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Effect of shape change and initial geometry on water diffusivity estimation during drying of gel model systems

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ABSTRACT

The mathematical modeling of simultaneous shrinkage and shape change (deformation) during drying of gel model systems (GMS) was investigated. Developed theory was applied to estimate water diffusivities during drying of GMS (70 °C, air velocity of 2 m/s) shaped as square prisms (9.53 mm × 9.53 mm × 80 mm) and longitudinal sections (quarters and halves) of cylinders (12.7 mm diameter × 140 mm length) by considering the product shrinkage with and without deformation. The contours of transversal product slices, obtained from digital images, were averaged to extract relevant characteristics of the dried samples, whereas compactness and roundness were used to evaluate product deformation. Experimental shape patterns were used to estimate the initial and final mesh matching the real product geometry during simulation via a new algorithm. The obtained results demonstrate that although shrinkage occurs from the beginning of drying, changes in product shape are noticeable only after the free moisture fraction is below 0.3. Water diffusivities estimated considering the shape change of product were in the narrow range of 3.37 -3.58×10^{-10} m^2/s for studied geometries, and are overestimated in about 6–12% when this phenomenon is not included in drying model. No significant differences were observed in water diffusivity values between studied geometries ($p > 0.05$).

1. Introduction

Drying of food products is a complex process involving simultaneous momentum, mass and energy transport throughout a system undergoing multiple changes in both structure and composition characteristics; however, changes in product dimensions (shrinkage) and shape are the more readily apparent. Shrinkage and deformation (SD) characteristics are useful for explaining the structural properties dynamics in products during drying (Mayor and Sereno, 2004; Goplour et al., 2016; Udomkun et al., 2016). These phenomena are governed by several mechanisms such as glass transition, pore pressure and mechanical strength of food matrix (Kurozawa et al., 2012). It is well recognized that structural changes affect the food quality by modifying its rehydration capacity and/or sensory properties that influence and determine palatability, consumer acceptance and marketability. Furthermore, these structural changes have direct impact on food drying characteristics and the resulting drying time (Defraeye, 2014). In several studies negligible shrinkage of food products is considered to simplify calculations; nevertheless, this practice should be avoided because it may lead to poor reproduction of experimental data and unreliable estimation of moisture diffusivity (Hashemi et al., 2009). Moreover, product deformation has a significant effect in the estimation of mass transfer properties (Pacheco-Aguirre et al., 2015). Thus, appraisal and modeling of SD behavior during drying of food products remain an active topic (Janjai et al., 2010; Mrad et al., 2012; Aregawi et al., 2014; Karunasena et al., 2015; Pacheco-Aguirre et al., 2015; Md Salim et al., 2016; Udomkun et al., 2016).

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Selection of an appropriate shape to represent the product is essential to accurately correlate predicted moisture profiles with possible product damage during food drying. For example, Prakash and Pan (2012) demonstrated that simulated moisture gradients in rice kernels represented by an ellipsoid geometry enable to explain grain fissuring, as opposed to moisture distribution generated with mathematical models based on sphere and spheroid shapes. Moreover, a drying model describing changes in product geometry would be more helpful for accurately indentifying the development of possible quality problems than one ignoring them (Pacheco-Aguirre et al., 2015).

Biopolymer gels are sometimes used as model systems because they are structurally and mechanically similar to many gel-like food products such as meats, cheese, gelatin desserts, frankfurters, yogurt, among others (Czerner et al., 2016). Moreover, they represent a convenient way to avoid the inherent variability of raw materials in characteristics such as composition and texture, thus allowing the study of relevant features such as shrinkage and shape change in controlled scenarios (Waje et al., 2005; Adamski et al., 2014).

The objective of this work was to study the shrinkage-deformation (SD) behavior of products by using gel systems as food models. GMS were shaped in three different geometries (square prisms, cylinders quarters and cylinder halves) and dried, characterizing their geometrical changes by image analysis techniques. This information was further used to appraise the impact of initial product geometry on water diffusivity estimation.

2. Methods and materials

2.1. Drying experiments

Gel model systems (GMS) were prepared by dissolving 5% (w/w) agar-agar (MCD Lab., México) and 20% (w/w) sucrose in distilled water. The solutions were homogenized under mild stirring for 15 min at 50 °C. Final heating of agar solution was carried out using a pressure cooker for 15 min (121 °C). The hot solution was then poured into molds, allowed to cool at room temperature, cut in the desired geometries: square prisms (9.53 mm × 9.53 mm × 80 mm) and longitudinal sections of cylinders (12.7 mm diameter × 140 mm length; halves and quarters) and further dried the same day. Drying experiments were conducted with 25 samples placed flat on a stainless steel welded mesh open tray (dimensions: 25 cm × 20 cm, openings: 0.45 cm × 0.50 cm, wire diameter: 0.07 cm) in a tunnel dryer (Armfield UOP8, Ringwood, UK) with airflow parallel to the longest product dimension. All geometries were dried at 70 °C for about 380–500 min with an air velocity of 2 m/s (relative humidity = 5%). Air velocity and product dimensions were chosen to allow: (1) a diffusion-controlled process (negligible external resistance to mass transfer) according to the analysis presented by Pavón-Melendez et al. (2002) and (2) two-dimensional mass transfer with shrinkage occurring almost exclusively along the minor dimensions of product. The use of a high air velocity also favors the assumption of constant air properties.

Two sets of air-drying experiments were conducted to obtain the SD behavior of GMS as a function of their moisture contents. Drying curves were obtained in the first experiment set, where moisture evolution was calculated by continuously recording the product weight throughout the process. The sampling times when a specific moisture fraction is reached in product ($\Psi = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8$ and 0.9) were calculated by interpolation from these drying curves. In the second experiment set, groups of 5 samples each were dried for a predefined sampling time (estimated during the first experiment set). Thereafter, a single transversal slice (perpendicular to the largest dimension) of about 1 mm-thick was cut with a sharp blade from the central part of the sample and digital images of the resulting slices were immediately acquired. Remaining product portions were analyzed for their moisture content. The aforesaid procedure was also applied to fresh ($\Psi = 1$) and equilibrium-dried ($\Psi = 0$) samples. A total of eleven 5-samples groups (55 specimens) were analyzed in this way to evaluate changes in product shape along drying for each geometry.

Required moisture contents were determined by oven-drying (Binder ED 53, Germany) samples at 105 °C until constant weight. Initial moisture content of product was 72.69 ± 2.02 g water/100 g product (mean ± s.d.).

2.2. Image acquisition and analysis

Sample slices were placed on a blue paper sheet to enhance contrast for background extraction. A black anodized metal washer (0.59 cm-diameter) was used as a reference object in order to recover real product dimensions. 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. A focal distance of about 10 cm, automatic settings and macro mode were used for taking the pictures. Digital images were stored in JPEG format at the maximum resolution available (4608 × 3456 pixels). 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 their analysis. Background extraction was performed by quantizing color data into 3 dominant color descriptors using the *k*-means clustering algorithm (Press et al., 2007) and further applying a foreground mask to the resulting image. Quantized image without background was transformed to gray-scale format and product boundary coordinates (400 points) were obtained from the latter. Cross-sectional area and perimeter were obtained for every sample. All image analysis operations were performed with the Matlab Image Processing Toolbox 7.0 (Matlab R2010a, MathWorks Inc., Natick, MA, USA).

2.3. Deformation behavior

Relevant characteristics of product deformation at sampled moisture contents were obtained by combining product contours to produce a single shape (Fig. 1). 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. Roundness and compactness (or isoperimetric quotient) were used as shape factors (Du and Sun, 2004) capable of detecting the appearance of product deformation with these contours:

$$\rho = \frac{\text{cross} - \text{sectional area of product}}{\text{area of the minimum circle enclosing product contour}} = \frac{A}{A_c} \tag{1}$$

$$C = \frac{\text{cross} - \text{sectional area of product}}{\text{area of a circle having the same perimeter as product}} = \frac{4\pi A}{P^2} \tag{2}$$