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Modelling of moisture diffusion in pores of banana foam mat using a 2-D stochastic pore network: Determination of moisture diffusion coefficient during adsorption process

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ABSTRACT

The purpose of this research was to determine the diffusion coefficient of moisture in the pores of banana foam mat using stochastic pore network. A 2-D pore network was used to represent the pore voids inside the banana foam sample and the moisture movement inside the individual pore segments was described by Fick's law. To determine the moisture diffusion coefficient, the adsorption experiments were carried out with standard static method using saturated salt solutions. Two banana foam densities of 0.21 and 0.26 g/cm^3 were used to adsorb the water vapour. The interactions between moisture and pore structure were illustrated using a 3-D pictorial representation of network concentration gradients in spaces with colour representing the moisture content. The network model described the experimental results relatively well. The diffusion coefficient of moisture in pores was in order of 10^{-9} m^2/s which was nine times higher than the effective diffusion coefficient calculated from the continuum model. The value of moisture diffusion coefficient was dependent on the temperature and independent of the foam densities and the relative humidity, except for the diffusivity determined from the condition at higher relative humidity of 70%.

1. Introduction

Moisture migration during storage is of great importance to food quality, in particular for dried crispy products such as biscuits, ready-to-eat cereals and snacks. An increase in the product moisture content, which in turn leads to the loss of crispness, generally occurs by migration of water vapor from the ambient into the product. The rate of moisture adsorption into porous food is governed by the environmental conditions, i.e., temperature and relative humidity. The rate also relies upon the porous structure of the food (Guillard et al., 2003; Roca et al., 2006). Therefore, an ability to model water migration in porous food is of great interest. To date, two different approaches have been developed for studying moisture movement in porous foods.

The first modeling is based on a continuum model. In this type of model, porous spaces are considered as a continuum, consistent with its appearance on the macroscopic scale. In this case, the effective moisture diffusivity includes in itself all microscopic complexities of the porous structure (e.g., sizes of pores and their connectedness) as well as mechanisms of mass transfer, which may occur by molecular diffusion or capillary flow, etc. (Efremov and Kudra, 2004; Roca et al., 2006). When a dried porous food is subject to humid air, water vapor transports from the air to the sample surface and is then assumed to diffuse into the internal area of the sample via the pores by assuming that the solid act as an impermeable surface. This adsorption phenomenon is described by the Fick's second law of diffusion. Under isothermal condition, moisture transport in a porous food with an infinite slab geometry (Chen, 2007) can be described by:

$$\frac{\partial M}{\partial t} = \nabla(D_{eff} \nabla M) \tag{1}$$

where M is the moisture content (kg/kg d.b.), t the time (s), D_{eff} the effective moisture diffusivity (m^2/s), which can be expressed by:

$$D_{eff} = \frac{\varepsilon D_p}{\tau} \tag{2}$$

where ε is the porosity of the material (dimensionless), D_p the actual diffusivity in the pore voids (m^2/s) and τ the tortuosity factor (dimensionless). Tortuosity factor accounts for the fact that the pore

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spaces do not provide straight line paths through, thereby lengthening the diffusive path and reducing the internal diffusional fluxes.

The second approach is based on the discrete model or pore network model. In this type of model, the pore sizes and topology of a porous material are taken into account by mapping them onto an equivalent network of the interconnected pores. Network models represent void spaces of a porous medium by a simple two- or more realistic three-dimensional lattice in which large and small pores are randomly interconnected. Each pore can be assumed to be cylindrical, slit, triangular and polygonal shapes. Segura and Toledo (2005) found that pore shapes used in the network model had an insignificant effect on the drying characteristic curves, vapour relative diffusivity, and liquid relative permeability. The pore network model is more useful and flexible than the first approach since the moisture calculation using continuum model requires use of the effective moisture diffusivity, which varies from material to material, whilst the pore network model requires only the structural parameters of the material such as total pore volume or pore size distribution (providing that the actual moisture diffusivity in the pore voids is known). However, at present, there is no available information on the actual diffusion coefficient of moisture in pore voids, D_p. To be able to estimate the actual diffusion coefficient, first the pore network model needs to be constructed, where more or less simplified geometries, and pore size distributions are used to describe the topology of the pore structure of a real material (Mann, 1993; Hollewand and Gladden, 1992; Androutsopoulos and Mann, 1979). Diffusion equation is then applied to an individual pore of the network; the flow of substances through pore segments can then be numerically predicted (Blunt, 2001; Yiotis et al., 2005; Prachayawarakorn et al., 2008) and compared with the experimental results. Although, theoretically, either experimental data on desorption (or drying) or adsorption could be used to calculate the moisture diffusivity in the pore voids, the adsorption experiment is preferred since the transfer rate of heat is usually faster than the transport rate of moisture and hence the temperature of the porous material remains close to the temperature of the experiment. Also, the morphology of porous food changes only slightly during adsorption experiment whilst it significantly changes during drying (Saravacos and Maroulis, 2001).

As the data on the moisture diffusivity in the pore voids of any porous food are not available, the aim of the present investigation was to determine the pore diffusivity by using a two-dimensional stochastic pore network. Banana foam mat was used as a representative porous medium. The Fick's second law was used to describe the moisture diffusion in individual pore segments and an optimization technique was implemented to determine the pore diffusivity under adsorption conditions. The actual moisture diffusion coefficient in pore voids obtained in this work may be applied to other porous foods as well.

2. Materials and methods

2.1. Dried banana foam preparation

The banana puree with 5% of fresh egg albumen used as foaming agent was foamed to densities of 0.3 and 0.5 g/cm^3. The selected foam densities were suitable to produce the snack since its texture provided the low hardness and crispiness as reported by Thuwapanichayanan et al. (2008a,b).

The density was determined by measuring the mass of a fixed volume of the prepared foam. The banana foam was poured slowly into a steel block with a dimension of $43 \times 43 \times 4$ mm^3 and then placed on a mesh tray, which was covered with aluminium foil. After that, it was dried to about 3% dry basis (d.b.) at a temperature of 80 °C and a 0.5 m/s superficial air velocity. The banana foam prepared from the initial foam densities of 0.3 and 0.5 g/cm^3 can produce the dried banana densities of 0.21 ± 0.02 and 0.26 ± 0.02 g/cm^3, respectively. The product thicknesses after drying were 2.8 mm and 3.2 mm for the densities of 0.21 and 0.26 g/cm^3, respectively.

2.2. Adsorption experiment

Moisture adsorption experiments were carried out using the static method. Samples were placed into the glass jars contained the saturated salt solutions ($MgCl_2 \cdot 6H_2O$, $Mg(NO_3)_2 \cdot 6H_2O$, KI, NaCl and KCl) which provided the relative humidity (RH) in range of 32–82% at the temperatures of 35, 40 and 45 °C. The glass jars were kept in the hot air oven that controlled the temperature with an accuracy of ±1 °C (UFE500, Memmert, Germany). Samples were weighed at different exposure times ranging from 1 to 120 h. At RH > 74%, a small amount of toluene held in a vial was fixed in the glass jars in order to prevent microbial spoilage of the samples (Kaya and Kahyaoglu, 2005). Moisture content of each sample after reaching the equilibrium condition was determined by drying it with the hot air oven at a temperature of 103 °C for 3 h. Under this moisture content determination condition, the percentage error was approximately 0.4% when compared to the result obtained by the standard vacuum method (AOAC, 1995) at a temperature of 70 °C and at a negative pressure of 13.3 kPa for 24 h. This error might be caused by the vaporization of volatile compounds. Thuwapanichayanan (2007) reported that the loss of volatile compounds after drying of banana foam was approximately 90%. The experiment at each sorption condition was repeated three times and the mean value was reported.

2.3. SEM photograph

The morphologies of dried banana foam mats were characterized using scanning electron microscope (SEM) with an accelerating voltage of 10 kV. Before photographing, the specimens were cut into a dimension of 5×5 mm^2 and then glued on the metal stub. The samples were coated with gold, scanned, and photographed at 15× magnification.

To quantify the porous banana foam characteristics such as pore diameter and pore area, Image J software was used. Each pixel of the SEM micrograph was assigned a value of gray intensity between 0 and 255 and the binary images were generated. The pixels with gray levels lower than the selected threshold were assigned as pore, which appeared as black colour, and the pixels with gray levels above the selected threshold were set as solid phase, which appeared as white colour in binary image. The pore diameter was estimated from the known pore area by counting the number of pixels filled in the specified space.

2.4. Estimation of activation energy

The diffusion coefficient of moisture was related with the temperature through the following Arrhenius equation:

$$D_p = D_0 \exp\left(\frac{-E_a}{RT}\right) \quad (3)$$

where D_0 is the constant value (m^2/s), E_a is the activation energy (kJ/mol), R is the universal gas constant and T is the temperature (K). In this work, the pore diffusivity data obtained from the experimental conditions at the relative humidity below 70% and at the temperatures of 35–45 °C were used to determine the values of E_a and D_0. Under the specified conditions, the moisture content of banana foam ranged between 0.038 and 0.37 kg/kg d.b.