. **Transactions of the ASAE**, Saint Joseph, v. 11, n. 4, p. 582-589, 1968.

VERMA, L. R.; BUCKLIN, R. A.; ENDAN, J. B.; WRATTEN, F. T. Effects of drying air parameters on rice drying models. **Transactions of the ASAE**, Saint Joseph, v. 28, n. 1, p. 296-301, 1985.

VILELA, C. A. A.; ARTUR, P. O. Secagem do açafrão (*Curcuma longa* L.) em diferentes cortes geométricos. **Ciência e Tecnologia de Alimentos**, Campinas, v. 28, n. 2, p. 387-394, 2008.

WANG, C. Y.; SINGH, R. P. A single layer drying equation for rough rice. Saint Joseph: ASAE, 1978.