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Drying kinetics of olive stone: A valuable source of biomass obtained in the olive oil extraction

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ABSTRACT

Olive stone is a by-product of the olive grove especially suitable for thermal purpose in industrial, residential and home. To avoid maintenance problems in boilers and to increase the combustion efficiency, olive stone needs to be dried to moisture equilibrium, about 8% (wet basis). The thin layer drying kinetics was investigated in a drying tunnel. Isothermal drying tests were performed with different drying air temperatures: 100, 150, 200 and 250 °C for each sample thickness: 10, 20 and 30 mm. Drying curves were analyzed from the different mathematical models studied by the researchers to date. A new mathematical model is proposed in this work, Two Term Gaussian, which presents the best results of fit. The drying rate is calculated and analyzed. The effective diffusivity values range from $3.98 \cdot 10^{-9}$ to $5.97 \cdot 10^{-8}$ m^2/s. Furthermore, the activation energies values were 14,208, 15,356 and 16,270 J/mol for each sample thickness: 10, 20 and 30 mm, respectively.

1. Introduction

Olive grove is the main source of biomass residues in Andalusia (Spain). There are more than 1.4 million hectares for the olive grove cultivation in Andalusia which produce an average total of 4,700,000 tons of olives per year [1]. The current process of olive oil extraction, two-phase system, separates the virgin olive oil from alpeorujo (olive cake and vegetable water mixture). The alpeorujo is formed by all wastes of the olives: skin, pulp, crushed olive stones, olive oil content about 5% and vegetable water with organics compounds.

The average annual production of olive stone ranges from 360,000 tons per year [2]. The olive stone and olive pulp are separated from the alpeorujo by physical media in olive oil mill and extracted factories [3]. This by-product is used for many applications: activated carbon, liquid and gas fuel produced by pyrolysis, plastic filled, cosmetics, abrasives and furfural production [4]. However, the vast majority of production is spent for the production of electrical and thermal renewable energy [5,6]. As first use, olive stone is employed as biofuel to provide heat in the beating stage, in the olive oil mills, and to produce heat in the drying of the alpeorujo, in the extracted factories [1]. More than 90% of the olive stone is used for thermal energy for industrial purposes and for space heating in commercial building, residential and homes [7,8].

This biomass product highlighted by low percentages of nitrogen and sulfur minimizing emission of NO_x and SO_2 which produce acid rain and cause the destruction of the ozone layer [9,10]. Furthermore, the olive stone combustion does not contribute to climate change with the CO_2 emissions to the atmosphere. The net calorific value is estimated at 19,200 kJ/kg [11].

Drying of the olive stone is necessary for two fundamental reasons. First, olive stone is accompanied by the olive pulp when is separated from the alpeorujo. The olive pulp contains some content of olive oil that needs to be extracted. To do so, it is essential the drying until equilibrium moisture content, where the solvent is more effective. On the other hand, high moisture content in the olive stone decreases the combustion yield [12] and provokes water vapor condensations that are unfavorable in the heating boilers. Moreover, the removal of the moisture content improves the storage and transport conditions.

So far, there are no works in the drying of olive stone in the literature. All researches in the drying of by-products of the olive grove focus on the drying of olive cake (40–50% moisture content, three-phase system) [13–16] and alpeorujo (60–70% moisture content, two-phase system) [17–19].

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Nomenclature

a, b, c, d, e, f, n	coefficients of the mathematical models
k, k_0, k_1, k_2, k_3	constants of the mathematical models (s^{-1})
D_{eff}	effective diffusivity (m^2/s)
D_0	pre-exponential factor of the Arrhenius equation (m^2/s)
E_a	activation energy (kJ/mol)
L	thickness of the slab (m)
R	universal gas constant ($kJ \cdot mol^{-1} \cdot K^{-1}$)
R^2	coefficient of determination
RMSE	root mean square error
t	time (s)
T	temperature (°C, K)
v	velocity ($m\ s^{-1}$)
X_e	equilibrium moisture content (kg moisture/kg dry matter)
X_0	initial moisture content (kg moisture/kg dry matter)
X_t	moisture content at time t (kg moisture/kg dry matter)
XR	dimensionless moisture ratio
x_v	drying rate (kg moisture/(kg dry matter·s))

This work presents a study about the drying kinetics of the olive stone (with olive pulp) in a drying tunnel, although the results can serve as starting point in other drying systems like: fluidized bed dryers, solar dryers and rotary dryers. First, drying curves were fitted with the main mathematical model in the drying of agricultural products. A new mathematical model, which obtains the best results of fit, is proposed, Two Term Gaussian. Second, the drying rate was calculated and analyzed. Third, the effective diffusivity values were obtained for each test. Finally, the activation energies were found for each sample thickness.

2. Materials and methods

2.1. Materials

Olive stone samples with olive pulp were kindly donated by an olive oil mill and a company of drying of the olive stone in the province of Jaen (Spain). The weight of the olive pulp was estimated at approximately 30% of the total weight. The olive stone size ranges from 1 to 3 mm of diameter. To find out the initial moisture content, the samples were dried in an oven (Memmert GmbH + Co.KG, SNB 167 Model 100, Germany) at 105 °C for 24 h. Drying samples were performed in triplicate. An average moisture content of 23 ± 0.5% (wet basis) was found. The same procedure was applied to obtain the equilibrium moisture content which was estimated at 8 ± 0.5% (wet basis).

2.2. Drying equipment and experimental procedure

Drying tests were carried out in a drying tunnel (Fig. 1). The drying equipment is formed by: a blower, electric resistances and a tunnel of 2 m of length with thermal insulation and 0.15 m of square section. The air velocity of the blower was controlled by a VFD (Variable Frequency Drive) connected to an electric AC motor. To achieve the desired temperature in each test, air was passed through a group of three independent resistances: 9 (first stage), 18 (second stage) and 18 kW (third stage), 45 kW in total. To control the constant temperature in each test, a PID (Proportional-Integral-Differential) controller acted over the resistances, measuring the temperature using a PT 100 sensor. The sensor was positioned just before the point of drying of samples. Once the test conditions were correct, the sample was introduced (with the corresponding thickness in each test) into the tunnel in a steel basket of 7 cm of square section. The basket was placed over a precision balance (Blauscal AH1200) with an error of ±0.01 g. It was connected to personal computer by USB port. Software measured the variation of mass every second and stored the test information in files. Drying experiments were stopped when the equilibrium moisture content of the sample was approximately accomplished. However, to obtain the exact moisture content, when the experiments were finished, samples were dried until 0% moisture content in the oven at 105 °C for 24 h.

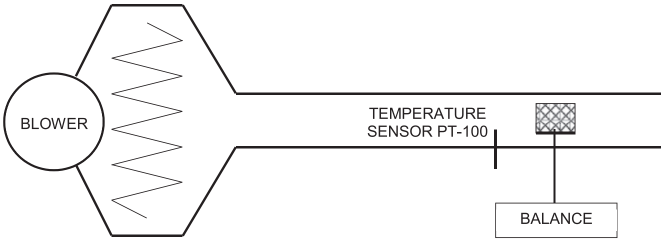

Fig. 1. Drying tunnel scheme.

Twelve experiments were performed. For each sample thickness: 10, 20, 30 mm, four tests with constant drying air temperatures at 100, 150, 200 and 250 °C were carried out. The drying air velocity was established in 1 ± 0.1 m/s.

3. Results and discussion

3.1. Drying curves

Drying curves represent the moisture ratio function versus drying time. The moisture ratio can be expressed as (Eq. (1)):

$$XR = \frac{X_t - X_e}{X_0 - X_e} \tag{1}$$

where X_t is the moisture content at time t, X_0 is the initial moisture content and X_e is the equilibrium moisture content. Nevertheless, the moisture ratio can be expressed like $XR = X_t/X_0$ when the equilibrium moisture content value, X_e, is small with respect to others variables.

Figs. 2–4 show the drying curves for sample thicknesses: 10, 20 and 30 mm, respectively. As can be seen, the drying time decreases when the drying air temperature increases. On the other hand, drying times increase when the sample thickness increases. The drying time falls to approximately four times when the drying temperature rises from 100 °C to 250 °C, for each of the sample thicknesses. When the moisture content, in tests carried out at 250 °C, reaches the equilibrium moisture content, the external surface of the sample begins to burn, regardless of the sample thickness. Tests were stopped at the beginning of the combustion. This indicates that the drying air temperature should be controlled, because this phenomenon causes energy characteristics of the olive stone getting worse.

Drying is a complex physic process which depends on diffusion and convection phenomena. Drying curves were fitted with the main mathematical models in the drying of products. Thirteen mathematical models were used to approximate the drying curves by non-linear regression analysis. Table 1 indicates the names of the fit mathematical models and their expressions. A new mathematical model is presented in this work, Two Term Gaussian.