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Mathematical modeling for drying flint corn in a thin layer

Abstract – The objective of this work was to adjust the coefficients of six mathematical models and to identify the one that best represents the drying of flint corn grains in a thin layer. For this purpose, a drying column was developed to obtain experimental data. Nine tests were performed for each model, using the velocities of 0.5, 1.0, and 1.5 m s^{-1} at 40, 50, and 60°C, respectively, for drying air. The thin-layer drying models of Lewis, Page, Thompson, Overhults, Brooker, and Midilli were tested. All adjusted models represent the phenomenon of flint corn drying at 5% probability (χ^2 test). After adjusted, the models of Page, Midilli, and Overhults are the best ones for drying corn, with a coefficient of determination equal to 1.000 for all tests and errors lower than 1.0%. For the drying conditions of this work, the n parameter of the model of Page does not depend on the velocity and temperature of drying air, while the k parameter depends only on air temperature, which is confirmed by the analysis of variance. The adjusted model of Page can be used with precision for the prediction of thin-layer flint corn drying.

Index terms: *Zea mays*, drying column, fixed-bed drying,

Modelagem matemática para secagem de milho “flint” em camada delgada

Resumo – O objetivo deste trabalho foi ajustar os coeficientes de seis modelos matemáticos e identificar aquele que melhor representa a secagem de grãos de milho “flint” em camada delgada. Para isso, desenvolveu-se uma coluna de secagem para a obtenção dos dados experimentais. Nove testes foram realizados para cada modelo, tendo-se utilizado as velocidades de 0,5, 1,0 e 1,5 m s^{-1} a 40, 50 e 60°C, respectivamente, para o ar de secagem. Testaram-se os modelos de Lewis, Page, Thompson, Overhults, Brooker e Midilli para camada delgada. Todos os modelos ajustados representam o fenômeno da secagem do milho “flint” a 5% de probabilidade (teste χ^2). Após ajustados, os modelos de Page, Midilli e Overhults são os melhores para a secagem de milho “flint”, com coeficiente de determinação igual a 1,000 para todos os testes e erros inferiores a 1,0%. Para as condições de secagem deste trabalho, o parâmetro n do modelo de Page não depende da velocidade e da temperatura do ar de secagem, enquanto o parâmetro k depende apenas da temperatura do ar, o que é confirmado pela análise de variância. O modelo de Page ajustado pode ser usado com precisão na predição da secagem de milho “flint” em camada delgada.

Termos para indexação: *Zea mays*, coluna de secagem, secagem em leito fixo.

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Introduction

Drying is the process of removing moisture from grains by evaporation; initially, it involves the moisture migration from the interior of grains to the surface and, subsequently, the evaporation. The process can be accelerated by the insufflation of hot air through the grain bed, removal of the surface moisture and promotion of the grain heating. Moisture is a major factor for corn growing, as it determines the appropriate time for harvesting and the conditions for storage (Kucuk et al., 2014). For an adequate storage, humidity levels close to 13% on a wet basis (wb) are necessary, and they may present a value of up to 11% for very long stocks (Elias et al., 2017).

Several thin-layer models are found in the literature, and they are applied to the most diverse types of agricultural products; however, there is not a universal model, since the parameters in the equations vary with the type of product and the region of cultivation. Thus, obtaining experimental data that accurately represents the thin-layer drying process is essential for choosing the best model (Kucuk et al., 2014).

The thin layer is characterized as a very thin grain surface that shows a maximum exposure in relation to the air flow (Bala, 2017). The models developed by Lewis, Page, Thompson, Overhults, Brooker, and Midilli were chosen for the analysis in this work because they showed good results in previous studies on grains of different types (Liu et al., 2015; Souza et al., 2015; Sun et al., 2016; Abasi et al., 2017; Nejadi & Nikbakht, 2017; Jian & Jayas, 2018; Prakash & Siebenmorgen, 2018).

The adjustment of several thin-layer drying models has been observed in recent years for several agricultural products. Thin-layer drying composed a set of partial differential equations, in the prediction of thick-layer corn drying; however, the validity of the model was limited, mainly due to the coefficients of thin-layer equations (Liu et al., 2015). The Overhults' model was employed with the coefficients adjusted to the experimental data, to compose a model of mass and energy balance and to satisfactorily simulate the drying process of soybean seed in a fixed bed (Souza et al., 2015)

The Midilli's model was successfully applied by Nejadi & Nikbakht (2017) to study the corn drying in a fluidized bed with heating by infrared irradiation. The variations of coefficients were studied for the Page and Brokker's empirical equations for distinct maize species, and both equations showed a good correlation with the experimental data, and the authors concluded that the coefficients were significantly influenced by the grain texture (Sun et al., 2016). The Lewis' exponential model was applied in the analysis of drying corn straw, grasses, and plants for silage, and proved to be useful for planning logistics operations (Khanchi & Birrell, 2017).

Five thin-layer models were investigated by Doymaz (2017) for drying carrot slices; among them, the Midilli model was the one that best characterized drying at 50, 60, and 70°C at 2 m s^{-1} air velocity. A new theoretical model of thin-layer drying was proposed by Jiang et al. (2017), who tested it using experimental data from potato drying. Although the model showed satisfactory data, it is limited, as the diffusion of the product's internal moisture was neglected. The drying of different rice cultivars was analyzed, using the Page, Lewis, and Midilli's models, which were considered valid for predicting the drying of rice after adjustments (Prakash & Siebenmorgen, 2018). The drying of saffron roots was evaluated using eleven exponential models that showed statistically satisfactory results in relation to the experimental data (Karthikeyan & Murugavelh, 2018).

A diffusion model of moisture in grains was analyzed by Giner (2019) during the drying of wheat. Variable boundary conditions were applied and the analytical and numerical solutions of the process were compared, using coefficients obtained in previous research. Other recent works are also found in the literature for drying various products, such as flowers and fruits (George et al., 2017; Amer et al., 2018; Chauhan et al., 2018; Buzrul, 2022), organic waste (Zhou et al., 2017), sawdust (Bryś et al., 2021), and minerals (Fadhel et al., 2018).

Despite the many works on thin-layer drying of corn in the literature, only few of them give emphasis to the variety, especially to the flint type that is the main cultivar grown in the Brazilian territory.

The objective of this work was to adjust the coefficients of six mathematical models and to identify the one that best represents the drying of flint corn grains in a thin layer. For this, a drying column was also developed, in order to obtain experimental data. The data obtained in the development of this work can be used in the simulation and validation of mathematical models for drying corn.

Materials and Methods

In order to carry out the experiments, a drying system consisting of a fixed-bed dryer and a thin-layer drying chamber was designed and built. This project was elaborated aiming to obtain an equipment to allow of an efficient control of the temperature and regulation of air velocity at the entrance. The system consists of an air-blower ventilator, heating chamber, air distribution chamber (plenum), temperature and velocity controller, and a base to couple the drying chamber and gauges (Figure 1). This equipment was built by researchers from the Mechanical Engineering Department of Centro Federal de Educação Tecnológica de Minas Gerais (Cefet - MG) for drying studies. Drying systems with dimensions similar to those used can also be found in Zare & Chen (2009), ElGamal et al. (2017), and Zhao et al. (2018).

The air blower consists of a ventilator Siroco 2P (Varivelox Industrial Ltda., Toledo, PR, Brazil) that uses a single-phase 220 V motor, 1/3 HP, and 3,500 rpm rotation, with a maximum flow rate of approximately 12 m^3 min^{-1}. The heating chamber consists of a set of four finned electric resistors, each with 1 kW heat dissipating power of air. The chamber was built using galvanized sheet 22 (0.8 mm thick), and it has a central expansion area and two reductions at the ends, with angles of approximately 17° and 97 mm diameter. The air distribution chamber was made of the same material as the heating chamber; this part of the system is necessary to obtain a more uniform air distribution near the entrance of the drying column. The plenum has 220 mm height and 35° angle, and it was thermally insulated to obtain a better uniformity in boundary conditions. The base for fitting the drying column has 100 mm diameter, it also includes velocity and relative humidity meters, as well as two thermocouple inlets, one for the temperature controller, and the other for the measurements in the tests.

The temperature control is carried out by a proportional, integral, and derivative controller (PID), coupled to a solid state relay, a type J thermocouple, allowing of the automated control of temperature at the entrance of the drying column, and enabling or disabling the resistances in the heating chamber. The system enables the temperature at the inlet to be kept constant throughout the grain drying experiment, allowing of the user to turn the resistors on and off independently by means of switches, in addition to controlling the ventilator.

To carry out the experiments in a thin layer, a drying column was built (Figure 2) with a diameter close to that of the accommodation base (Figure 1) and low height. The column was designed with 200 mm maximum height and 130 mm diameter, and the manufacturing material was galvanized steel 26 (0.50 mm thick). In order to contain the grains inside the chamber and allow of upward air passage, a perforated steel plate was used. The perforated plate was positioned 50 mm from the base of the column to enable a satisfactory fitting surface with the plenum. Despite the 200 mm height, only 30 mm were used as a grain bed for drying. To monitor air temperatures,

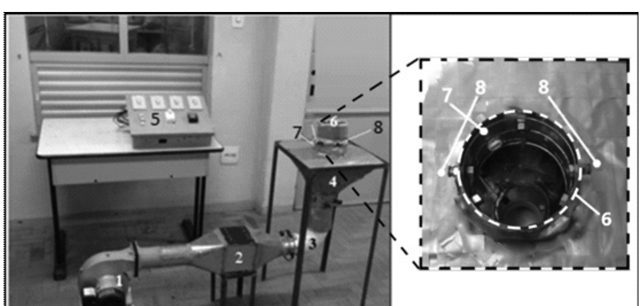

Figure 1. Diagram of the drying system parts: 1, fan; 2, heating chamber; 3 connection curve; 4, plenum; 5, temperature controller; 6, base for attaching the drying chamber; 7, point to measure the velocity and relative humidity; 8, point for connecting the thermocouples. Photos by Leonardo Alves da Costa

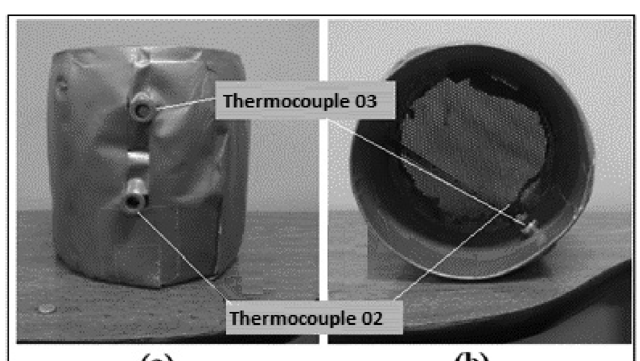

Figure 2. Column manufactured to study the drying of flint corn (*Zea mays*) in a thin layer. Photos by Leonardo Alves da Costa

two thermocouples were positioned on the column: the first at 60 mm (thermocouple 02), and the second at 140 mm (thermocouple 03) from the base. The thermocouple connected to the coupling base was used to monitor the temperature of the incoming air and was designated as thermocouple 01.

Temperature measurements were performed using 100 mm type J stainless steel thermocouples, which were previously calibrated using a thermostatic bath and bulb thermometer (uncertainty of ± 0.2°C, in the range of -10 to 62°C). To measure the velocity of the drying air, a hot wire thermo-anemometer was used, with a 0.01 m s^{-1} resolution in the 0 to 30 m s^{-1} range. The relative humidity measurements were performed with a digital thermohygrometer, from 15 to 95% measurement range and 1% resolution.

To monitor the air temperatures at the entrance and in the drying column, thermocouples 01, 02, and 03 were coupled to a multifunctional data acquisition system. The system consists of a computer, a data recording unit, and a module with the necessary channels for the application. The moisture content of the corn samples was determined with the use of an airrenewal oven, of 40 L capacity and adjustment of the desired temperature by thermostat. Sample masses were measured using a digital scale with 0.1 g resolution and 500 g maximum capacity.

In order to carry out the experiments, grains of the BG7640VYH corn cultivar were used, which is a hybrid of the flint type (glassy texture) provided by Embrapa, with wide adaptation to tropical regions and without any restriction for the growing season. The grains were harvested and threshed mechanically by a grain harvesting machine, and the plant was in the ideal stage of physiological maturation, with a moisture content close to 22% in dry basis (18% wet basis).

The tests were carried out following an experimental factorial design (3^2) at three temperatures and three air flow velocities (Table 1). During the experiments, the mass of the corn bed, relative humidity, and temperature of the thermocouples were recorded every 10 min. Drying time was 150 min for each test. The experiments were carried out on clear days, with relative humidity between 50 and 60%, which guaranteed a satisfactory degree for comparison between the tests.

Corn initial moisture content was determined by weighing a mass of approximately 100 g of wet corn; then the mass was taken to the oven for drying at 105±1ºC and, after 24 hours, the sample was removed from the oven and a new weighing was carried out. The sample for drying in a thin layer was homogenized and, immediately after weighing its mass (Table 1), it was taken to the drying column. The drying system was turned on and the velocity value was adjusted, using the thermo-anemometer and the temperature controller. The temperature was stabilized at ±1ºC. Thermocouples 02 and 03 were coupled to the thin-layer column and to the data acquisition system.

Initial measurements of grain bed temperature, temperature, and relative humidity of the drying air were performed. Soon after, the thin-layer column was coupled to the drying system and the test started. Measurements of temperature and relative humidity of the drying air, temperature, and mass of the grain bed were taken every 10 min, for 150 min. At the end of the experiment, the experimental data were processed.

The moisture content of the grains on a dry basis (M_d) was determined in the thin layer, using successive

Table 1. Planning of the experiment of thin-layer flint corn (*Zea mays*) drying. Nine tests were carried out at different temperatures and drying air velocities. The results of these tests were used to evaluate the prediction efficiency of the mathematical models tested.

Test	Drying temperature (°C)	Drying air velocity (m s^{-1})	Wet mass corn (g)	Corn layer height (cm)	Initial moisture content (% db)	Time of drying (min)
Test 01	40					
Test 02	50	0.5	250	3	22	150
Test 03	60					
Test 04	40					
Test 05	50	1.0	250	3	22	150
Test 06	60					
Test 07	40					
Test 08	50	1.5	250	3	22	150
Test 09	60					

measures of wet (m_w) and dry (m_d) corn mass, and calculated according to the following equation:

$$M_d = \left(\frac{m_w - m_d}{m_d}\right) \quad (1)$$

The grain moisture ratio (MR) is a useful quantity used in drying research area; it allows of the comparison of experiments carried out with different initial humidity values, and it can be expressed in the following form:

$$MR = \left(\frac{M_d - M_e}{M_i - M_e}\right) \quad (2)$$

The initial moisture content (M_i) was determined before the start of the tests, while the equilibrium moisture content (M_e) was determined using the Henderson's (Liu et al., 2015) equation, as follows:

$$M_e = \left[-\frac{\ln(1-RH)}{\left(A(T+273.16)\right)}\right]^{\frac{1}{B}} \quad (3)$$

where: RH and T are respectively the relative humidity and the temperature of the drying air, under equilibrium conditions. The values of the coefficients (A and B) in Equation (3) were confirmed experimentally, being given by the constants: $A = 3.1\times10^{-5}$ and $B = 1.76$

The six thin-layer drying tested models are shown in mathematical equations (Table 2). The analysis of these models was carried out in order to select the one that best represents the drying-curve equation for the corn cultivar used. For that, the values of the parameters of the equations were evaluated for temperature changes and velocity of the drying air.

The results of the thin-layer drying models were compared with the experimental ones, to identify the best model that represented the phenomenon and, for this purpose, the determination coefficient (R^2), the estimated standard error (SE), and the relative average error (P) were used as statistical parameters for the selection of the model. Better quality models have high values for R^2, and lower values for other parameters, which are expressed as:

$$R^2 = \frac{\left[\Sigma_{i=1}^{N}\left(MR_{exp,i} - \overline{MR}_{exp}\right)\left(MR_{pre,i} - \overline{MR}_{pre}\right)\right]^2}{\Sigma_{i=1}^{N}\left(MR_{exp,i} - \overline{MR}_{exp}\right)^2 \Sigma_{i=1}^{N}\left(MR_{pre,i} - \overline{MR}_{pre}\right)^2} \quad (4)$$

$$SE = \sqrt{\frac{\Sigma_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{DFM}} \quad (5)$$

$$P = \frac{100}{N}\sum_{i=1}^{N}\frac{\left(MR_{exp,i} - MR_{pre,i}\right)}{MR_{exp,i}} \quad (6)$$

where: $MR_{exp,i}$ and $\overline{MR}_{exp}$ are the instantaneous and average experimental moisture ratios, respectively; $MR_{pre,i}$ and $\overline{MR}_{pre}$ are the moisture ratios predicted by the instantaneous model and average, respectively; and DFM are the degrees of freedom of the model (number of experimental measurements minus the number of parameters considered in the model).

The statistical analysis was complemented with the chi-squared test (χ^2) of adherence, and the values of χ^2 were calculated according to Equation (7) for each model, in each drying condition, and compared to the critical value, as follows:

$$\chi^2 = \frac{\Sigma_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{DFM} \quad (7)$$

The values of the humidity ratio in each model were initially calculated using the parameters suggested by the literature, and then the value of each parameter was adjusted to the experimental data. For this purpose, the Microsoft Excel "solver" function was used, which performs non-linear data regression by adjusting the values of the equation parameters. After choosing the best quality model for drying corn, an analysis was performed for the dependence of the parameters on the temperature and air velocity. For this purpose, the analysis of variance was applied using the Microsoft Excel "data analysis" function. For all statistical tests, 5% probability (α) was assumed.

Table 2. Thin-layer mathematical drying models tested for flint corn (*Zea mays*).

Model	Model equation	Reference
Lewis	$MR = \exp(-kt)$	Khanchi & Birrell (2017)
Page	$MR = \exp(-kt^n)$	Sun et al. (2016)
Thompson	$MR = \exp\left(\frac{-a-(a^2+4bt)^{0.5}}{2b}\right)$	Kucuk et al. (2014)
Overhults	$MR = \exp((-kt)^n)$	Souza et al. (2015)
Brooker	$MR = c\exp(-kt)$	Doymaz (2017)
Midilli	$MR = c\exp(-kt^n) + dt$	Doymaz (2017)

MR, moisture ratio; a, b, c, d, k, n: empirical parameters of the equations.

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Results and Discussion

The experimental results of thin-layer drying corn in the drying conditions used are presented (Figure 3). The final moisture ratio of corn was between 0.49 and 0.62, representing moisture contents between 12.1 and 16.7% dry basis (db). Measurement uncertainties were adequately identified and estimated quantitatively, considering all measurement cycles and expansion formulae, and the results generated in Microsoft Excel and Engineering Equation Solver (EES) showed uncertainty of ±0.05% (db) for the moisture content, and ±0.004 for the grain moisture ratio.

It was observed that in experiments carried out at the same velocity, there was a reduction of the grain moisture ratio with the increase of temperature. Due to the increase of the rate of energy supplied to the bed by the resistances, this observation was more accentuated in the drying at a lower velocity (tests 01, 02, and 03). There were no significant changes of the moisture content with the increase of the flow velocity at the same temperature, although this variable is important in the displacement of the drying front.

An approximately linear behavior was observed during the drying time, with small deviations during the first minutes of the process because of the transient heating of the grains. This behavior is typical of drying curves and shows the control of the process by convective phenomena of heat and mass on the surface of the grains.

The statistical parameters calculated for each corn drying model were analyzed according to different temperatures and air velocities (Table 3). The available

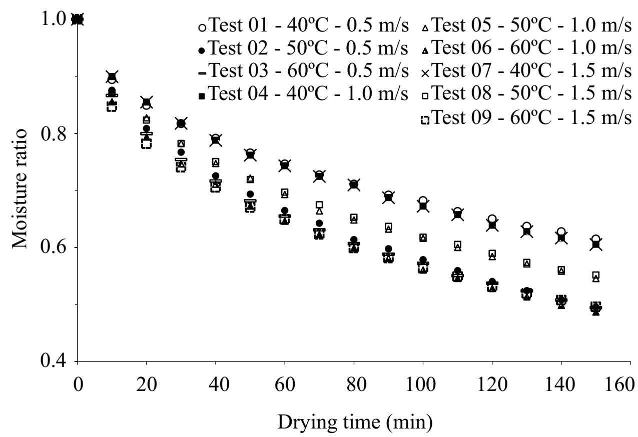

Figure 3. Moisture ratio data obtained during the thin-layer drying of flint corn (*Zea mays*), for all experimental tests carried out in the drying column manufactured for the present work.

Table 3. Determination coefficient (R^2), relative average error (P, %), estimated standard error (SE) and chi-square (χ^2) test for the thin-layer drying models analyzed. These statistical parameters were calculated for each flint-corn (*Zea mays*) drying model, and analyzed according to different temperatures and air velocities. The available data were obtained after adjusting the model equations in relation to the experimental values of thin layer drying.

Model	Air Temp.	R^2			SE			P			χ^2 (x 10^{-3})		
	(°C)	0.5 m s^{-1}	1.0 m s^{-1}	1.5 m s^{-1}	0.5 m s^{-1}	1.0 m s^{-1}	1.5 m s^{-1}	0.5 m s^{-1}	1.0 m s^{-1}	1.5 m s^{-1}	0.5 m s^{-1}	1.0 m s^{-1}	1.5 m s^{-1}
	40	0.942	0.951	0.951	0.048	0.045	0.045	5.3	5.0	5.0	2.293	2.054	2.055
Lewis	50	0.957	0.944	0.942	0.053	0.055	0.055	6.7	6.6	6.6	2.783	2.972	3.044
	60	0.946	0.945	0.932	0.058	0.061	0.066	7.5	7.9	8.5	3.407	3.675	4.324
	40	0.935	0.944	0.944	0.028	0.027	0.027	2.5	2.4	2.4	0.804	0.747	0.748
Brooker	50	0.949	0.935	0.933	0.033	0.034	0.034	3.5	3.3	3.2	1.117	1.137	1.128
	60	0.937	0.934	0.920	0.037	0.038	0.041	3.9	4.1	4.2	1.379	1.462	1.680
	40	0.998	0.996	0.996	0.006	0.010	0.010	0.7	1.1	1.1	0.038	0.099	0.099
Thompson	50	0.993	0.997	0.998	0.017	0.010	0.008	1.9	1.0	0.9	0.275	0.091	0.059
	60	0.997	0.997	0.999	0.012	0.011	0.005	1.3	1.2	0.6	0.146	0.114	0.028
	40	1.000	1.000	1.000	0.002	0.002	0.002	0.2	0.2	0.2	0.003	0.005	0.005
Page	50	1.000	1.000	1.000	0.002	0.003	0.002	0.3	0.3	0.2	0.005	0.010	0.003
	60	1.000	1.000	1.000	0.003	0.002	0.002	0.3	0.2	0.3	0.007	0.004	0.004
	40	1.000	1.000	1.000	0.002	0.002	0.002	0.2	0.2	0.2	0.003	0.006	0.006
Midilli	50	1.000	1.000	1.000	0.002	0.003	0.002	0.3	0.3	0.2	0.005	0.010	0.003
	60	1.000	1.000	1.000	0.002	0.002	0.002	0.2	0.1	0.2	0.003	0.002	0.004
	40	1.000	1.000	1.000	0.002	0.002	0.002	0.2	0.2	0.2	0.003	0.005	0.005
Overhults	50	1.000	1.000	1.000	0.002	0.003	0.002	0.3	0.3	0.2	0.005	0.010	0.003
	60	1.000	1.000	1.000	0.003	0.002	0.002	0.3	0.2	0.3	0.007	0.004	0.004

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data were obtained after adjusting the parameters in relation to the experimental values of thin-layer drying.

After the adjustment, all statistical parameters proved to be satisfactory, obtaining a coefficient of determination (R^2) of 0.920 minimum and 1.000 maximum. The Page, Midilli, and Overhults' models showed R^2 values equal to 1.000 for all tests. The values for the relative average error (P) below 8% were obtained for all tests, and those below 1% were obtained for the Page, Midilli and Overhults' models. Regarding the estimated standard error (SE), all models showed very low values, with emphasis on the Page, Midilli, and Overhults' models with values very close to zero.

The chi-square test was performed on all models, and very small values were obtained, always below the critical value (χ^2 critical > 20), in addition to presenting a p-value equal to one (p=1.000) in all tests. Therefore, as p>0.05 and calculated χ^2 values do not belong to the region of critical values, it can be stated that, at 5% probability, the distance between the moisture ratio values predicted by the models and those obtained experimentally was very small in all analyzed cases; that is, the models apply to the results of the experiments. The Page, Midilli, and Overhults' models stood out again, with χ^2 values about 1,000 times lower than the others. It is important to mention that the lower is the value of χ^2, the better will the model fit the experimental data (Kucuk et al., 2014).

The results of the statistical analysis (R^2, P, SE, and χ^2) were evaluated according to Brooker et al. (1992), Dinçer & Zamfirescu (2016), and Bala (2017). Similar works are found in the literature (Hemis et al., 2011; Yi et al., 2012; Doymaz, 2017; Khanchi & Birrell, 2017; Prakash & Siebenmorgen, 2018; Ramaj et al., 2021), and the accuracy of the models is assessed by the same statistical tests, and with similar compatibility.

As the adjusted models of Page, Midilli, and Overhults showed higher quality, and their results showed a very great similarity, only the Page's model was chosen for a more in-depth study for the dependence of the parameters on temperature and air velocity, and it was selected to represent the thin-layer drying of corn analyzed in the present work (Figure 4).

The dependence of the Page's model parameters on temperature and velocity was performed using the analysis of variance. For all tests, a significance level (α) of 0.05 was assumed. For the k parameter, the F-test of global significance showed F <0.05, indicating the statistical evidence that at least one of the variables (temperature and / or velocity) is related to the variation in the k value.

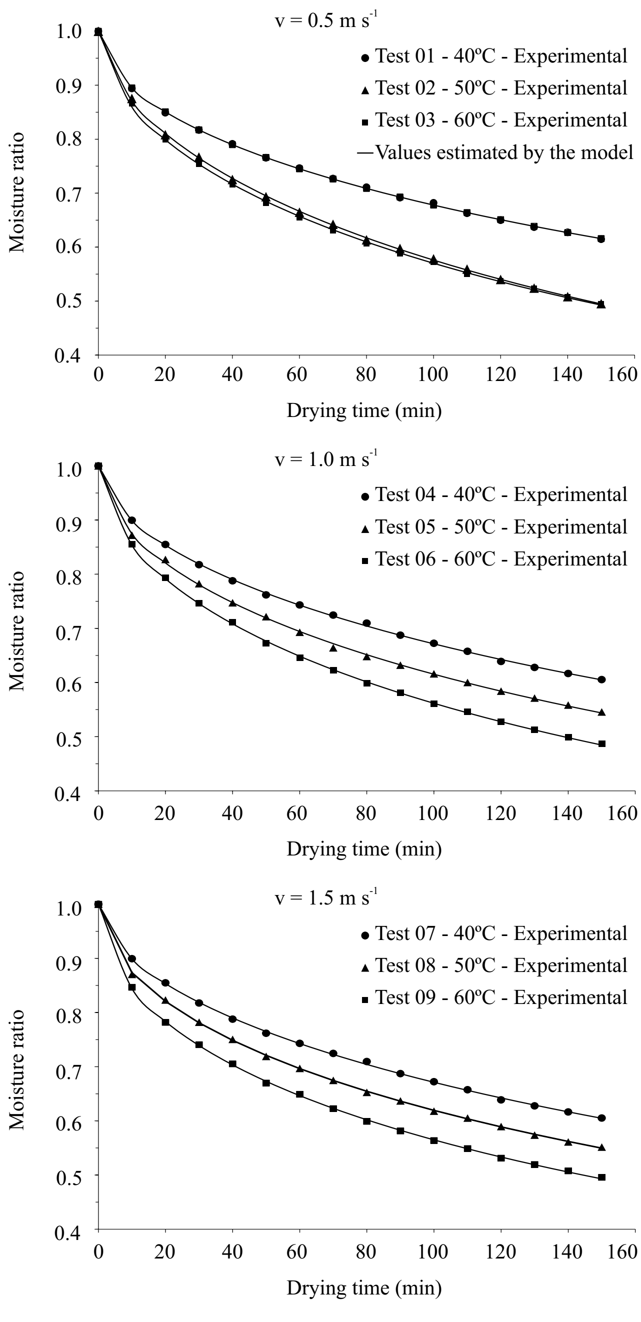

Figure 4. Experimental and estimated moisture ratio by the Page's model, obtained for the drying of flint corn (*Zea mays*) at different values of temperature and drying-air velocity.

The individual significance test showed a p-value <0.05 for the intersection of the curve and for the temperature variable, and a p-value >0.05 for the air velocity variable, indicating statistical evidence of a relationship between the k value and temperature, while no evidence was observed for velocity. The analysis of variance for the parameter n showed p-value >0.05 for the global and individual significance test for both variables; therefore, there is no evidence of a relationship between the values of n and the temperature or air velocity for drying corn in a thin layer. The value of n was determined by the simple average of the obtained values, which is given as $n = 0.562 \pm 0.021$. The equation for the parameter k of the Page model was determined by linear regression of the data obtained at different temperatures (T), as follows: $\ln k = -0.019T + 1.951$, $R^2=0.99$.

Conclusions

1. The drying column constructed can be used for drying flint corn (*Zea mays*) grains, as the aspect of the drying curves of the nine experimental tests is similar to those obtained by other authors in the literature.

2. All adjusted models represent well the phenomenon of flint corn drying with precision; the Page, Midilli, and Overhults' models are the best ones for drying flint corn, after the adjustment, and any of these three models can be used for drying of thin-layer flint corn precisely; the Brooker and Lewis' models are the least indicated ones.

3. The Page's model adjusted in the present work can be used with precision in the prediction of thin-layer flint corn drying, and it can also be coupled to other differential equations in the study of thick-layer drying.

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References

ABASI, S.; MINAEI, S.; KHOSHTAGHAZA, M.H. Effect of desiccant system on thin layer drying kinetics of corn. **Journal of Food Science and Technology**, v.54, p.4397-4404, 2017. DOI: https://doi.org/10.1007/s13197-017-2914-z.

AMER, B.M.A.; GOTTSCHALK, K.; HOSSAIN, M.A. Integrated hybrid solar drying system and its drying kinetics of chamomile. **Renewable Energy**, v.121, p.539-547, 2018. DOI: https://doi.org/10.1016/j.renene.2018.01.055.

BALA, B.K. **Drying and storage of cereal crains**. 2nd ed. Chichester: J. Wiley & Sons, 2017. 354p. DOI: https://doi.org/10.1002/9781119124207.

BROOKER, D.B.; BAKKER-ARKEMA, F.W.; HALL, C.W. **Drying and storage of grains and oilseeds**. New York: Van Nostrand Reinhold, 1992. 450p.

BRYŚ, A.; KALETA, A.; GÓRNICKI, K.; GŁOWACKI, S.; TULEJ, W.; BRYŚ, J.; WICHOWSKI, P. Some aspects of the modelling of thin-layer drying of sawdust. **Energies**, v.14, art.726, 2021. DOI: https://doi.org/10.3390/en14030726.

BUZRUL, S. Reassessment of thin-layer drying models for foods: a critical short communication. **Processes**, v.10, art.118, 2022. DOI: https://doi.org/10.3390/pr10010118.

CHAUHAN, P.S.; KUMAR, A.; NUNTADUSIT, C.; BANOUT, J. Thermal modeling and drying kinetics of bitter gourd flakes drying in modified greenhouse dryer. **Renewable Energy**, v.118, p.799-813, 2018. DOI: https://doi.org/10.1016/j.renene.2017.11.069.

DINÇER, İ.; ZAMFIRESCU, C. **Drying phenomena**: theory and applications. Chichester: J. Wiley & Sons, 2016. 512p. DOI: https://doi.org/10.1002/9781118534892.

DOYMAZ, İ. Drying kinetics, rehydration and colour characteristics of convective hot-air drying of carrot slices. **Heat and Mass Transfer**, v.53, p.25-35, 2017. DOI: https://doi.org/10.1007/s00231-016-1791-8.

ELGAMAL, R.A.; KISHK, S.S.; ELMASRY, G.M. Validation of CFD models for the deep-bed drying of rice using thermal imaging. **Biosystems Engineering**, v.161, p.135-144, 2017. DOI: https://doi.org/10.1016/j.biosystemseng.2017.06.018.

ELIAS, M.C.; OLIVEIRA, M. de; VANIER, N.L. **Tecnologias de pré-armazenamento, armazenamento e conservação de grãos**. Capão do Leão: Universidade Federal de Pelotas, 2017.

FADHEL, A.; CHARFI, K.; BALGHOUTHI, M.; KOOLI, S. Experimental investigation of the solar drying of Tunisian phosphate under different conditions. **Renewable Energy**, v.116, p.762-774, 2018. DOI: https://doi.org/10.1016/j.renene.2017.10.025.

GEORGE, C.; MOGIL, Q.; ANDREWS, M.; EWING, G. Thin layer drying curves for shredded breadfruit (*Artocarpus altilis*). **Journal of Food Processing and Preservation**, v.41, e13146, 2017. DOI: https://doi.org/10.1111/jfpp.13146.

GINER, S.A. Estimation of the influence of variable boundary conditions when using thin layer equations for grain dryer simulation. **Biosystems Engineering**, v.186, p.228-233, 2019. DOI: https://doi.org/10.1016/j.biosystemseng.2019.08.004.

HEMIS, M.; SINGH, C.B.; JAYAS, D.S. Microwave-assisted thin layer drying of wheat. **Drying Technology**, v.29, p.1240-1247, 2011. DOI: https://doi.org/10.1080/07373937.2011.584999.

JIAN, F.; JAYAS, D.S. Characterization of isotherms and thin-layer drying of red kidney beans, Part II: Three-dimensional finite element models to estimate transient mass and heat transfer coefficients and water diffusivity. **Drying Technology**, v.36, p.1707-1718, 2018. DOI: https://doi.org/10.1080/07373937.2017.1422514.

JIANG, J.; DANG, L.; YUENSIN, C.; TAN, H.; PAN, B.; WEI, H. Simulation of microwave thin layer drying process by a new theoretical model. **Chemical Engineering Science**, v.162, p.69-76, 2017. DOI: https://doi.org/10.1016/j.ces.2016.12.040.

KARTHIKEYAN, A.K.; MURUGAVELH, S. Thin layer drying kinetics and exergy analysis of turmeric (*Curcuma longa*) in a mixed mode forced convection solar tunnel dryer. **Renewable Energy**, v.128, p.305-312, 2018. DOI: https://doi.org/10.1016/j.renene.2018.05.061.

KHANCHI, A.; BIRRELL, S. Drying models to estimate moisture change in switchgrass and corn stover based on weather conditions and swath density. **Agricultural and Forest Meteorology**, v.237/238, p.1-8, 2017. DOI: https://doi.org/10.1016/j.agrformet.2017.01.019.

KUCUK, H.; MIDILLI, A.; KILIC, A.; DINCER, I. A review on thin-layer drying-curve equations. **Drying Technology**, v.32, p.757-773, 2014. DOI: https://doi.org/10.1080/07373937.2013.873047.

LIU, Z.; WU, Z.; WANG, X.; SONG, J.; WU, W. Numerical simulation and experimental study of deep bed corn drying based on water potential. **Mathematical Problems in Engineering**, v.2015, art.539846, 2015. DOI: https://doi.org/10.1155/2015/539846.

NEJADI, J.; NIKBAKHT, A.M. Numerical simulation of corn drying in a hybrid fluidized bed-infrared dryer. **Journal of Food Process Engineering**, v.40, e12373, 2017. DOI: https://doi.org/10.1111/jfpe.12373.

PRAKASH, B.; SIEBENMORGEN, T.J. Single-parameter thin-layer drying equations for long-grain rice. **Transactions of the ASABE**, v.61, p.733-742, 2018. DOI: https://doi.org/10.13031/trans.12555.

RAMAJ, I.; SCHOCK, S.; MÜLLER, J. Drying kinetics of wheat (*Triticum aestivum* L., cv. 'Pionier') during thin-layer drying at low temperatures. **Applied Sciences (Switzerland)**, v.11, art.9557, 2021. DOI: https://doi.org/10.3390/app11209557.

SOUZA, G.F.M.V.; MIRANDA, R.F.; LOBATO, F.S.; BARROZO, M.A.S. Simultaneous heat and mass transfer in a fixed bed dryer. **Applied Thermal Engineering**, v.90, p.38-44, 2015. DOI: https://doi.org/10.1016/j.applthermaleng.2015.06.088.

SUN, L.-X.; LIU, S.-X.; WANG, J.-X.; WU, C.-L.; LI, Y.; ZHANG, C.-Q. The effects of grain texture and phenotypic traits on the thin-layer drying rate in maize (*Zea mays* L.) inbred lines. **Journal of Integrative Agriculture**, v.15, p.317-325, 2016. DOI: https://doi.org/10.1016/S2095-3119(15)61052-8.

YI, X.-K.; WU, W.-F.; ZHANG, Y.-Q.; LI, J.-X.; LUO, H.-P. Thin-layer drying characteristics and modeling of Chinese jujubes. **Mathematical Problems in Engineering**, v.2012, art.386214, 2012. DOI: https://doi.org/10.1155/2012/386214.

ZARE, D.; CHEN, G. Evaluation of a simulation model in predicting the drying parameters for deep-bed paddy drying. **Computers and Electronics in Agriculture**, v.68, p.78-87, 2009. DOI: https://doi.org/10.1016/j.compag.2009.04.007.

ZHAO, Y.; HUANG, K.; CHEN, X.F.; WANG, F.H.; CHEN, P.X.; TU, G.; YANG, D.Y. Tempering-drying simulation and experimental analysis of corn kernel. **International Journal of Food Engineering**, v.14, art.20170217, 2018. DOI: https://doi.org/10.1515/ijfe-2017-0217.

ZHOU, J.; ZHANG, R.; WANG, X.; CHEN, S.; LUO, A.; NIU, D.; CHAI, X.; ZHAO, Y. NaHCO3-enhanced sewage sludge thin-layer drying: Drying characteristics and kinetics. **Drying Technology**, v.35, p.1276-1287, 2017. DOI: https://doi.org/10.1080/07373937.2016.1249878.