Biomass and Bioenergy 107 (2017) 8–19

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: http://www.elsevier.com/locate/biombioe

Research paper

Drying kinetics of granulated cork: Effect of air drying stream conditions and granule size

R.O. Madaleno [a], L.M. Castro [a, b], M.N. Coelho Pinheiro [a, c, *]

[a] Departamento de Engenharia Química e Biológica, Instituto Superior de Engenharia do Instituto Politécnico de Coimbra, Rua Pedro Nunes, Quinta da Nora, 3030-199 Coimbra, Portugal

[b] GERST–DCE/FST, Group on Environment, Reaction, Separation and Thermodynamics, Department of Chemical Engineering, Faculty of Sciences and Technology, University of Coimbra, Rua Sílvio Lima, Pólo II, 3030-790 Coimbra, Portugal

[c] Centro de Estudos de Fenómenos de Transporte, Faculdade de Engenharia da Universidade do Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

ARTICLE INFO

Article history:
Received 4 April 2017
Received in revised form
20 August 2017
Accepted 21 August 2017

Keywords:
Bio-residue
Granulated cork
Convective drying
Drying kinetics
Characteristic drying curve

ABSTRACT

Granulated cork is a by-product of natural cork stoppers manufacturing which is incorporated into highly valued products such as agglomerated cork stoppers and expanded cork insulation. Prior to this, the cork granules must be dried.

This work presents an experimental study for the characterization of wet granulated cork drying kinetics with different morphologies: a powder and granules with different sizes (2–2.8, 2.8–4 and 4–5.6 mm). A drying process with hot air stream flowing tangentially to the solid was used for a systematic analysis of the influence of air stream conditions (temperature and flowrate) on drying kinetics. Under these conditions, the influence of the stream temperature was much more relevant than its velocity with the drying time almost halving when the temperature rose from 35.0 °C to 56.5 °C. The drained humid solid with higher granulometry was dried entirely during a falling drying rate period. All others products presented a constant drying rate period before the falling drying rate period.

The results revealed that the falling drying rate period is conditioned by water migration through the solid and presents a similar shape for all products. Thus, the behavior can be described by a single characteristic drying curve, allowing predicting drying rate as a function of the solid normalized humidity, despite the cork granules dimensions. This normalized curve is a useful tool for dryer equipment dimensioning in the cork manufacturing industry.

To predict the time of drying for defined air drying conditions, a simple procedure was proposed using the characteristic drying rate obtained.

1. Introduction

Cork is the bark of oak tree (*Quercus Suber* L.), a native tree of the Mediterranean region. Portugal is the country with the largest area occupied by cork oak (736,775 ha, 34% of the total), as well as the leading producer (100,000 t, 49.6% of the total), manufacturer and exporter with a share of 897.2 million euros in 2015, 62.7% of the total [1].

Cork as a natural, renewable and sustainable product has deserved special attention as potential raw material for new applications.

Cork has good mechanical properties, as elasticity and compressibility, and is impermeable to liquids and gases due to the suberin and other waxes in the cork cells [2]. These properties make the cork an excellent natural product with sealant characteristics, which associated to the good biological and chemical stability, have been driving the use of natural cork stoppers to seal wine bottles.

The air filling the interior of the suberized cells in the cork is responsible for the good performance of this material as insulator (thermal and acoustic). Although agglomerated cork panels are widely used in the construction industry, recently its application also as decorative element by architects can bring harmony between the building and nature.

The main residue of the cork sector is cork powder. This residue results from the mechanical operations as part of the

* Corresponding author. Departamento de Engenharia Química e Biológica, Instituto Superior de Engenharia do Instituto Politécnico de Coimbra, Rua Pedro Nunes, Quinta da Nora, 3030-199 Coimbra, Portugal.
E-mail address: mnazare@isec.pt (M.N. Coelho Pinheiro).

https://doi.org/10.1016/j.biombioe.2017.08.025
0961-9534/

manufacturing of cork stoppers and is used to produce natural colmated cork stoppers where the pores are filled with the cork powder.

The fabrication of the most important product of the cork sector, natural cork stoppers, also produces significant amounts of cork plank waste. After transformation to cork granules these are used in the production of agglomerated cork stoppers, by molding or extrusion, which are a very economical solution for sealing wine bottles for short periods. In the production of agglomerated cork insulation panels this by-product is also used. Creating value from these industrial bio-wastes is the basis of the cork sector's sustainability strategy as a part of the circular economy.

In order to maintain mechanical properties and the low density of cork products it is important to control the water content of the raw materials [3]. Prior to its use in the production of agglomerated cork stoppers and insulation panels, the granulated cork must be dried to the desired humidity content. The most common drying process uses a hot air stream contacting directly with the humid cork granules in a rotary dryer. Thus, to characterize the drying curves of the cork by-products it is fundamental to success in the dryer scale-up procedures in the cork sector.

Because the water content of natural products is, in general, an important technological parameter, several studies have recently been carried out to characterize the drying of bio-residues. For example, Vega-Gálvez et al. [4] studied the convective dehydration of olive cake, an agro-industrial residue, and Chen et al. [5] used a thermogravimetric method to evaluate the drying kinetics of a forest residue, the poplar sawdust. The list of studies concerning the dehydration of food products and its impact on quality attributes is very long. However, a systematic study of convective drying of cork products allowing the optimization of operation conditions of the process has not yet been published.

In fact, the studies about convective drying of cork are very scarce. Carpintero et al. [6] studied the convective drying of cork planks using a kiln drying technique and compared with the traditional drying process; Costa and Pereira [3] studied the solar drying process of raw cork planks in a cork pile; Belghit and Bennis [7] studied the drying kinetics of small cork slabs in a laboratory dryer.

The present work describes an experimental study to characterize the kinetics of drying of granulated cork in a tray dryer operating under different conditions. Temperature and velocity of the air stream flowing tangentially to the tray surface were modified separately. The effect of the wet cork granule sizes on drying kinetics was also evaluated. The comparison of the different drying curves obtained was facilitated using the methodology recently proposed by the authors [8]. The conclusions drawn can contribute to determine the optimal operating conditions to be used in the industrial drying of granulated cork with economic benefits in terms of energy consumption. More than ever, this is now a fundamental aspect in the cork transformation industry as in recent years cork disinfection with water vapour at high temperatures became a common process and the obtained by-products have higher moistures and must be dried in subsequent steps of the production process.

2. Materials and methods

2.1. Materials and sample preparation

The cork powder and granulated cork used in the experiments were a by-product of cork planks transformation and were obtained by courtesy of a Portuguese cork stoppers industry. The solids were stored in sealed plastic bags until they were dimensionally characterized and were used in drying experiments.

The size distribution of the cork powder was obtained by (wet) laser diffraction (Malvern Mastersizer 3000 with the Hydro MV dispersion unit) in a suspension of powder in ethanol. Three percentiles for the volume diameter were obtained, 10%, 50% (median) and 90%, with values of 16.4 μm, 79.3 μm and 270 μm, respectively, using the Fraunhofer scattering model in the powder analysis. The particles size constituting the bulk of the sample volume, which is represented by the volume moment mean, was also reported from the analysis and has a value of 116 μm. The specific surface area, measured by laser diffraction, was 184.1 $m^2\ kg^{-1}$.

The size distribution of the granulated cork was obtained by (dry) sieving using a stack of four sieves, with nominal opening dimensions of 5.6 mm, 4 mm, 2.8 mm and 2 mm, in a sieve shaker. The granulated cork was divided into three different size fractions with particle sizes in the range of 4–5.6 mm, 2.8–4 mm and 2–2.8 mm.

The samples of the solid materials used (powdered and granulated forms) in the drying process congregate fine particles and their volumes (bulk volumes) include the solid material volume, the pores volume and the interparticle void volume. The bulk volume depends on the size, shape and level of packing of the individual fine particles. The bulk (apparent) density of the cork powder and the different size fractions of granulated cork were evaluated with a methodology based on the ISO 2031:2015 standard [9]. The values obtained with the corresponding confidence interval (confidence level of 95%) were: (67.3 ± 0.9) kg m^{-3} for powder and (77.3 ± 3.5) kg m^{-3}, (78.6 ± 1.9) kg m^{-3} and (79.8 ± 2.2) kg m^{-3} for granulated with dimensions between 2 mm and 2.8 mm, 2.8 mm and 4 mm and 4 mm and 5.6 mm, respectively. The determinations were repeated nine times for each product but as the cork granules are very irregular the dispersion of the bulk density values are high. However, it presents a slight increase of mean values with cork granule dimensions.

In order to prepare the samples to be dried, the solid was immersed in water. After removing the excess of water from the cork the humid solid was transferred to the tray. An effort was made to guarantee as close as possible to the same initial humidity in all the similar solid samples. Care was also taken to have a uniform thickness of wet solid material in the tray, which was measured before placing it into the drying chamber. Measurements of the free height of the tray were carefully performed in six different locations using a digital paquimeter. By difference from the total height of the tray, the humid solid thickness was determined and a mean value was used to characterize the solid bed thickness.

2.2. Experimental procedure and conditions

A laboratory scale tray dryer (Armfield Ltd, model UOP8) was used to perform single layer with forced convection drying kinetics experiments with the cork products. This drying unit is described in detail in a previous study of the authors [8] and is equipped with an axial flow fan and heating elements near the tunnel entrance with adjustable speed and heat power, respectively. The drying chamber accommodates a metallic structure suspended from a digital balance outside the tunnel where the stainless steel tray used in this work (0.0509 m^2 surface and 0.015 m depth) was mounted. The balance (OHAUS, Adventurer Pro AV8101) had an accuracy of measurement of ±0.1 g. Using the HyperTerminal emulator for the connection, the readings from the balance were saved in a computer with an acquisition frequency of 0.025 Hz (period of 40 s) or 0.050 Hz (period of 20 s) depending on the cork granulometry used in the experiment.

Regular measurements were made of the air temperature and humidity upstream the drying chamber and of the air stream