Journal of Food Engineering 240 (2019) 120–132

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Analysis of mass transfer and morphometric characteristics of white mushroom (*Agaricus bisporus*) pilei during osmotic dehydration

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A R T I C L E I N F O

Keywords:
Diffusion
Deformation
Hemispherical shell
Image analysis
Shrinkage

A B S T R A C T

The shrinkage-deformation (SD) behavior and mass transfer characteristics of white mushroom (*Agaricus bisporus*) pilei during osmotic dehydration (OD) were investigated. The morphometric characteristics of the product (including product contours, cross-sectional area and roundness) were obtained from digital images. Moreover, product contours were averaged to extract relevant deformation characteristics of osmodehydrated samples. An unsteady state 2D-diffusion model taking into account both radial and angular mass transfer, where product is shaped as a hemispherical shell was proposed to describe experimental data. Water and solute diffusivities in product were estimated with and without considering product shrinkage, defined as the shortening of radial dimension. Besides, diffusion coefficients were obtained using simplified models for both the proposed hemispherical shell geometry and a simpler sphere-shaped product, in the latter, under different similitude criteria. Estimated water and solute diffusivities reflecting dimensional changes of product were in the ranges of 1.1–4.6 × 10^{-10} and 1.5–1.8 × 10^{-10} m^2/s, respectively, and are overestimated in about 39–113% for water and in about 24–66% for solute when shrinkage is not included in the OD model. Moreover, diffusion coefficients can also be corrected for geometry using the appropriate similitude criterion.

1. Introduction

Osmotic dehydration is a solid-liquid contact operation involving the immersion of food products in hypertonic solutions (Pacheco-Angulo et al., 2016). This operation produces a partial dewatering of food material with a simultaneous solute uptake from the solution into the product (da Silva Júnior et al., 2017). OD is used as a pretreatment for some processes, mainly convective drying, where it may contribute to improve quality characteristics in the final product, for example, preventing oxidative browning and reducing structural damage (Ahmed et al., 2016; Assis et al., 2016). Nevertheless, OD on its own also induces several changes in food, and product shrinkage is one of the most evident (Mayor et al., 2011; Souraki et al., 2014).

The effect of product shrinkage on drying simulation and estimation of mass transfer properties is well-known (Souraki et al., 2014). However, unlike drying, product shrinkage is very often neglected during the modeling and simulation of OD as highlighted by several authors (Toğrul and İspir, 2007; Souraki et al., 2014; de Farias Aires et al., 2016, 2017). Besides, all OD models including shrinkage have been validated with simple geometries (spheres, flat slabs, cylinders, parallelepipeds) (Toğrul and İspir, 2007; da Silva et al., 2014; Souraki et al., 2014; de Farias Aires et al., 2016, 2017; da Silva Júnior et al., 2017). When modeling OD processes, very few studies have attempted to represent the natural product shape (Bordin et al., 2018), but shrinkage has been neglected.

Besides shrinking, foods also may suffer a considerable deformation (i.e., shape change) during OD, as demonstrated by Mayor et al. (2011), which can affect both the visual appeal and packing properties of product. However, studies on product deformation during OD are near to non-existent. Reporting morphometric changes of product also introduces an additional challenge: no sample shrinks and deform in the same way, even under the most controlled scenarios. Thus, the use of SD data for advanced process simulations requires the extraction of common features of product behavior. Ortiz-García-Carrasco et al. (2015) introduced a novel image analysis methodology to estimate the simultaneous SD of dried foods, aimed at extracting relevant information on both the dimensional and shape changes of product in dominant mass transfer directions with modeling and simulation purposes. This

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https://doi.org/10.1016/j.jfoodeng.2018.07.026
Received 27 April 2018; Received in revised form 19 June 2018; Accepted 23 July 2018
Available online 23 July 2018

methodology allowed to appraise the impact of changes in product shape on water diffusivity estimation during air drying (López-Méndez et al., 2018). However, this technique has yet to be applied to osmo-dehydrated products.

White mushroom (*Agaricus bisporus*) is a very appreciated fungus that is eaten fresh or cooked. Due to its high moisture content, it is extremely perishable; thus, a suitable processing method such as wet brining with NaCl (Bordin et al., 2018) is required to extend its shelf-life. Most current studies on white mushroom OD have focused on the effect of this operation as a pre-treatment for a further drying operation (Torringa et al., 2001; Walde et al., 2006; Giri and Prasad, 2007; Shukla and Singh, 2007), without fully characterizing the mass transfer characteristics of the product (equilibrium point and water/solute diffusivities) and its shrinking behavior. Moreover, the few references on mass transfer during OD of white mushroom have ignored the effect of product shrinkage (Rezagah et al., 2011; Bordin et al., 2018). The objective of this study was to evaluate the effect of shrinkage on the mass transfer during the osmotic dehydration of white mushroom pilei. To fully achieve this purpose the following topics were covered: (i) the modeling of water loss and solute gain using an unsteady state 2D-diffusion model where product is shaped as a hemispherical shell, (ii) the evaluation of morphometric changes of product along dominant mass transfer directions by image analysis techniques and the mathematical description of resulting data, (iii) the integration of mass transfer and shrinkage models during estimation of diffusion coefficients, (iv) the development of a simple method to estimate diffusion coefficients corrected for shrinkage in proposed geometry and (v) the exploration of different similitude criteria when product is described by a simpler shape such as a sphere.

2. Materials and methods

2.1. Osmotic dehydration experiments

Fresh white button mushrooms (*Agaricus bisporus*), 3.4–3.7 cm in diameter, were locally purchased (Puebla, Pue., México) and processed the same day. White mushrooms were washed, dried with a cloth and then their stipe was manually removed. Food grade NaCl (99.5% minimum purity) dissolved in distilled water was used as osmotic agent. Pilei were numbered with a marker and their weight was individually registered before each experiment (m_{p0}). Prepared samples were thereafter put into in the osmotic solution, preset at the desired temperature and kept submerged between two perforated stainless-steel circular plates. Heating and stirring (at about 120 rpm, using a polygon magnetic stirring bar with pivot ring, 50 mm × 8 mm) of osmotic medium was done with a modified digital hot plate stirrer equipped with an external proportional-integral controller (Arduino UNO board, Arduino, Turin, Italy), where brine temperature was directly acquired by an LM35 immersed sensor (linear output of 10 mV/°C) to maintain a precise temperature control (± 1 °C).

Experimental conditions were set up according to a 2 × 3 factorial design including the resulting combinations of brine concentration (0.10 and 0.25 g solute/g solution) and temperature (40, 60 and 80 °C) levels, respectively. All experiments were carried out in triplicate. A 15:1 solution-to-product mass ratio was used in all experiments to avoid a significant brine dilution (Herman-Lara et al., 2013). Samples were withdrawn from the solution (without replacement) at predefined immersion times (5, 10, 15, 20, 25, 30, 40, 50, 60, 80, 100, 120, 150, 180, 210 and 300 min), quickly rinsed with distilled water to remove the excess of solute adhered to the product surface, and gently blotted dry with a paper towel to remove adhering osmotic solution. Product was weighted (m_{pt}) and then a single transversal slice (perpendicular to the stipe axis) of about 1 mm-thick was cut with a sharp blade from the central part of the pilei to evaluate the SD behavior of the product. Digital images of resulting slices were immediately taken. Remaining product portions and fresh pilei were analyzed for their moisture content (Y_t and Y_0, respectively) by oven drying the samples (105 °C) until constant weight was attained (Molnár, 2006). Initial moisture content of product was 92.0 ± 1.2 g water/100 g product (mean ± s.d.).

In this study, the solids leaching out of the product during its processing were considered negligible. Average water loss ($\overline{W}$) and solute gain ($\overline{S}$) were calculated with the formulas:

$$\overline{W} = \frac{m_{p0}Y_0 - m_{pt}Y_t}{m_{p0}} \tag{1}$$

$$\overline{S} = \frac{m_{pt}(1 - Y_t) - m_{p0}(1 - Y_0)}{m_{p0}} \tag{2}$$

2.2. Image acquisition and shrinkage-deformation analysis

Sample slices and a black anodized metal washer (0.59 cm-diameter, used as a reference object to recover real product dimensions) were placed on a blue paper sheet to enhance contrast for background extraction. No special illumination was used as color standardization was not needed between images. A digital camera (Coolpix L810, Nikon Corp., Japan) was positioned with its sight line normal to product surface for taking the pictures (JPEG format, 4608 × 3456 pixels, focal distance of about 10 cm, automatic settings and macro mode). The schematic view of the experimental image acquisition setup is described in a previous study (Ortiz-García-Carrasco et al., 2015).

Color information obtained from pictures was transformed to CIELAB color space for its analysis. Background was eliminated and resulting image was transformed to gray-scale format to extract its product boundary coordinates (600 points) (Fig. 1). Relevant characteristics of product shrinkage and deformation at selected sampling times were obtained by combining product contours to produce a single shape (Fig. 2). As reported by Ortiz-García-Carrasco et al. (2015), contours were translated and aligned with respect to a reference point by minimizing the cumulative sum of the square of Euclidian distances between their coordinates. Cross-sectional area (A) and inner-to-outer radius ratio ($\rho_{\text{in}}/\rho_{\text{out}}$) were obtained for every sample. Cross-sectional area was further related to water loss or solute gain using the following model:

$$\frac{A}{A_0} = 1 - \frac{K(A_e/A_0)x}{1 + Kx} \tag{3}$$

where K and A_e/A_0 are adjustable parameters and x denotes either the average water loss ($\overline{W}$) or solute gain ($\overline{S}$). In addition, roundness was used as a shape factor capable of detecting the appearance of product deformation with these contours:

$$\phi = \frac{\text{cross-sectional area of product}}{\text{area of the minimum circle enclosing product contour}} \tag{4}$$

2.3. Model development

The unsteady state diffusion equation within a homogeneous and isotropic material is very often used to describe the mass transfer of the specie j ($j = 1, \ldots, n$) between disperse and continuous phases in an OD process and was applied in this study (Pacheco-Angulo et al., 2016; de Farias Aires et al., 2016; da Silva Júnior et al., 2017; Pinheiro et al., 2017). The mass transfer model was developed under the following assumptions: (i) product shape can be approximated by a hemispherical shell geometry with mass transfer occurring in radial and azimuthal directions; (ii) water and solute are the only diffusing substances ($j = s, w$); (iii) diffusion coefficients do not change during process (diffusivities are not described as a function of time, space, water loss or solute gain during model solution); (iv) negligible external resistance to mass transfer at product surface because of the stirred system (Dirichlet or first-type boundary condition); (v) uniform distribution of diffusing