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Water vapor transport properties during staling of bread crumb and crust as affected by heating rate

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ABSTRACT

In order to develop a mathematical model to simulate mass transfer occurring between the crumb and the crust during bread staling, water vapor sorption properties, i.e., moisture diffusivity, WVP and sorption of bread crumb and crust were investigated at 15 °C. Two types of bread baked with two heating rates (7.39 °C/min and 6.32 °C/min) were considered. Sorption and desorption isotherms were determined using Dynamic Vapor Sorption (DVS) and FF and GAB models were applied in the range of 0–0.95 a_w, to fit isotherm curves. Diffusivity was determined from sorption isotherms by using Fick's law and WVP was measured by two methods (gravimetric and from sorption data). Results exhibited maximum values of D_{eff} in the range of 0.1 and 0.14 g/g d.b. moisture contents. They varied between 0.88×10^{-10} and 0.92×10^{-10} m^2/s for the crust and between 2.24×10^{-10} and 2.64×10^{-10} m^2/s for the crumb, baked respectively at 220 °C and 240 °C. Results of WVP showed that the crust baked at 240 °C was significantly more permeable than the crust baked at 220 °C. This fact was attributed to the difference in porosity and the molecular structure due to heating effects. Also, the presence of steam in the oven atmosphere enhanced the development of higher porosity in the crust, leading to different structures and properties. Moreover, SEM images showed that starch granules were intact and less swelled in the upper crust when baking at 240 °C, resulting in higher WVP.

1. Introduction

One of the most important physical phenomena occurring in foods during staling is water transfer, leading to a loss of the texture and organoleptic properties of bread and resulting in a dehydration of the material and the deterioration of its quality. Moisture migration occurs by diffusion of water in the solid matrix and water vapor through the void spaces. In the macromolecular scale, water diffuses from the crumb to the crust and vaporizes to the ambiance due to a difference in partial vapor pressure. Knowledge of water vapor transfer properties (moisture diffusivity, sorption and water vapor permeability (WVP)) of bread crumb and crust is of great importance to understand and to control the phenomenon of staling.

Many factors affect these properties, namely the degree of crystallinity (Mali, Grossmann, Garcia, Martino, & Zaritzky, 2006), the thickness of the material (Bertuzzi, Castro Vidaurre, Armada, & Gottifredi, 2007), the respective content of amylose and amylopectin (Phan, Debeaufort, Luu, & Voilley, 2005; Rindlav-Westling, Stading, Hermansson, & Gatenholm, 1998) and conditions of storage (temperature and relative humidity) (McHugh, Avena-Bustillos, & Krochta, 1993).

Also, as reported by Daniels and Fisher (1976), Hoseney (1986) and Junge and Hoseney (1981), transfer properties can be affected by porosity and formulation. Other factors like the temperature of processing and the bread making process are recently investigated. Angellier-Coussy, Gastaldi, Gontard, and Guillard (2011) studied the influence of processing temperature on the water vapor transport properties of wheat gluten based films. Altamirano-Fortoul, Le-Bail, Chevallier, and Rosell (2011) found that WVP of the bread crust significantly decreased when increasing the amount of steam applied during baking. But, no research has been done in order to study the effect of baking conditions on water vapor transfer.

To describe moisture diffusivity, many predictive models based on Fick's second law have been used. Solutions of this second law are of two types: analytical and numerical (Crank, 1975), adapted for different geometries and boundary conditions. Determination of the effective moisture diffusion coefficient (D_{eff}) is commonly obtained from kinetic data from three processes: drying, sorption and permeation, but the most used is sorption experiments performed with DVS instrument. It is identified by adjusting calculated moisture content values to experimental data, using an analytical solution of Fick's second law. Many studies have been carried out to investigate the diffusivity in cereal-based products (Guillard, Broyart, Bonazzi, Guilbert, & Gontard,

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2003a; Roca, Guillard, Broyart, Guilbert, & Gontard, 2008; Tong & Lund, 1990). These authors have developed other models relating variations of D_{eff} with moisture content. However, there is a little information available on diffusivity in bread crust; Meinders and van Vliet (2009) have studied models of bread crust, i.e. protein rich model bread crust, but not the real bread crust.

Concerning WVP, some authors used Fick's first law and Henry's law to calculate the permeability of porous food materials such as biscuit and sponge cake during storage (Guillard et al., 2003a), and assumed that the solubility and diffusivity of the food are constant. Others modeled transfer of gazes in porous materials using Darcy's law. The applicability of this last law requires the uniformity of the porous structure; so a less uniform sample would require larger sample size to make measurements reliable (Goedeken & Tong, 1993).

The purpose of this research was to investigate the effect of heating rates on the water vapor transport properties, i.e., diffusivity, sorption and WVP of the bread crumb and crust. The results of this study should be useful to model water migration in bread during staling, at the macromolecular scale from the crumb to the crust.

2. Materials and methods

2.1. Pan bread preparation

Wheat flour was delivered by Girardeau (Boussay, France). Obtained from a mixture of varieties of soft and malted flour, it had the following characteristics: 15.5% (d.b.) moisture content, 11% (d.b.) protein content, 0.62%–0.75% (d.b.) ash content and 280 s Hagberg falling. Alveograph parameters were: W 210–220 and P/L = 1. The basic dough recipe of pan bread contained 2000 g of wheat flour, 1240 g of water, 40 g of salt (Esco, Levallois Perret, France S.A.), 40 g of dry milk powder (Régilait, France), 40 g of sugar (Béghin Say, France), 40 g of sunflower oil (TransGourmet-Senia 524-Orly, France), 80 g of compressed yeast (l'Hirondelle, France), and 0.2 g of ascorbic acid. All ingredients were mixed in a spiral mixer (VMI SP10, Montaigu, France) for 4 min at low speed (100 rpm/min), followed by 8 min at high speed (200 rpm/min). Water and yeast were added firstly, followed by the rest of ingredients. After mixing, dough temperature was 25 °C ± 1.6. Dough pieces of 770 g each were rested for 15 min before being divided and molded manually. Then, dough pieces were rolled mechanically in MB230 molder and placed in molds (10 cm × 10 cm × 27 cm) made with Tefal. Proofing was carried out in a fermentation cabinet (ARG68, France) at 35 °C, 95% RH during 70 min.

When fermentation was achieved, the molds were put in an electrical deck oven (MIWE CO 1.1208, Germany) equipped with a stone hearth (1.02 m^2) to be baked at 220 °C and 240 °C during 25 min. The steam injection was adjusted at 300 mL which correspond to 0.99 L/m^3 and was done at the beginning of baking. K type thermocouples, related to a data logger (SA 32-AOIP-France), were introduced in three locations to measure the central temperature of the dough. From the temperature profile obtained for each baking condition, heating rate can be deduced. It was calculated in the linear region of rapidly increasing temperature between 40 and 90 °C so that, breads baked at 240 °C had the highest heating rate (7.39 °C/min) while breads baked at 220 °C had the lowest heating rate (6.32 °C/min). In addition, a baking plateau was observed at 98 °C about 2 min for the internal thermal profile of breads baked at 240 °C.

The breads were withdrawn from the oven, turned out of the pan and placed in a controlled chamber (25 °C, 70% RH) to cool down during 2 h. Crumb samples used for sorption measurements were taken from the center of the bread and crust samples were extracted from the upper crust of each bread baked at each temperature. However, for permeability experiments, the three parts of the crust surrounding the crumb were used: the upper, the lateral and the bottom crust noted as 'TC', 'SC' and 'BC' respectively.

2.2. Sorption isotherms

Dynamic gravimetric vapor sorption (DVS Advantage, Surface Measurement Systems Ltd., London, UK) is used for the determination of vapor sorption isotherms. Cylindrical samples of crumb (5 mm of diameter and 21.5 ± 0.3 mm of length) were taken from the center of pan bread and placed into a diffusion cell to allow unidirectional diffusion. For the crust, a small section (1 cm^2) of samples (1.92 ± 0.06 mm of thickness) was used. Samples were then equilibrated at successive levels of relative humidity: from 0 to 80% RH with steps of 10% RH and of 5% from 80 to 95% RH. An addition step was added 93% RH. The steps automatically changed when the variation in sample mass was lower than 0.002%/min. Isotherms were determined at 15 °C ± 0.4 °C and performed at least twice. Water sorption isotherms are modeled using GAB (Guggenheim, Anderson and De Boer) and FF (Ferro Fontan) equations (Ferro Fontan, Chirife, Sancho, & Iglesias, 1982; Guillard, Broyart, Bonazzi, Guilbert, & Gontard, 2003b; Iglesias & Chirife, 1995) in the range of water activity 0–0.95. The GAB equation is as followed,

$$\frac{X}{X_m} = \frac{C_G K a_w}{(1-Ka_w)(1+(C_G-1)Ka_w)}. \tag{1}$$

Where X is the moisture content of the material on dry basis (g/g d.b.), C_G is the Guggenheim constant related to heat of sorption of the first layer, a_w the water activity, K is the constant related to multilayer molecule properties, in other words to the heat of sorption of the multilayer and X_m is the moisture content of monolayer (g/g d.b.).

However, the FF model is given by Eq. (2):

$$X = \left[\frac{1}{a}\ln\left(\frac{\gamma}{a_w}\right)\right]^{-\frac{1}{\gamma}}. \tag{2}$$

Where α is a constant, γ is the parameter which accounts for the structure of sorbed water and r is a constant which entails net isosteric heat with moisture content.

The two models were simulated using Matlab software 7.5.0.342 (R2007b) and parameters were identified using the Lsqcurvefit method implemented in the optimization toolbox. The root mean square error (*RMSE*) was used to estimate the quality of model fitting and was calculated as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(y_{\exp_i} - y_i\right)^2}{(N-p)}}. \tag{3}$$

Where $y_{\exp_i}$ and y_i are respectively the experimental and predicted moisture content values (g/g d.b.), N is the number of moisture content measurements and p is the number of estimated model parameters.

2.3. Effective moisture diffusivity

The effective moisture diffusivity values at 15 °C in the crumb and the crust were determined from transient state moisture contents (m in g/g d.b.) of the sorption kinetic and by minimizing the sum of squares of errors between experimental data obtained from moisture sorption kinetics in a controlled atmosphere microbalance (DVS) and calculated data using an analytical solution of Fick's second law, as described by Roca, Broyart, Guillard, Guilbert, and Gontard (2007) and Roca et al. (2008) and specific boundary conditions. From each step-functionally changed RH level, one diffusivity value was determined.