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EFFECTS OF INITIAL MOISTURE CONTENT AND HEATING RATE ON WHEAT (OAKES) DRYING KINETIC PARAMETERS

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ABSTRACT

The goal of this study was to determine the effects of initial moisture content and heating rate on the drying kinetic parameters of wheat under non-isothermal conditions. Wheat (OAKES) samples at initial moisture contents of 20.7%, 18.5%, 16.8%, and 14.8% wet basis (w.b.) were dried using a thermogravimetric analyzer. The analyzer was set at five heating rates (2, 3, 4, 5 and 10ºC/min) to determine the drying kinetic parameters, i.e., activation energy, of the heated samples from room temperature of 30°C to 170ºC. The experimental moisture ratio data were fitted to the four empirical models, namely Page, Newton, Logarithmic, and Henderson models. The goodness of fit criterion was used to determine the best-fitting model.

Heating rate and initial moisture content affected the activation energy required for drying wheat. Increasing the heating rate expedited the drying curve. The heating rate of 10°C/min for wheat at an initial moisture content of 14.8% w.b. resulted in the greatest activation energy of 28.174 kJ/mol. The heating rate of 2°C/min for wheat at an initial moisture content of 20.7% w.b. resulted in the lowest activation energy of 14.760 kJ/mol. The Logarithmic and Henderson models were adjudged as best fit models for the entire drying curves by R^2, RMSE, and X^2. This study highlighted that the energy required to dry wheat from 20.7% w.b. to acceptable safe level could be minimized by reducing the heating rate.

KEYWORDS: Wheat drying; Activation energy; Non-isothermal kinetics; Heating rate; Moisture content.

INTRODUCTION

Wheat, a major crop in the United States, has diverse usage in the manufacturing of numerous products. According to the USDA ERS's [23] report, wheat production in the United States reached about 2.0 billion bushels with an average yield of 43.7 bushels per acre. Wheat is usually harvested at a moisture content (MC) less than 25% and must be dried to 13% or below to protect it from molds [9]. Understanding the drying kinetics of wheat is crucial in devising process conditions, which optimize wheat drying to achieve safe storage MC without compromising quality.

Drying curves provide useful information to understand the mechanism of water migration from a product [5]. Knowledge of drying kinetics of a product is essential to control the overall drying process and the quality of the final dried product [10]. The key kinetic parameter, which is being studied in various drying processes, is the activation energy. To optimize energy consumption during drying, it is necessary to match the external energy demand of a particular drying operation with that determined by drying kinetics. Various techniques of thermal analysis had been employed to investigate the drying kinetics of a wide range of products. Thermogravimetric analysis (TGA) is one such technique, which measures the amount, and rate of change of mass of a sample with respect to temperature or time under controlled heating conditions [3].

The reason for increasing popularity of TGA is its ease of operation, minimal material requirement, precise control over temperature, and option for online recording of data. TGA has been used successfully to study the decomposition kinetics of polymers, edible oils, and biomass [7; 19; 26]. Souza et al. [21] used thermogravimetry to study the thermal stability of sunflower oil and its decomposition into polysaturated, monosaturated and saturated fatty acids. Moisture and ash content of the flour from the wheat were investigated using TGA, and the results did not show any difference from those obtained by official methods, proving it a reliable technique for future use [1].

TGA and derivative thermogravimetric analysis (DTA) were employed to understand the state of moisture within grains [16]. In the pharmaceutical industry, TGA and DTA were found to be a beneficial method in the moisture determination over the Karl-Fischer (KF) method as some of the drugs are not soluble in KF reagents [12]. Also, TGA has played a key role in understanding water transport in the case of pharmaceutical products [20]. Madhava et al. [14] determined drying kinetics of paddy with TGA, and observed that most of the moisture loss occurred between 60 to 100°C. Thermogravimetric analysis can also be used to evaluate the moisture diffusivity of solids under isothermal conditions [13]. Wang [25] used the thermogravimetric technique to study the kinetics of moisture removal from non-food products. Ogawa et al. [17] used thermogravimetry for prediction of pasta drying process, and determined for the first time that the constant rate period of drying was a useful predictor of drying curves for pasta. Vuataz et al. [24] used TGA and DTA to design reference methods for moisture determination in food powders as they found precise control over the process. TGA had also been used to study the starch retrogradation process by measuring the degree of bound water, and the results were comparable with differential scanning calorimetry [22].

Ogawa et al. [18] conducted a thermal analysis of drying process of durum wheat dough under programmed temperature-rising conditions with TGA. They estimated the activation energy for mass transfer coefficient of drying to be 32 kJ/mol at MC of 0.14 kg H2O/kg dry matter or higher, and the value of activation energy increased rapidly when the moisture content dropped below this level. Giner and Mascheroni [11] investigated thin layer drying kinetics of wheat and found the value of activation energy as 27.0 kJ/mol. Mohapatra and Rao [15] investigated the drying kinetics of parboiled wheat using the thin layer-drying model in the temperature range of 40°C-60°C. They found that the total drying occurred in the falling rate period, signifying diffusion over evaporation from the surface; the activation energy for parboiled wheat was found to be 37.013 kJ/mol.

As mentioned earlier, drying kinetics of wheat has been studied mostly under thin layer isothermal conditions. Much work has been reported on kinetic parameters of wheat products by conventional drying methods, but lesser control over the temperature in these methods given rise to a high level of experimental error. Even though TGA had been employed for diverse applications, there is not much work being reported on the use of the technique to investigate dehydration behavior of wheat under non-isothermal conditions. Additionally, the effects of the initial moisture content and a heating rate of wheat on the drying kinetic parameters is not appropriately considered, and the data collected are rare and not conclusive. Thus, the objectives of this paper were to study the effects of initial moisture contents and heating rate on the wheat-drying kinetic parameters under non-isothermal conditions and to choose the best-fitting mathematical models for the drying curves.ll content should be written in English and should be in 1 column.

MATERIALS AND METHODS

Wheat (*OAKES*) was procured from a local farm, transported to the Rice Research and Extension Center, Stuttgart, Arkansas, and then stored at 4ºC. The initial moisture content of wheat was determined using the standard method [2] and found to be 13.2% w.b. A wheat sample of about 10 kg was visually inspected to avoid any damaged wheat grains. The sample was divided into four subsamples and stored in polyethylene bags. The required amount of distilled water was calculated and added to the wheat in the polyethylene bag with the help of spray bottles to achieve targeted moisture content levels of 15.0%, 17.0%, 19.0%, and 21.0% w.b. Following the addition of distilled water, the samples, placed in the food grade plastic bags, were mixed vigorously to ensure uniform distribution of the added water. These four subsamples were again stored in the refrigerator at 4ºC for 24 hours. After that, three subsamples were collected from each bag to determine the final moisture content. The moisture contents of the samples were found to be 20.7%, 18.5%, 16.8%, and 14.8% w.b. Wheat samples were dried using a thermogravimetric analyzer (Model TGA 4000, PerkinElmer, Inc. Waltham, MA). A weight calibration was performed using the reference weights provided by the company. The kinetics of wheat drying were studied at different heating rates (2, 3, 4, 5, and 10ºC/min) from 30 to 170ºC. The temperature range selected for this study is considerably below that which could cause thermal decomposition of the wheat grain. Hence, the mass loss observed is only due to the release of moisture from the grain. Nitrogen gas was used as a purge gas at a rate of 30 mL/min. A single grain was placed in the crucible and heated at the desired rate by the programmable furnace. Crucibles were cleaned and inspected before each run to avoid any influence of the remaining residuals.

Drying kinetic analysis

The following equation calculates the moisture ratio of the grain under non-isothermal condition:

$$MR = \frac{M - M_e}{M_0 - M_e} \tag{1}$$

Where:

MR	is the moisture ratio (-),
M	is the mass at time > 0 (g),
M_0	is the initial mass (g), and
M_e	is the mass at the end of the drying process (g).

Under non-isothermal conditions, the sample temperature is correlated to the heating rate and drying time [5] as follows:

$$T = T_0 + \beta t \tag{2}$$

Where:

T	is the sample temperature (ºC),
T_0	is the initial temperature (°C),
β	is the heating rate (°C/min), and
t	is the drying time (min).

The temperature dependence of drying rate constant was represented by an Arrhenius-type relation [4]:

$$k = k_0 exp\left(\frac{E_a}{R(T + 273.15)}\right) \tag{3}$$

Where:

k	is the drying constant (1/min),
k_0	is the pre-exponential factor (1/min),
E_a	is the activation energy (kJ/mol), and
R	is the universal gas constant (8.314 J/°K.mol).

The non-isothermal models [5] used in this study are listed below.

Page
$$MR = exp\left[-k_0 exp\left(-\frac{E_a}{R(T + 273.15)}\right)\left(\frac{T - T_0}{\beta}\right)^n\right] \tag{4}$$

Newton
$$MR = exp\left[-k_0 exp\left(-\frac{E_a}{R(T + 273.15)}\right)\left(\frac{T - T_0}{\beta}\right)\right] \tag{5}$$

Logarithmic
$$MR = a + b\ exp\left[-k_0 exp\left(-\frac{E_a}{R(T + 273.15)}\right)\left(\frac{T - T_0}{\beta}\right)\right] \tag{6}$$

Henderson
$$MR = a\ exp\left[-k_0 exp\left(-\frac{E_a}{R(T + 273.15)}\right)\left(\frac{T - T_0}{\beta}\right)\right] \tag{7}$$

where

a, b	are model constants,
n	is the reaction order (-).

Model fitting to experimental data

The experimental data obtained was fitted into the four models mentioned above. The nonlinear regression was performed by using the Solver feature of the MS-Excel®. To calculate the moisture ratio, an initial guess of the model parameters was made based on values reported in published literature. The minimization technique was used to reduce the sum of square difference between the experimental moisture ratio values and those obtained by fitting the data to the models. The values of coefficient of determination (R^2), chi-square (X^2), and root mean square error (RMSE) have been presented along with kinetic parameters as shown below to determine the best-fit scenario. The model having the highest R^2 and least X^2 and RMSE values was chosen as the best model fitting the experimental data.

$$\chi 2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N - z} \quad (8)$$

$$RMSE = \sqrt{\frac{1}{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2} \quad (9)$$

Where:

$MR_{exp,\,i}$ is the experimental moisture ratio (-),
$MR_{pre,\,i}$ is the predicted moisture ratio (-),
N is the number of experimental data points (-), and
z is the number of parameters (-).

RESULTS AND DISCUSSION

Effects of initial moisture content and heating rate on drying curves

Figures 1 through 5 illustrate the effects of drying time and heating rate on the moisture ratio at different initial moisture contents. Five drying rates, 2, 3, 4, 5, and 10ºC/min, were tested. It should be mentioned that data could be presented as a function of temperature and/or as a function of time since temperatures, and heating rates are correlated, as depicted by equation 2. The results showed that increasing the heating rate shifted the mass loss curves to the left, which could be translated to an accelerated decrease in the moisture ratio. The lowest moisture ratio values were observed at the heating rate of 10ºC/min. Each moisture ratio loss-curve showed two distinctive stages, including a heating stage and a moisture loss stage. The heating stage took place during the initial 6 to 12 minutes, depending on the heating rate, and corresponded to a small to negligible mass loss as shown by the small slopes. Following the heating stage, there was a sharp decrease in the moisture ratio, and this was characterized as the falling stage, where a period between 14 and 70 minutes was needed to raise the temperature of 30ºC to 170ºC, at heating rates of 10ºC/min and 2ºC/min, respectively. Increasing the heating rate and/or the initial moisture content increased the slope of the falling rate. In other words, there was a positive correlation between the heating rate and/or the initial moisture content and the rate of moisture reduction. The change in moisture loss was directly affected by the binding forces between moisture and wheat kernels. Based on bonding schemes, water in any material is divided into two forms: free water and bound water. Free water is usually on the surface, and displays weak attraction forces with the material, leaving through evaporation. On the other hand, bound water is distributed throughout the material and is attached by strong forces, requiring more energy for removal [6]. Table 1 shows the effects of heating rate and initial moisture content of the moisture ratio when the sample temperature reached 100ºC. The moisture ratio values of wheat grains were maximum at the lowest initial moisture content of 14.8% for all the studied heating rates. In other words, the moisture reduction was minimum at this level of initial moisture content. The only exception to these observations was found at the heating rate of 10ºC/min and the moisture content of 14.8%. As the heating rate increased, the corresponding moisture reduction decreased. It was demonstrated by the increased values of moisture ratios. These observations could be attributed to the fact that at higher heating rates the time required for moisture migration from the grains was not sufficient, whereas at lower heating rates the grains had more time to release moisture. Madhava et al. [14] investigated drying kinetics of 20.2% w.b. paddy by heating from 28°C to 220° with heating rates of 1, 3 and 10°C/min. They also observed decreases in weight loss when increasing the heating rate from 1°C/min to 10°C/min.

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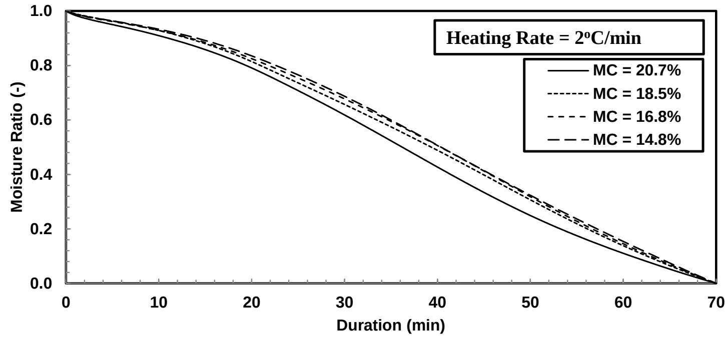

Figure 1. Effects of initial moisture content on the moisture ratio at the heating rate of 2°C/min.

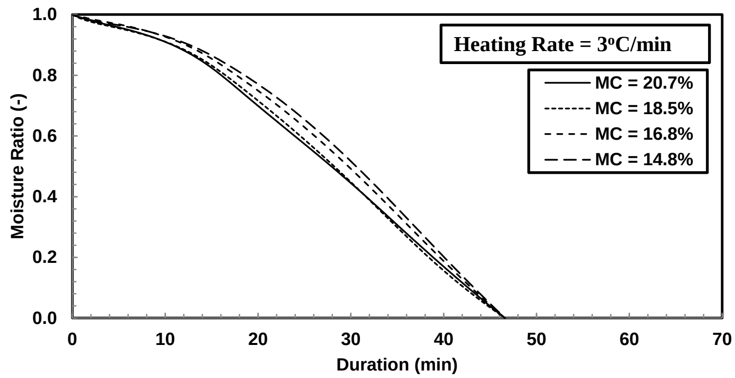

Figure 2. Effects of initial moisture content on the moisture ratio at the heating rate of 3°C/min.

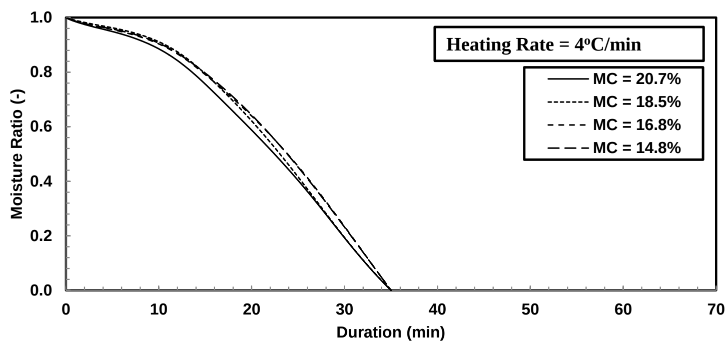

Figure 3. Effects of initial moisture content on the moisture ratio at the heating rate of 4°C/min.

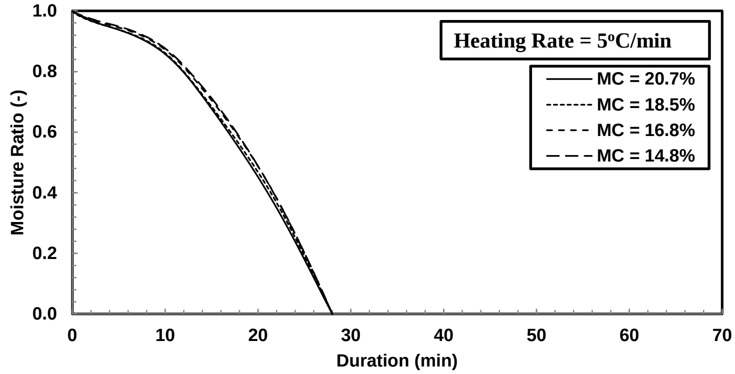

Figure 4. Effects of initial moisture content on the moisture ratio at the heating rate of 5ºC/min.

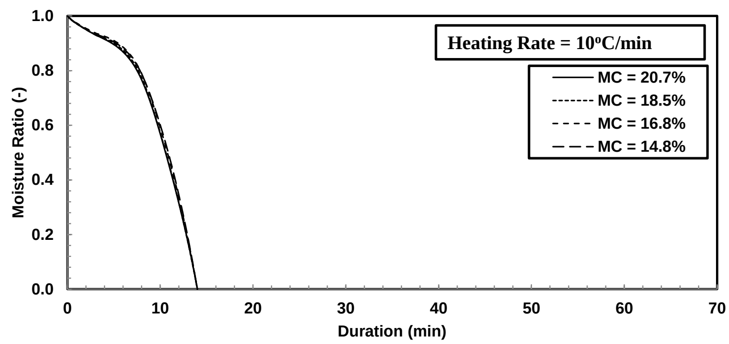

Figure 5. Effects of initial moisture content on the moisture ratio at the heating rate of 10ºC/min.

Table 1. Effects of heating rates and initial moisture content on the moisture ratio (-) at 100ºC.

Heating Rate (°C/min)	**Moisture Content (% w.b.)**			
	20.7	**18.5**	**16.8**	**14.8**
2	0.5234	0.5744	0.5944	0.5994
3	0.6161	0.6327	0.6717	0.6963
4	0.6730	0.7111	0.7183	0.7243
5	0.7193	0.7237	0.7426	0.7494
10	0.8285	0.8357	0.8483	0.8455

Effects of initial moisture content and heating rate on weight loss derivative

Figures 6 through 9 show the weight loss derivative as a function of the drying duration at different heating rates and initial moisture contents. The graphs illustrated that peak weight loss derivative shifted towards the left as the heating rate increased; signifying that maximum weight loss for a step change in temperature was accelerated with higher heating rates. Maximum peak temperatures (T_{maxp}), obtained for each weight loss derivative curve at the maximum absolute weight loss, are presented in Table 2. Results showed that increasing the heating rate caused T_{maxp} values to rise also. On the other hand, increasing the initial moisture content did not correlate with increases in T_{maxp}. In fact, T_{maxp} ranged between 103.8ºC and 170.0ºC; 121.2 and 170.0ºC; 122.6 and 167.0ºC; and 116.0 and 170.0ºC for the initial moisture contents of 20.7%, 18.5%, 16.8% and 14.8% w.b., respectively. On the contrary, the absolute maximum weight loss derivative showed a clear trend with the initial moisture contents and the heating rate. Mostly, weight loss derivative increased were caused by increasing the heating rate. The weight loss derivative reached its highest value of 0.558 g/min at the moisture content of 20.7% and the heating rate of 10ºC/min. On the other hand, the weight loss derivative reached its lowest value of 0.093 g/min at the initial moisture contents of 14.8% and the heating rate of 2ºC/min. Ogawa et al. [18] also observed higher drying rates when durum-wheat dough temperatures were increased, where weight loss derivative initially rose to a peak, followed by a decrease to a lower level. As the drying process proceeded, less free water on the surface of the grain was available, and the rate of moisture removal declined. This is mostly the case of the later stage of drying of for most agricultural commodities [4]. The heating rate of 10ºC/min resulted in the highest absolute maximum weight loss derivative for all the tested initial moisture contents. The trend of weight loss derivative in this study was similar to that obtained in Chen et al. [6], where, using TGA techniques, they reported peak moisture loss of 0.1%/ºC at temperature ranges of 67-77ºC at 20°C/min. Madhava et al. [14] investigated the drying kinetics of paddy at three different heating rates over one temperature range. The peak weight loss for all three heating rates was observed at different temperatures, and these peak temperatures increased with increasing heating rates. It can be postulated from their results that heating rate may affect the free moisture loss from the grain.

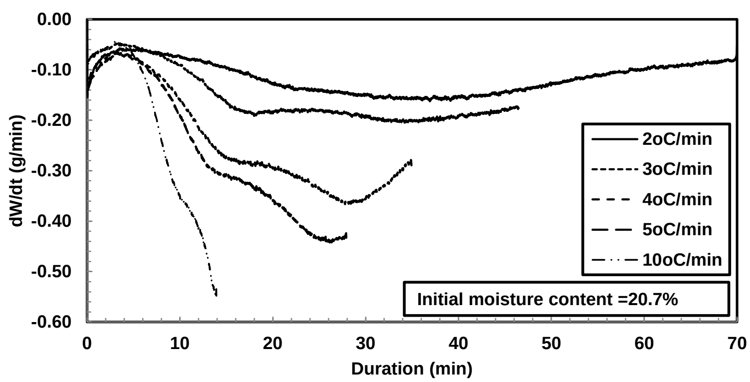

Figure 6. Effects of heating rate on the weight loss derivative at an initial moisture content of 20.7% w.b.

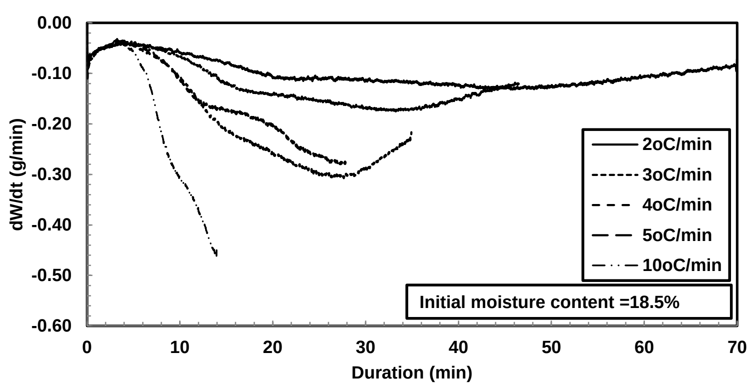

Figure 7. Effects of heating rate on the weight loss derivative at an initial moisture content of 18.5% w.b.

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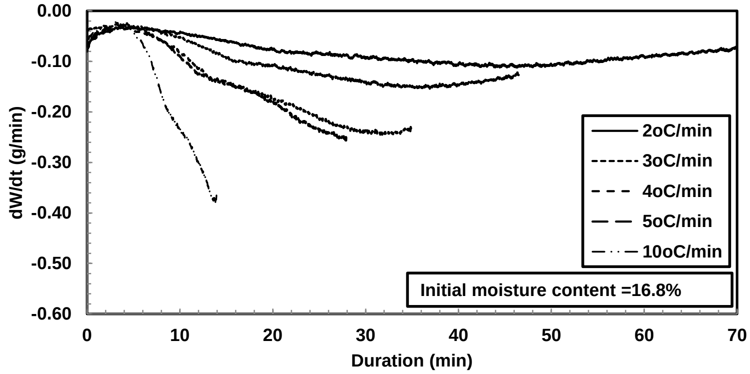

Figure 8. Effects of heating rate on the weight loss derivative at an initial moisture content of 16.8% w.b.

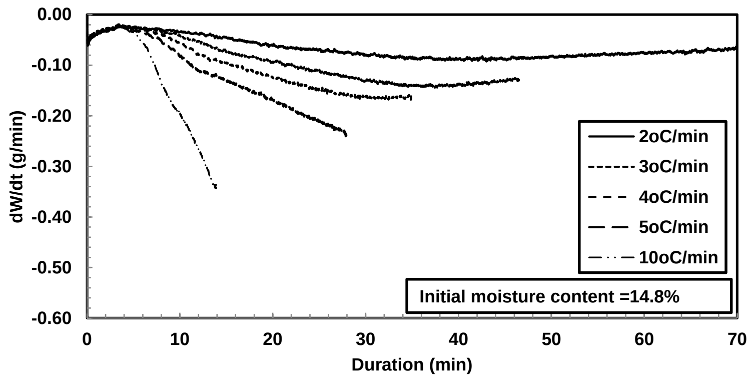

Figure 9. Effects of heating rate on the weight loss derivative at an initial moisture content of 14.8% w.b.

Table 2. Effects of heating rate on the maximum weight loss derivative at various moisture contents.

Heating Rate (°C/min)	Moisture Content (%w.b.)							
	20.7		18.5		16.8		14.8	
	T_{maxp} °C	dW/dt_p g/min	T_{maxp} °C	dW/dt_p g/min	T_{maxp} °C	dW/dt_p g/min	T_{maxp} °C	dW/dt_p g/min
2	103.8	-0.162	121.2	-0.132	122.6	-0.112	116.0	-0.093
3	132.6	-0.205	130.3	-0.176	140.7	-0.154	142.3	-0.144
4	141.1	-0.366	140.6	-0.308	149.1	-0.246	170.0	-0.168
5	161.2	-0.443	168.1	-0.281	170.0	-0.257	170.0	-0.246
10	170.0	-0.558	170.0	-0.467	167.0	-0.380	170.0	-0.352

Effects of initial moisture content and heating rate on drying kinetic parameters

As mentioned earlier, wheat grains were studied under four initial moisture contents and five heating rates. Four models, *i.e.*, Page, Newton, Logarithmic and Henderson, were fitted to moisture ratio values for all the combinations of initial moisture contents and heating rates. Tables 3 through 6 show the drying constants along with the statistical parameters, *i.e.*, R^2, RMSE and X^2, which were used as criteria to determine the model that best fit the experimental data. All the models had R^2 values greater than 0.98, indicating good fit. The best combination for each model is highlighted here, which has highest R^2, least RMSE and X^2. Unexpectedly, both the Page and Newton models did not meet all the criteria of the best-fit models in all the studied cases of initial moisture content and heating rates.

Alternatively, the Henderson and Logarithmic models met the criteria of the best-fit model in all the studied 20 cases of initial moisture content and heating rate. The Henderson model fit 11 cases out of the 20 cases, representing 55% of the studied cases. The Logarithmic model fit 9 cases out of the 20 cases, representing 45% of the studied cases. Accordingly, it can be suggested that either the Henderson model or the Logarithmic model could be utilized to determine the wheat drying constants, including its activation energy. These results are in full agreement with the results reported earlier in the literature. Chen et al. [5] investigated the drying kinetics of rice straw using TGA and found the Henderson model to be the best fit under non-isothermal conditions.

The initial moisture content values negatively affected the activation energy values, as shown in Figure 10. It was observable that the lower the moisture content and/or the higher the heating rate, the higher the activation energy value. The activation energy reached its maximum value of 28.174 kJ/mol at a heating rate of 10°C/min and a moisture content of 14.8% (w.b). On the other hand, the lowest activation energy of 14.760 kJ/mol was found at a heating rate of 2°C/min and moisture content of 20.7% w.b. The values of activation energies obtained are in the range of that reported by literature [11; 15; 18]. As mentioned earlier, Mohapatra and Rao [15] found the activation energy for diffusion of wheat as 37.013 kJ/g.mol.K in a thin layer drying experiment under isothermal conditions. Increasing the heating rate by 8°C/min increased the activation energy by 2.2 times. It can be translated as additional energy is needed to bring the moisture down to acceptable moisture content as the heating rate increased. That is understood from the point that at lower moisture content there is less freely bound water available for removal, and strong forces of attraction strongly hold it by grain mass. To overcome these forces, there is an increasing demand of heat energy required to evaporate this water. The value of order of reaction varies from 0.602 for 20.7% w.b. to 1.094 for 14.8% w.b.

Table 3. Effects of heating rate on the drying constants for the studied models under initial moisture content of 20.7% w.b.

Model	Heating Rate	Drying Constants					Statistical Parameters		
	°C/min	E_a kJ/mol	k_o	n	a	b	R^2	RMSE	X^2
Page	2.0	19.834	4.674	0.603			0.99913	0.01024	0.00010
Newton	2.0	13.111	0.026				0.99797	0.01703	0.00029
Logarithmic	2.0	24.260	0.902		0.061	0.869	0.99337	0.02644	0.00070
Henderson	**2.0**	**14.760**	**0.042**		**0.966**		**0.99923**	**0.00972**	**0.00009**
Page	3.0	17.660	0.490	0.820			0.99656	0.01967	0.00039
Newton	3.0	14.941	0.056				0.99598	0.02184	0.00048
Logarithmic	3.0	17.313	0.110		0.000	0.968	0.99713	0.01736	0.00030
Henderson	**3.0**	**17.055**	**0.102**		**0.969**		**0.99715**	**0.01731**	**0.00030**
Page	4.0	23.062	15.149	0.602			0.99705	0.01891	0.00036
Newton	4.0	16.967	0.135				0.99572	0.02419	0.00059
Logarithmic	**4.0**	**19.463**	**0.275**		**0.000**	**0.963**	**0.99751**	**0.01669**	**0.00028**
Henderson	4.0	19.804	0.305		0.962		0.99747	0.01664	0.00028
Page	5.0	18.374	0.385	0.922			0.99326	0.02856	0.00082
Newton	5.0	17.638	0.179				0.99321	0.02934	0.00086
Logarithmic	**5.0**	**20.045**	**0.347**		**0.000**	**0.961**	**0.99594**	**0.02085**	**0.00043**
Henderson	5.0	21.177	0.490		0.958		0.99583	0.02039	0.00042
Page	10.0	20.611	0.494	1.051			0.98935	0.03490	0.00122
Newton	10.0	21.683	0.949				0.98960	0.03446	0.00119
Logarithmic	**10.0**	**24.363**	**1.960**		**0.000**	**0.964**	**0.99289**	**0.02569**	**0.00066**
Henderson	10.0	26.104	3.314		0.960		0.99276	0.02505	0.00063

Table 4. Effects of heating rate on the drying constants for the studied models under initial moisture content of 18.5% w.b.

Model	Heating Rate	Drying Constants					Statistical Parameters		
	°C/min	E_a kJ/mol	k_o	n	A	b	R^2	RMSE	X^2
Page	2.0	18.226	0.709	0.762			0.99757	0.01659	0.00028
Newton	2.0	14.486	0.035				0.99672	0.02001	0.00040
Logarithmic	2.0	16.664	0.065		0.000	0.966	0.99793	0.01487	0.00022
Henderson	**2.0**	**16.547**	**0.063**		**0.967**		**0.99795**	**0.01488**	**0.00022**

Page	3.0	18.614	0.530	0.852			0.99745	0.01818	0.00033
Newton	3.0	16.459	0.091				0.99708	0.02013	0.00041
Logarithmic	3.0	18.877	0.182		0.000	0.966	0.99845	0.01311	0.00017
Henderson	**3.0**	**19.038**	**0.191**		**0.965**		**0.99845**	**0.01312**	**0.00017**
Page	4.0	20.267	0.463	0.961			0.99795	0.01682	0.00028
Newton	4.0	19.856	0.310				0.99794	0.01719	0.00030
Logarithmic	**4.0**	**21.680**	**0.519**		**0.000**	**0.973**	**0.99883**	**0.01195**	**0.00014**
Henderson	4.0	21.876	0.553		0.975		0.99877	0.01185	0.00014
Page	5.0	18.839	0.399	0.926			0.99169	0.03093	0.00096
Newton	5.0	18.153	0.194				0.99157	0.03162	0.00100
Logarithmic	**5.0**	**21.553**	**0.506**		**0.000**	**0.957**	**0.99468**	**0.02270**	**0.00052**
Henderson	5.0	21.937	0.567		0.956		0.99465	0.02263	0.00051
Page	10.0	20.037	0.478	1.030			0.99050	0.03253	0.00106
Newton	10.0	20.875	0.748				0.99083	0.03225	0.00104
Logarithmic	10.0	22.350	1.100		0.000	0.967	0.99320	0.02463	0.00061
Henderson	**10.0**	**24.847**	**2.299**		**0.963**		**0.99361**	**0.02340**	**0.00055**

Table 5. Effects of heating rate on the drying constants for the studied models under initial moisture content of 16.8% w.b.

Model	Heating Rate	Drying Constants					Statistical Parameters		
	°C/min	E_a kJ/mol	k_o	n	A	b	R^2	RMSE	X^2
Page	2.0	18.801	0.720	0.777			0.99744	0.01734	0.00030
Newton	2.0	15.385	0.044				0.99666	0.02054	0.00042
Logarithmic	**2.0**	**17.480**	**0.079**		**0.000**	**0.968**	**0.99815**	**0.01414**	**0.00020**
Henderson	2.0	17.875	0.089		0.963		0.99815	0.01399	0.00020
Page	3.0	19.861	0.521	0.888			0.99675	0.01954	0.00038
Newton	3.0	18.313	0.140				0.99648	0.02073	0.00043
Logarithmic	**3.0**	**20.536**	**0.264**		**0.000**	**0.971**	**0.99756**	**0.01610**	**0.00026**
Henderson	3.0	21.359	0.340		0.968		0.99736	0.01640	0.00027
Page	4.0	20.061	0.439	0.940			0.99427	0.02586	0.00067
Newton	4.0	19.439	0.235				0.99423	0.02626	0.00070
Logarithmic	4.0	21.929	0.473		0.000	0.967	0.99621	0.01961	0.00039
Henderson	**4.0**	**22.676**	**0.590**		**0.963**		**0.99622**	**0.01945**	**0.00038**
Page	5.0	19.956	0.418	0.959			0.99166	0.03033	0.00092
Newton	5.0	19.701	0.290				0.99177	0.03067	0.00094
Logarithmic	5.0	20.864	0.390		0.000	0.969	0.99395	0.02424	0.00059
Henderson	**5.0**	**23.522**	**0.854**		**0.960**		**0.99447**	**0.02266**	**0.00051**
Page	10.0	21.749	0.577	1.072			0.99073	0.03204	0.00103
Newton	10.0	23.214	1.430				0.99107	0.03149	0.00099
Logarithmic	10.0	25.927	3.030		0.000	0.967	0.99358	0.02367	0.00056
Henderson	**10.0**	**27.251**	**4.477**		**0.965**		**0.99360**	**0.02337**	**0.00055**

Table 6. Effects of heating rate on the drying constants for the studied models under initial moisture content of 14.8% w.b.

Model	Heating Rate	Drying Constants					Statistical Parameters		
	°C/min	E_a kJ/mol	k_o	n	A	b	R^2	RMSE	X^2
Page	2.0	19.044	0.715	0.784			0.99772	0.01612	0.00026
Newton	2.0	15.722	0.047				0.99710	0.01887	0.00036
Logarithmic	**2.0**	**17.378**	**0.075**		**0.000**	**0.972**	**0.99828**	**0.01373**	**0.00019**
Henderson	2.0	17.910	0.088		0.967		0.99825	0.01352	0.00018
Page	3.0	19.866	0.260	0.971			0.99596	0.02205	0.00049
Newton	3.0	19.667	0.197				0.99599	0.02231	0.00050
Logarithmic	3.0	22.000	0.379		0.000	0.969	0.99753	0.01630	0.00027
Henderson	**3.0**	**22.445**	**0.435**		**0.967**		**0.99746**	**0.01620**	**0.00026**
Page	4.0	20.450	0.489	0.939			0.99510	0.02441	0.00060
Newton	4.0	19.746	0.256				0.99489	0.02495	0.00062

Logarithmic	4.0	20.641	0.318		0.000	0.974	0.99656	0.01991	0.00040
Henderson	**4.0**	**22.760**	**0.603**		**0.965**		**0.99667**	**0.01833**	**0.00034**
Page	5.0	20.592	0.578	0.935			0.99213	0.02892	0.00084
Newton	5.0	19.951	0.302				0.99212	0.02945	0.00087
Logarithmic	**5.0**	**22.503**	**0.608**		**0.000**	**0.965**	**0.99465**	**0.02266**	**0.00051**
Henderson	5.0	23.502	0.823		0.963		0.99451	0.02233	0.00050
Page	10.0	22.053	0.543	1.094			0.99014	0.03291	0.00108
Newton	10.0	23.797	1.660				0.99073	0.03227	0.00104
Logarithmic	10.0	26.400	3.407		0.000	0.969	0.99337	0.02373	0.00057
Henderson	**10.0**	**28.174**	**5.710**		**0.963**		**0.99358**	**0.02323**	**0.00054**

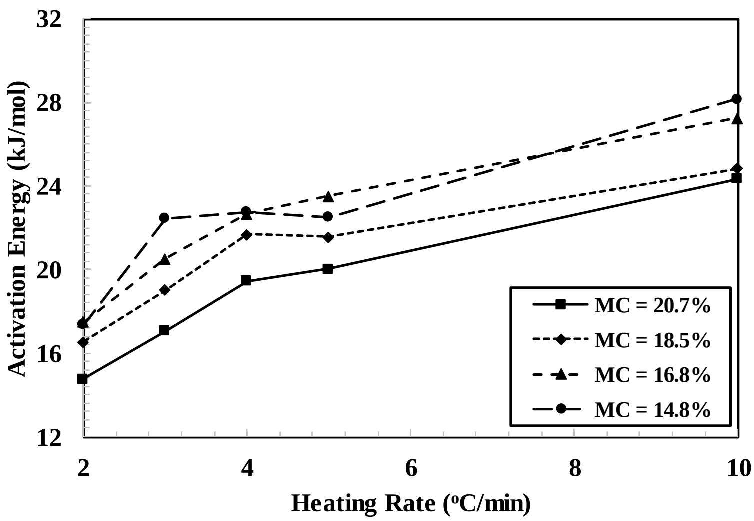

Figure 10. Effects of heating rate and initial moisture content on the activation energy.

Numerical modelling

Wheat grains, if it needed to be stored as seeds for replanting the next season, have special storage requirements. They need to be stored at a moisture content range of 10-12%. Storage of seeds at lower moisture contents is linked to increased longevity [8]. Logarithmic and Henderson models could prove useful to understand the drying kinetics of wheat below the normal storage moisture content of 13.5%. The multiple regression methods were used to develop an empirical correlation for the determination of the activation energy as a function of heating rate and the initial moisture content. The multiple linear regressions resulted in the following empirical equation:

$$AE = 33.071 + 1.086 \times HR - 0.946 \times MC \qquad (10)$$

Where:

AE is the activation energy, kJ/mol,

HR is the heating rate, ºC/min, and

MC is the moisture content, % w.b.

It should be mentioned that this empirical equation is valid for the determination of wheat drying activation energy within the heating rates between 2ºC/min and 10ºC/min and initial moisture content between 14.8% and 20.7% w.b. with an adjusted correlation coefficient of 0.86.

CONCLUSION

From the experimental work described in this article, several important conclusions can be drawn.

- It was shown that TGA techniques could be used as a powerful tool to explore the drying kinetic parameters of wheat.
- The heating rate and initial moisture content affected the drying rate, with the former having positive effect and the later showing negative effect on the drying rate.

- The Henderson and the Logarithmic models best fit the experimental moisture reduction data.
- Activation energy reached its maximum value of 28.174 kJ/mol at a heating rate of 10°C/min and a moisture content of 14.8% w.b and its lowest value of 14.760 kJ/mol at a heating rate of 2°C/min and moisture content of 20.7% w.b.
- The activation energy was correlated empirically with both the heating rate and the initial moisture content with an adjusted correlation coefficient of 0.86.

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REFERENCES

[1] R. Acquistucci, R. Bucci, A. Magri, and A. Magri. 1991. Evaluation of the moisture and ash contents in wheat mills by multistep programmed thermogravimetry. *Thermochim. Acta.* 188(1): 51-62. http://dx.doi.org/10.1016/0040-6031(91)80204-V.
[2] *ASABE Standards.* 2008. ASAE S352.2: Moisture measurement-unground grain and seeds. St. Joseph, Mich.: ASABE.
[3] R. Blaine, 1998. A faster approach to obtaining kinetic parameters. *Am. Lab.*: 3021-23.
[4] J. Cai, and S. Chen. 2008. Determination of drying kinetics for biomass by thermogravimetric analysis under nonisothermal condition. *Dry. Technol*. 26(12): 1464-1468. http://dx.doi.org/10.1080/07373930802412116.
[5] D. Chen, Y. Zhang, and X. Zhu. 2012a. Drying kinetics of rice straw under isothermal and nonisothermal conditions: a comparative study by thermogravimetric analysis. *Energ. Fuel.* 26(7): 4189-4194. http://dx.doi.org/10.1021/ef300424n.
[6] D. Chen, D. Zhang, and X. Zhu. 2012b. Heat/mass transfer characteristics and nonisothermal drying kinetics at the first stage of biomass pyrolysis. *J. Therm. Anal. Calorim.* 109(2): 847-854. http://dx.doi.org/ 10.1007/s10973-011-1790-4.
[7] C. Doyle. 1961. Estimating thermal stability of experimental polymers by empirical thermogravimetric analysis. *Anal. Chem.* 33(1): 77-79. http://dx.doi.org/ 10.1021/ac60169a022.
[8] R. Ellis, T. Hong, E. Roberts, and K. Tao. 1990. Low moisture content limits to relations between seed longevity and moisture. *Ann. Bot-London.* 65(5): 493-504.
[9] FAO. 1999. Wheat post-harvest operations. http://www.fao.org/fileadmin/user_upload/inpho/docs/Post_Harvest_Compendium_-_WHEAT.pdf. Accessed May 20, 2015.
[10] P. Ferrao, A. Figueiredo, and F. Freire. 1998. Experimental analysis of the drying kinetics of a food product. *Dry. Technol.* 16(8): 1687-1702. http://dx.doi.org/10.1080/07373939808917486.
[11] S. Giner, and R. Mascheroni. 2002. PH-Postharvest Technology: diffusive drying kinetics in wheat, Part 2: applying the simplified analytical solution to experimental data. *Biosyst. Eng.* 81(1): 85-97. http://dx.doi.org/doi:10.1006/bioe.2001.0004.
[12] H. Komatsu, K. Yoshii, and S. Okada. 1994. Application of thermogravimetry to water-content determinations of drugs. *Chemical. Pharm. Bull.* 42(8): 1631-1635.
[13] Z. Li, and N. Kobayashi. 2005. Determination of moisture diffusivity by thermo-gravimetric analysis under non-isothermal condition. *Dry. Technol.* 23(6): 1331-1342. http://dx.doi.org/10.1081/DRT-200059523.
[14] M. Madhava, P. Rao, and T. Goswami. 2001. Drying kinetics of paddy using thermogravimetric analysis. *Dry. Technol.* 19(6): 1201-1210. http://dx.doi.org/10.1081/DRT-100104815.
[15] D. Mohapatra, and P. Rao. 2005. A thin layer drying model of parboiled wheat. *J. Food. Eng.* 66(4): 513-518. http://dx.doi.org/10.1016/j.jfoodeng.2004.04.023.
[16] M. Neher, R. Pheil, and C. Watson. 1973. Thermoanalytical study of moisture in grain. *Cereal Chem.* 50(5): 617-628.
[17] T. Ogawa, T. Kobayashi, and S. Adachi. 2012. Prediction of pasta drying process based on a thermogravimetric analysis. *J. Food. Eng.* 111(1): 129-134.

http://dx.doi.org/10.1016/j.jfoodeng.2012.01.011.

[18] T. Ogawa, S. Koizumi, and S. Adachi. 2014. Thermal analysis of drying process of durum wheat dough under the programmed temperature-rising conditions. *Food. Bioprod. Process.* 92(1): 9-13. http://dx.doi.org/10.1016/j.fbp.2013.07.001.

[19] J. Santos, I. Santos, A. Souza, S. Prasad, and A. Santos, 2002. Thermal stability and kinetic study on thermal decomposition of commercial edible oils by thermogravimetry. *J. Food Sci.* 67(4): 1393-1398. http://dx.doi.org/10.1111/j.1365-2621.2002.tb10296.x.

[20] K. Soppirnath, and T. Aminabhavi. 2002. Water transport and drug release study from cross-linked polyacrylamide grafted guar gum hydrogel microspheres for the controlled release application. *Eur. J. Pharm. Biopharm.* 53(1): 87-98. http://dx.doi.org/10.1016/S0939-6411(01)00205-3.

[21] A. Souza, J. Santos, M. Conceição, M. Silva, and S. Prasad. 2004. A thermoanalytic and kinetic study of sunflower oil. *Braz. J. Chem. Eng.* 21(2): 265-273. http://dx.doi.org/10.1590/S0104-66322004000200017.

[22] Y. Tian, Y. Li, X. Xu, and Z. Jin. 2011. Starch retrogradation studied by thermogravimetric analysis (TGA). *Carbohyd. Polym.* 84(3): 1165-1168. http://dx.doi.org/10.1016/j.carbpol.2011.01.006.

[23] USDA ERS U.S. (2015). Acreage, production, yield and farm price. http://www.ers.usda.gov/datafiles/Wheat_Wheat_Data/Yearbook_Tables/US_Acreage_Production_Yield_and_Farm_Price/wheatyearbooktable01.pdf. Accessed April 20, 2015.

[24] G. Vuataz, V. Meunier, and J. Andrieux. 2010. TG-DTA approach for designing reference methods for moisture content determination in food powders. *Food Chem.* 122(2): 436-442. http://dx.doi.org/10.1016/j.foodchem.2009.05.066.

[25] H. Wang. 2007. Kinetic analysis of dehydration of a bituminous coal using the TGA technique. *Energ. Fuel.* 21(6): 3070-3075. http://dx.doi.org/10.1021/ef070170y.

[26] L. Wang, A. Kumar, M. Hanna, C. L. Weller, and D. Jones. 2009. Thermal degradation kinetics of distillers grains and solubles in nitrogen and air. *Energ. Source., Part A.* 31(10): 797-806. http://dx.doi.org/10.1080/15567030701752743.