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Experimental determination of the effective moisture diffusivity and activation energy during convective solar drying of olive pomace waste

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ABSTRACT

The drying of olive pomace waste was performed using a partially indirect solar convective dryer operating in forced convection. This comparative study is focused on the drying kinetics of two types of residue, namely, raw olive pomace and deoiled olive pomace. These products have been spread out in thin layers on perforated circular racks before they be placed in the dryer. The sample thicknesses considered are 0.5, 1.0 and 1.5 cm. Kinetic measurements are carried out for three temperatures (40, 60 and 80 °C) and two drying air flow rates (0.042 and 0.083 $m^3\ s^{-1}$). The relative humidity varies between 28% and 65% throughout the drying period. The increase of temperature in the environment reduces significantly the drying time. The characteristic drying curve (CDC) applicable to both types of olive pomace has been established as a polynomial of order 4 in reduced moisture content. Data obtained from dried products were used to determine the effective diffusivity values during the drying period with decreasing curve. In this period, the moisture transfer from the pomace was described by applying the Fick diffusion model. Effective diffusivity varies between 1.6×10^{-8} and $34.7 \times 10^{-8}\ m^2\ s^{-1}$ with the increase of the medium air drying temperature but also with the sample thickness. The activation energy value is estimated at 29.06 kJ mol^{-1}.

1. Introduction

This research investigation has been conducted within the framework of VERA project supported by the "Region Centre Val de Loire, France". It aims to optimize an integrated process for energy recovery from agricultural waste, including olive pomace. This product is obtained from the extraction of olive oil and it mainly consists of solid residue and an important quantity of water which represents 20–50% of the total weight of the processed olives [4]. The disposal of this waste without any treatment causes serious environmental problems. But, it could be used as: a fertilizer, an animal feed and for energy generation. We note that the burning of this biomass for the heat generation is targeted by the VERA project in order to electricity production. This will be satisfying a real need of vast Moroccan rural areas, which must undergo a technical revolution to stop the rural exodus by contributing to the creation of permanent employments. In the recent study [15], we showed that raw olive pomace waste contains residual olive oil which could have a negative impact on the combustion quality and hence on the environment. So, the uses of deoiled olive pomace wastes are

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required, and after undergoing a solar drying, they will be ready for the different aforementioned uses.

On the other hand, the relationship between the shelf-life of a food product and the degree of hydration has always been known, water is involved in a very large number of alteration phenomenon: biochemical or biophysical modifications, enzymatic reactions or again the microbiological processes. The shelf-life can be greatly enhanced by lowering the water activity, regardless of the implementation technique to reduce this activity: drying, salting. In the alimentary sector, a lot of work has been done to optimize the operation of drying [18,1]. This operation consists of rationalizing both the consumption of energy required and safeguarding the quality of the dried product. In this regard, solar drying is an appropriate solution for developing countries in conventional energy resources and having a significant solar radiation throughout the year [13,15].

The drying kinetics of raw and deoiled olive pomace are studied, using a solar dryer equipped with an auxiliary heating system and operating in forced convection [18, 13, 15]. This study aims to contribute to the analysis and the understanding of diffusion mechanisms that affect the drying process of agricultural residues, especially, the olive pomace for which little attention has been given. So, to determine the effective moisture diffusivity and the corresponding energy activation, the drying rate determined empirically from the characteristic drying curve is used [29,14,23,3,26,31].

2. Mathematical formulation

2.1. Moisture content and characteristic drying curve (CDC)

First of all, it is necessary to point out that for all experimental tests conducted here, the temperature and the drying air flow rate values are fixed. Then, the evolution of the wet weight $M_h(t)$ of the product to be dried has been tracked by successive weightings until it becomes stationary. This is followed by dehydration of the product in an oven at 105 °C for 24 h in order to determine the dry mass M_d of the product. The moisture content in dry base at time t is defined by:

$$X(t) = \frac{M_h(t) - M_d}{M_d} \times 100 \quad (1)$$

Determining the kinetic of drying is by direct calculation of the derivative of the moisture content from the experimental points using the software “LISSAGE” under MS-DOS.

The principle of the method developed by Van Meel [28] consists of a normalization representing the ratio between the drying rate $\left(\frac{-dX}{dt}\right)$ at time t and the rate of first phase $\left(\frac{-dX}{dt}\right)_I$, under the same conditions of air as a function of the reduced moisture content $\frac{X(t)-X_{eq}}{X_{cri}-X_{eq}}$. Since the first phase of drying does not exist in the case of residual pomace [15], then we consider that $\left(\frac{-dX}{dt}\right)_I = \left(\frac{-dX}{dt}\right)_0$ and $X_{cri} = X_0$. So, the general form of the equation of the drying characteristic curve is given by $V^* = f(X^*)$:

$$X^* = \frac{X(t) - Xeq}{X_{cri} - Xeq} = \frac{X(t) - Xeq}{X_0 - Xeq} \quad (2)$$

$$V^* = \frac{\left(-\frac{dX}{dt}\right)_t}{\left(-\frac{dX}{dt}\right)_I} = \frac{\left(-\frac{dX}{dt}\right)_t}{\left(-\frac{dX}{dt}\right)_0} \quad (3)$$

The equilibrium of moisture content is determined from the isotherms of desorption of the product. For a reasonable range of constant experimental conditions during drying (air drying temperature, air flow rate, humidity of air and dimensions of the product to be dried), the characteristic drying curve (CDC) verifies the following properties [9, 24]:

$$\begin{cases} V^* = 0 & \textit{for} \quad X^* = 0 \\ 0 \le V^* \le 1 & \textit{for} \quad 0 \le X^* \le 1 \\ V^* = 1 & \textit{for} \quad X^* \ge 1 \end{cases} \quad (4)$$

2.2. Effective moisture diffusivity and activation energy

Drying processus is distinguished by the existence of different transport mechanisms such as: pure diffusion, surface diffusion, capillary flow, Knudsen diffusion, evaporation and condensation. Water migrates from the inside to the product surface under the action of these various mechanisms that can be combined. Similarly to food products, it is reasonable to attribute the water transport within the olive pomace to a pure diffusion of liquid water under the effect of the concentration gradient [10]. Therefore, the mass transfer rate by pure diffusion is proportional to the concentration gradient of the moisture content, with the coefficient of effective moisture diffusivity. The determination of this last coefficient (diffusivity) is indispensable to describe the mass transfer processus by Fick's second law equation which describes the rate of accumulation (or depletion) of concentration within the volume as proportional to the local curvature of the concentration gradient [10]:

$$\frac{\partial X^*}{\partial t} = \nabla\left[D_{eff}\nabla X^*\right] = D_{eff}\nabla^2 X^* \quad (5)$$

D_{eff} is the effective moisture diffusivity (in $m^2\ s^{-1}$) which varies with temperature and moisture content of the product and is also affected by the retraction of the solid matrix.

Assuming that the transport of moisture carries out by diffusion, that shrinkage is neglected, and that diffusion coefficient and temperature take constant values, the analytical solution of Fick's second law equation is developed by Ref. [6] in the case of an infinite plate:

$$X^* = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-(2n+1)^2\frac{\pi^2 D_{eff} t}{4L^2}\right] \quad (6)$$

For a sufficiently long drying time, all terms of the above series are negligible compared with the first term. Thus, Eq. (6) becomes:

$$X^* = \frac{8}{\pi^2}\exp\left[-\frac{\pi^2 D_{eff} t}{4L^2}\right] \quad (7)$$

where L (in m) is the half-thickness of the used samples.

The effective moisture diffusivity can be deduced by using the slope method, 2010 The effective moisture diffusivity can be deduced by using the slope method. Indeed, Eq. (7) is transformed into[7,24,25].

$$\mathrm{Ln}(X^*) = \mathrm{Ln}\left(\frac{8}{\pi^2}\right) - \frac{\pi^2 D_{eff}}{4L^2}t \quad (8)$$

and D_{eff} coefficient can be calculated from the slope of Eq. (8) by fitting experimental data of drying model.

The activation energy in a drying process, E_a, is the minimum