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# Experimental determination of effective moisture diffusivity during the drying of clean olive stone: Dependence of temperature, moisture content and sample thickness

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ABSTRACT

Drying of clean olive stone (free of olive pulp) means a revaluation as biofuel especially used for thermal processes. This work has studied the time-dependent effective moisture diffusivity from isothermal drying experiments in a convective dryer. A new method, based on a modification of the *simplified method*, has been established to calculate this coefficient. A comparison between this method and the *slope method* has been carried out and similar results have been obtained. *Modified simplified method* requires fewer calculations than the *slope method*. The dependence between the effective moisture diffusivity, the temperature and the moisture ratio was analyzed by multiple regression analysis from a second order multivariate polynomial model and the mechanisms of moisture transport were exposed. Finally, the activation energy was analyzed and its values were shown with respect to the moisture ratio and the sample thickness.

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## 1. Introduction

Biomass is one of the most important renewable energy sources in the production of thermal energy. In the last years, the price of fossil fuels has made that olive stone is emerging as one of the biomass products most highly valued in the production of thermal energy, especially in the European Union which produces more than 75% of the total of olive oil in the world [1]. Olive stone is particularly used for space heating in the industry, residential buildings and homes [2]. The excellent combustion characteristics due to low ash content, low sulfur content and a net calorific value of 19,200 kJ/kg are very well suited for biomass boilers [3].

Olive stone is obtained in the olive oil extraction process. It is contained in the main by-product of the olive oil, the *alpeorujo*. Approximately 80% of olive is a thick sludge formed by pulp, skin, olive stones and vegetation water with organic compounds. The *alpeorujo*, with a moisture content of 60–70%, is a serious environmental problem due to its high biochemical oxygen demand (BOD) and should be dried in industrial rotary dryers of the extracting plants [4]. After drying and subsequently treatments with solvents, olive pomace oil and "*orujillo*" (another biomass product) are obtained. However, olive stone is separated from the *alpeorujo*, before drying, in the olive oil mills by means of mechanical procedures [5]. Its moisture content ranges between 20% and 30% (wet basis), which depends on several factors such as particle sizes, quantity of pulp and the conditions in the stages of the olive oil extraction process (washing, milling, crushing and kneading) [6]. However, recently new techniques in the olive stone separation process are allowing the obtainment of a by-product free of olive pulp, which implies moisture contents less than 20% (wet basis) and avoids possible problems in boilers.

Nevertheless, drying of olive stone up to equilibrium moisture content is an important stage for its revaluation as biofuel. The combustion yield in the biomass boilers increases when the olive stone moisture content decreases and high moisture contents cause water vapor condensations which are unfavorable in the biomass boilers [7]. Furthermore, drying process contributes to a cleaner production with a significant reduction in the cost of transport [8].

The porous nature of olive stone is similar to olive cake (three-phase system) and *alpeorujo* (two-phase system). The drying of olive cake [9–13], *alpeorujo* [14–19] and olive stone [20] has been studied by different researchers. All studies agree that the vast majority of the drying of these by-products is mainly produced by diffusion, capillarity and evaporation-condensation phenomena, in the falling rate period. In this sense, researchers usually obtain the average values of the effective moisture diffusivity in all drying process. However, effective moisture diffusivity can be studied as a time-dependent variable which represents

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**Nomenclature**

| | |
|---|---|
| $a,b$ | Coefficients of the quadratic polynomial fit. |
| $a_0,a_1,a_2,a_3,a_4,a_5$ | Coefficients of the second order multivariate polynomial model. |
| $D_{eff}$ | Effective moisture diffusivity ($m^2 \cdot s^{-1}$) |
| $D_0$ | Pre-exponential factor of the Arrhenius equation ($m^2 \cdot s^{-1}$) |
| $E_a$ | Activation energy ($J \cdot mol^{-1}$) |
| $F_o$ | Fourier diffusion number |
| $L$ | Thickness of the slab (m) |
| $m$ | Slope |
| $R$ | 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) |
| $x$ | Spatial dimension of mass transport (m) |
| $X_0$ | Initial moisture content (kg moisture/kg dry matter) |
| $X_t$ | Moisture content at time t (kg moisture/kg dry matter) |
| $XR$ | Dimensionless moisture ratio |

an overall moisture transport property [21]. This variable involves not only diffusion phenomenon, but also other phenomena such as capillary movements, vaporization-condensation sequence flow, Knudsen diffusion, non-Fickian or stress-driven diffusion [22].

Commonly, in the field of numerical modeling of heat and mass transfer, the values of effective moisture diffusivity are constant [23] or are based on an Arrhenius type relationship which depend on the temperature [24,25]. In this sense, effective moisture diffusivity of olive stone can be estimated experimentally as an explicit function of moisture content, temperature and shrinkage. The objective of this work was to determine the effective moisture diffusivity of clean olive stone (free of olive pulp) in a convective dryer and its relationship with other variables such as drying air temperature and moisture ratio, for each sample thickness studied. A new method to calculate the time-dependent effective moisture diffusivity has been employed, the *modified simplified method*. The results obtained have been compared to the *slope method* and similar outcomes have been found. Finally, an experimental relationship for the activation energy with respect to moisture ratio and sample thickness was calculated.

## 2. Materials and methods

### 2.1. Materials

Clean olive stone was supplied by several olive oil mills in the province of Jaén (Spain). Samples were obtained during the olive harvesting period, at the beginning of November 2014. This ensured the original moisture content in all samples studied. Olive stone, free of olive pulp, presented different particle sizes. To obtain the distribution of particle sizes, a quantity of solids was screened using a vibratory screen (Restch, Mod. Vibro). The results showed that clean olive stones had a particle size between 7 and 5 mm (9.7%), 5–3 mm (43.1%), 3–1 mm (36.9%), and <1 mm (10.3%). Approximately, an average particle size of 3.1 mm was found. Similar results have been obtained by other authors [26]. Regarding the porosimetric data of olive stone, Cuevas et al. [27] have found a total cumulative volume (TCV) of 0.172 $cm^3 \cdot g^{-1}$, a specific surface area (SSA) of 15.8 $m^2 \cdot g^{-1}$ and an average pore diameter (APD) of 6.92 nm using the mercury porosimetry method. Fig. 1 shows the SEM images in the external and internal surface of a particle of olive stone which were performed with a Merlin—Carl Zeiss instrument operating at 15 kV. The moisture content of clean olive stone samples was obtained by drying in an oven (Memmert GmbH + Co. KG, SNB 167 Model 100, Germany) at 105 °C for 24 h. Drying of samples was carried out in triplicate. An average initial moisture content of 19 ± 0.3% (wet basis) was found. A value of equilibrium moisture content of 7 ± 0.5% was obtained. Surrounding air presented a relative humidity of 50% and a temperature of 20 °C.

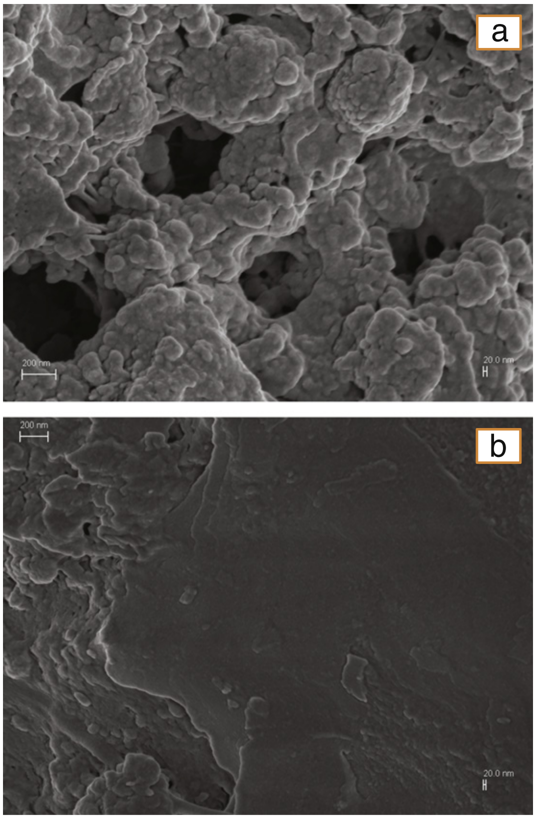

**Fig. 1.** SEM images of crushed olive stone, (a) external surface and (b) internal surface.

### 2.2. Experimental procedure

Experiments design was based on isothermal tests at four drying air temperature (100, 150, 200 and 250 °C) and three sample thickness (10, 20 and 30 mm), with a drying air velocity of 1 ± 0.1% m/s. The

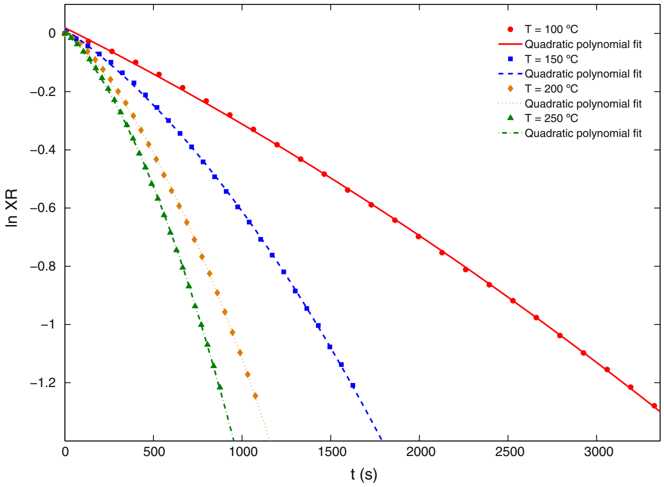

**Fig. 2.** Logarithmic drying curves at different temperatures and their fit by quadratic polynomial for $L = 10$ mm.

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