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Crambe grain drying: Evaluation of a linear and double resistance driving force model and energetic performance

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ABSTRACT

In this study, a review of the main industrial applications of crambe grains, as well as the modeling of drying kinetics applying the double resistance and the linear driving force model are presented. Fixed bed drying characteristics of crambe grains were investigated in a convective drier, on the drying air conditions at temperatures of 40, 50 and 60 °C and 1.5, 2.0 and 2.6 m s^{-1}. The drying kinetics was phenomenologically modelled, for such, the main hypotheses adopted were the double resistance and the linear driving force model for water diffusion inside the grains. Centesimal composition of the grains was calculated, in order to determine their thermophysical properties. The mass transfer inner coefficient was considered as a linear function of the humidity of the bed. The theoretical mathematical model suggested, the linear approximation of the mass transfer inner coefficient, and the empirical model for the heat transfer convective coefficient resulted in a relative mean error of 7.79%. The specific energy consumption values ranged from 12.45 to 5.98 MJ kg^{-1}, respectively for drying conducted at 40 °C and 2.5 m s^{-1} and at 60 °C and 1.5 m s^{-1}.

1. Introduction

Crambe, *Crambe abyssinica* Hochst, is an oleaginous plant from the Brassicaceae family, whose grains are non-edible, and whose oil has a high erucic acid content, 50–60% [1]. A notable characteristic of this oil is its diversity of application, such as, for example, for hydraulic fluids, additives, fibers, resins, plastic, lacquer, among others [2]. In addition, erucic acid has a low point of ignition, easy combustion and lubricating characteristics, which makes it a valuable raw material for biodiesel production [3]. Recently, some studies have shown the feasibility of using crambe as a low cost biosorbent for cadmium [4] and lead(II) [5] removal from water. The advantages offered by this culture are a high oil yield from the seed, tolerance to drought and cold conditions, and an accelerated development cycle, approximately 90 days. These characteristics allow crambe to be cultivated during winter.

Like other biological products, crambe grains are subject to several challenging conditions after harvesting, such as deterioration due to microorganisms. The grain storage practice and associated operations, such as cleaning, drying and prophylactic treatments are inserted into a context of strategic planning, which is fundamental to assure a continuous production offer during the entire year [6]. Although the literature shows some papers that studied extraction techniques [7,8], and the physical-chemical characteristics of crambe oil [9,10], few studies investigated the aspects of crambe grain drying, such as the storage subjected to different drying conditions [11] and the influence of drying on the physiological quality [12–16]. Studies related to drying kinetics, in turn, was restricted to the application of empirical models or simplified models, with an analytical solution [1,17–20]. However, for the consolidation of the crambe culture, more in-depth studies on the drying and storage of these grains are essential, making it possible for post-harvest structures to be built based on appropriate technical parameters.

The drying of biological materials, such as crambe grains, is a complex operation, which involves, simultaneously, heat and mass transfer processes. In that sense, determining the equilibrium isotherms is essential to study the drying kinetics, since it predicts the final humidity content, making it possible to calculate the energy expenditure to reach this equilibrium, specify the storage conditions

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and predict the shelf life of the product. As important as knowing the equilibrium isotherms are the mathematical models that describe the drying kinetics. When theoretical or phenomenological models are applied to describe this kinetics, unlike empirical models, the obtained equations may be used on simulation, control and optimization strategies for processes [21,22]. These applications are possible, since the theoretical models offer the temperature and humidity distributions on the material and the equipment.

For the description of the drying processes, it is fundamentally important to use an equation that describes the mass transfer rate, or the drying rate. However, considering all the mechanisms that work inside the grains oftentimes makes it unfeasible to solve and, consequently, to apply the model. In that sense, using mathematical models of concentrated parameters, allied to the use of simplified expressions to describe the drying kinetics is an appealing alternative. Although the use of double resistance model is more common in adsorption studies, such as dye reactive blue 5G [23], Zn^{2+}- Na^{+} ions [24], and dissolved oxygen [25], some researchers have used them to describe drying processes. For example, drying studies involving carrot cubes [26], industrial coal [27], and cubes [28] may be mentioned.

The objective of this study was to obtain, through experiments, the equilibrium and drying kinetics isotherms for crambe grains on a fixed bed. Simplified equations were adjusted and a phenomenological mathematical model was developed, in which the linear driving force and the double resistance model were used, in order to describe the drying kinetics. The mass transfer inner coefficient was evaluated as a linear function of the grain bed humidity, the model was validated, and the specific energy consumption was investigated.

2. Experiments

2.1. Material

On the equilibrium and drying kinetics experiments, *in natura* crambe grains were used, which were supplied by Fundação MS, crop of 2014.

The humidity content of the grains was determined (in triplicate) by the oven method. Glass petri dishes were used containing, approximately, 2 g of the sample, placed in an air-circulation oven (CIENLAB CE-220), with controlled temperature at 105 ± 3 °C for 24 h. After drying, the samples were weighted and the humidity content, X, was determined:

$$X = \frac{M_w - M_d}{M_d} \tag{1}$$

where X is the grain moisture content in dry basis (d.b.), M_w is the mass of the moist grain (kg), and M_d is the mass of dry grain (kg).

2.2. Thermophysical properties of crambe grains

Since during the drying process the humidity content of the grain varies in relation to time, consequently, the thermophysical properties, such as density and specific heat, vary throughout the operation. Therefore, the solution for the obtained model from the mass and energy balance tends to be more precise considering these variations.

The specific mass, ρ_S, and specific heat, cp_S, parameters of crambe grains were calculated based on the centesimal composition, which was experimentally determined according to the literature [29]. For the calculations, the relations suggested by [30] were used:

$$\rho_S = \frac{1-\varepsilon_{bed}}{\sum\left(\frac{x_j}{\rho_j}\right)} \tag{2}$$

$$cp_S = \sum x_j \times cp_j \tag{3}$$

where ρ_S is the real bed density (kg m^{-3}), ε_{bed} is the bed porosity, x_j is the mass fraction of each pure component, cp_j is the specific heat of each pure component (kJ kg^{-1} °C^{-1}), and cp_S is the specific heat of the grain (kJ kg^{-1} °C^{-1}).

The granulometric analysis of the grains was obtained using a set of standardized sieves from the Tyler series and stirring equipment. The Tyler system sieves used were 28, 12, 9, 7 and 6. The mean diameter of the particles, $\overline{D}_n$, was calculated applying the mean diameter equation by Sauter, D_{Sauter}:

$$D_{Sauter} = \frac{1}{\sum_{n=1}^{n} \frac{\Delta \phi_n}{\overline{D}_n}} \tag{4}$$

$$\overline{D}_n = \frac{D_{n-1} + D_n}{2} \tag{5}$$

where D_{Sauter} is the Sauter average diameter (m), ϕ_n is the mass fraction retained, and $\overline{D}_n$ is the average particle diameter (m).

Since, if disregarded, the bed porosity may lead to erroneous analyses of the heat and mass transfer [31], this property was determined from the actual, ρ_S, and apparent, $\rho_{aparent}$ specific masses.

$$\varepsilon_{bed} = 1 - \frac{\rho_S}{\rho_{aparent}} \tag{6}$$

where $\rho_{aparent}$ is the apparent bed density (kg m^{-3}).

2.3. Equilibrium isotherms

The equilibrium experiments were conducted with pre-humidified crambe seeds around 24%, and this was the same condition used on drying kinetic experiments on deep beds. The seeds were inserted into plastic containers with small lateral holes, suspended on glass containers, with 140 mm of height and 85 mm of diameter, hermetically closed, with controlled temperature. Inside each glass container, there were 25 mL of sulfuric acid solution, at tem different concentrations, varying from 25% to 70%, at intervals of 5%. This variation on the acid concentration assured different relative humidity values for each one of the concentrations.

The containers remained on the drying oven (SP Labor, SP-102), and the mass of the set was periodically determined up to its balance. The initial mass varied from 1 to 3 g. The weightings were weekly conducted on an analytical scale (Shimadzu, AUX-220, with precision of 0.0001 g). The experiments were conducted at three different temperatures, 30, 45 and 60 °C. The assays were conducted in triplicates.

Table 1 shows the isotherm models tested in order to describe the hygroscopic balance of crambe grains.

For the adjustment of the parameters for the empirical models according to the experimental data, the Statistica 7 software was used. The parametrical optimization method used was Levenberg–Marquardt, with a 10^{-6} convergence criterion.

Table 1
Equilibrium isotherm models.

Model	Equation
Luikov	$X^* = \frac{A}{1 + BT\ln\left(\frac{1}{UR}\right)}$
Keey	$X^* = \frac{A}{1 + BT^3\ln\left(\frac{1}{UR}\right)}$
Henderson	$X^* = A\left(\frac{1}{T}\right)\ln\left(\frac{1}{1-UR}\right)^B$
Modified Halsey	$X^* = \left[\frac{\exp(AT+B)}{-\ln(UR)}\right]^C$
Modified Oswin	$X^* = (A + BT)\left(\frac{U_r}{1-UR}\right)^C$
Modified Smith	$X^* = \lvert(A + BT) - (C + DT)(1 - UR)^C\rvert$