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Anisotropic diffusion during osmotic dehydration of celery stalks in salt solution

M. Sareban, B. Abbasi Souraki*

Chemical Engineering Department, Faculty of Engineering, University of Guilan, Rasht, Iran

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ABSTRACT

In this study, mass transfer during osmotic dehydration of bulk of celery stalks in NaCl salt solution was investigated. Experiments were carried out in the three initial solution concentrations of 10%, 18% and 25% (w/w) and at the three temperatures of 35 °C, 45 °C and 55 °C. The fruit to solution volume ratios were considered 1:3. Due to the asymmetric structure of the celery stalks, two different geometries of cylindrical and cubical were considered for mathematical modeling of the dehydration process. A two-parameter model was used to evaluate the equilibrium values of moisture loss and solute gain by the samples. Water and salt effective diffusivities were obtained using the first six terms of the series solution of analytical solution of Fick's second law in the cubical and cylindrical geometries. Two different groups of celery stalks were used for estimation of moisture and salt effective diffusivities in different directions. Predictions of the mathematical model in both geometries were in agreement with the experimental data. The water and salt effective diffusivities in z direction (ranged from 0.972×10^{-9} to 3.663×10^{-9} (m^2/s)), were always much higher than those in x, y and r directions (ranged from 1.031×10^{-10} to 6.919×10^{-10} (m^2/s)). The values of water and salt effective diffusivities in z direction were close to each other in both geometries. The water and salt effective diffusivities were increased with increasing the initial solution concentrations and temperatures.

1. Introduction

Osmotic dehydration is widely used for partial removal of water from plant tissues by immersion in a hypertonic (osmotic) solution. The difference between the osmotic pressure in the material and solution gives rise to simultaneous counter-current water diffusion from the food to the solution and solute diffusion into the food. Osmotic dehydration has many advantages such as: improving the organoleptic food properties such as color, flavor, or aroma and texture; increasing the product storage time; energy saving compared to other drying techniques; simple process equipment and reducing the processing time due to the absence of phase change. This process is considered to be as a pre-process for conventional drying systems (Lewicki and Lenart, 2015).

The rate of mass transfer in osmotic dehydration is affected by concentration and temperature of the osmotic solution (Herman Lara et al., 2013; Rastogi and Raghavarao, 1994, 1997), agitation (Mavroudis et al., 1998), food to osmotic solution volume ratio (Da Conceicao Silva et al., 2012), food structure (porosity, etc.), shape and size (Ruiz Lopez et al., 2010; Sirousazar et al., 2009; Van Nieuwenhuijzen et al., 2001), nature and molecular weight of the osmotic solute (Lenart and Flink, 1984; Tsamoa et al., 2005) and pressure (Fito, 1994; Rastogi and Niranjan, 1998; Rastogi and Raghavarao, 1996). Fickian diffusion model is usually used for modeling of mass transfer during drying and osmotic dehydration of solids. In some researches, the dehydration process was carried out in high solution to material volume ratio in one dimensional (Abbasi-Souraki et al., 2012, 2013a,b) and multidimensional systems

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* *Corresponding author*. Tel.: +98 1316690485; fax: +98 1316690271.
E-mail addresses: sarebanmli@gmail.com (M. Sareban), b.abbasy@gmail.com, b.abbasi@guilan.ac.ir (B. Abbasi Souraki).

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Nomenclature

A_s	the sample area at $r = R$
C	concentration in solid (celery stalk) (g/cm^3)
C^l	concentration in solution (g/cm^3)
D_{er}	effective diffusivity in r direction (m^2/s)
D_{ex}	effective diffusivity in x direction (m^2/s)
D_{ey}	effective diffusivity in y direction (m^2/s)
D_{ez}	effective diffusivity in z direction (m^2/s)
J_0	Bessel function of the first kind order 0
J_1	Bessel function of the first kind order 1
K	partition factor
l	half of the thickness in x direction (m)
M	total amount of solute (moisture or salt) in celery stalk
N	number of samples
q_n	non-zero positive roots of Eqs. (8) for slab and (9) for cylinder
r,R	half of the thickness in r direction (m)
s	half of the thickness in z direction (m)
S	weight of solids in the fruit (g)
S_1	a constant related with solid gain (h^{-1})
S_2	a constant related with water loss (h^{-1})
SG	solid gain (g/100 g fresh fruit)
t	time (s or h)
T	temperature (°C)
V_s	volume of solid (celery stalk) (cm^3)
V_l	volume of solution (cm^3)
w	half of the thickness in y direction (m)
W	weight of fruit (g)
WL	water loss (g/100 g fresh fruit)

Subscripts

0	initial value
e	equilibrium
l	solution
s	solid (celery or salt)
t	at time t
w	water

Greek letters

α	a parameter related to Eqs. (13) and (15)
φ	predicted dimensionless concentration
∞	at time ∞ (equilibrium)

(Abbasi-Souraki and Mowla, 2008; Da Silva et al., 2014; Ruiz Lopez et al., 2010). Some researches were also carried out in low solution to material volume ratio and thus varying solution concentration in one dimensional (Singh et al., 2007; Telis et al., 2003) and multidimensional systems (Khin et al., 2006; Ruiz Lopez et al., 2010). Solutions of the Fickian diffusion equation with different boundary conditions have been developed, comprehensively, by Crank (1975).

In some agricultural products, internal textures could be different from the longitudinal direction compared with the lateral direction of growth (Fernando et al., 2011), and considering the same properties for all directions of the product (isotropic structure), could potentially lead to misleading predictions. In this regard, different methods have been used by various authors for taking into account the anisotropic nature of the food products. Rossello et al. (1997) and Abbasi-Souraki and Mowla (2008) studied the drying behavior of cylindrical green beans. In their research, the anisotropic structure of green bean samples has been taken account, by defining different diffusivities in the radial and axial directions. Fernando et al. (2011) estimated the axial and radial moisture diffusivities of anisotropic banana, cassava and pumpkin by using the drying curves of samples with different thicknesses. Zhang et al. (2011) calculated the salt diffusivities, in x and y directions, for anisotropic grass carp muscles by measuring the salt content of muscles in different points. Pacheco Aguirre et al. (2014) estimated the axial, radial and angular effective diffusivities of anisotropic cylindrical carrot samples. At first, the axial and radial diffusivities were obtained using the effect of increasing the length of samples on the drying curves, and then the angular diffusivity was obtained using the drying curves of samples with equal length and different cut angles.

The objectives of this research were to study the dehydration behavior of celery stalks during osmotic dehydration in salt solution and developing a mathematical model for explaining the anisotropic mass transfer in this foodstuff during dehydration. Experiments were carried out by dehydration of different cuts of celery stalks in salt solutions of different concentrations and temperatures in a batch osmo-reactor. Due to the asymmetric structure of the celery stalks, two types of geometries, cylindrical and cubical, were considered for mathematical modeling of the dehydration process. By fitting the experimental data to the models, effective diffusivities in different directions were estimated.

2. Materials and methods

2.1. *Materials*

In this work, fresh and green celery from Rasht, situated in the north of Iran, was used as raw material. Celeries were purchased from the same supplier to maximize reproducibility of results. Because of homogeneity of the samples, care was taken when selecting the samples, to take celeries with approximately the same shape, color and degree of ripening. Ends and leafy tops of bunches of celeries were removed and only the middle portions, were used to produce the required samples. Then celeries were kept in a plastic container in a refrigerator at 4 °C for more than 24 h to equilibrate the moisture content. They were removed from the refrigerator and left to equilibrate at room temperature. Then, they were further cut into slices with the dimensions shown in Figs. 1 and 2.

Due to the asymmetric structure of the celery stalks, cubical and cylindrical geometries were selected for mathematical modeling of mass transfer during osmotic dehydration. In order to estimation of effective diffusivities in x and y directions in the cubical geometry or in r direction in the cylindrical geometry, some 3 ± 0.2 cm long samples were prepared and the end surfaces were prevented from the solution contact using a silicone film (Fig. 1). Also, some 2 ± 0.2 cm long samples were prepared without closing their end surfaces (Fig. 2) using a micrometer with an accuracy of ±0.02 mm.

For cubical geometry, the dimension of the samples in x direction was measured 1.1 ± 0.3 cm by taking the average of lengths in five points, as shown in Fig. 1a. The dimension of samples in y direction in the cubical geometry and in r direction in the cylindrical geometry were evaluated 2.8 and 0.99 cm, respectively, by immersion of some samples in acetone and measuring the volume of the samples using the volume displacement method. Some measured physical