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Correction of moisture and sucrose effective diffusivities for shrinkage during osmotic dehydration of apple in sucrose solution

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ABSTRACT

Shrinkage, moisture and sucrose effective diffusivities were correlated for infinite slab shape samples of apple during osmotic dehydration in sucrose solution. Experiments were carried out in the sucrose solutions of different concentrations (30%, 40% and 50%) and temperatures (30 °C, 40 °C and 50 °C). The two parameter model, developed by Azuara et al. (1992), was used to predict water loss and solid gain at equilibrium condition. Moisture and sucrose diffusivities were estimated by fitting the experimental moisture loss and solid gain data to the modified form of Fick's second law of diffusion, considering the shrinkage of the apples during osmotic dehydration. Results showed that the volume of the samples decreased linearly with water loss (WL) and weight reduction (WR). For above conditions of osmotic dehydration, effective diffusivities without considering the shrinkage were found to be in the range of 1.36×10^{-10} m^2/s–2.00×10^{-10} m^2/s, and those with considering the shrinkage were in the range of 0.87×10^{-10} m^2/s–1.27×10^{-10} m^2/s. The values of the effective diffusivities estimated by considering the shrinkage were smaller than those without considering this phenomenon.

Keywords: Osmotic dehydration; Shrinkage; Effective diffusivities; Apple; Diffusion; Mass transfer

1. Introduction

Osmotic dehydration is used for the partial removal of water from fruits and vegetables by immersion in a hypertonic solution. For fruits, sugar solutions, with or without the addition of small quantities of salt, and for vegetables solutions of salts are mainly used (Brennan, 1994). The difference of the chemical potential between the material and the solution gives rise to simultaneous counter-current water diffusion from the food to the solution and solute diffusion into the food. The rate of diffusion of water from the foodstuff depends upon factors such as: temperature and concentration of the osmotic solution, the size and geometry of the material, the solution-to-material mass ratio and the rate of agitation of the solution (Rastogi et al., 2002).

Foodstuffs are known to undergo volumetric changes upon water loss which are expressed as shrinkage. This phenomenon is usually quantified by the ratio of the volume of the sample after, to the volume before drying, as a function of moisture content, weight reduction (WR), or water loss (WL). The shrinkage phenomenon affects in particular the diffusion coefficient of the material, which is one of the main parameters governing the drying process; it also has an influence on the drying rate (Senadeera et al., 2000; Senadeera et al., 2003).

Although numerous studies have been performed on the modeling of drying behavior and estimation of effective diffusivity of materials by consideration of the shrinkage in air, freeze or vacuum drying (Arevalo-Pinedo and Murr, 2006; Abbasi and Mowla, 2008; Koc et al., 2008; Mayor et al., 2011; Mayor and Sereno, 2004), studies on the shrinkage phenomenon in the osmotic dehydration are restricted to the quantification of this phenomenon (Mavroudis et al., 1998; Moreira and Sereno, 2003; Nieto et al., 2004), and information concerning the consideration of shrinkage in the estimation of diffusivity is rarely reported (Toğrul and Ispir, 2007). Results of above mentioned studies show that neglecting the

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Nomenclature

C	Concentration (g/m^3 of fruit)
D_e	Effective diffusivity (m^2/s)
D_{es}	Effective sucrose diffusivity (m^2/s)
D_{ew}	Effective moisture diffusivity (m^2/s)
d	Diameter of beaker (0.105 m)
L	Half thickness (m)
m	Mass (g)
MR	Moisture ratio
NMC	Normalized moisture content
N	Agitation speed (rev/s)
S	Mass of sucrose (g)
S_1	a constant related with water loss (hr^{-1})
S_2	a constant related with solid gain (hr^{-1})
SG	Solid gain (g sucrose/g fresh fruit)
t	Time (s)
T	Temperature (°C)
V	Volume (m^3)
W	Mass of water (g)
WL	Water loss (g water/g fresh fruit)
WR	Weight reduction
x	Spatial coordinate (m)
Subscripts	
0	Initial
e	Equilibrium
Exp	Experimental
s	Sucrose
sol	Solution
t	At the time t
w	Water
x	Without considering shrinkage
y	With considering shrinkage
Greek letters	
φ	Dimensionless concentration
ρ	Density (kg/m^3)
μ	Viscosity (kg/m.s)
ν	Kinematic viscosity (m^2/s)

shrinkage, results in overestimation of diffusivity values in the air drying of materials.

Therefore, the objectives of this work were to investigate the effect of considering the shrinkage in the estimation of diffusivity in osmotic dehydration. As numerous theoretical and experimental studies were carried out on the osmotic dehydration of apple without considering the shrinkage (Kaymak-Ertekin and Sultanoglu, 2000; Magee et al., 1983; Azuara et al., 2009; Li and Ramaswamy, 2006; Moreira and Sereno, 2003), the experimental data were obtained from osmotic dehydration of infinite slab shape samples of apple in sucrose solutions of different temperatures and concentrations.

2. Theory

We consider an infinite slab shape foodstuff of thickness 2L, initially at uniform moisture and solute concentrations C_{w0} and C_{s0}, respectively. At t = 0 the material is immersed in a solution with constant concentration and temperature. It is assumed that the solution temperature and concentration

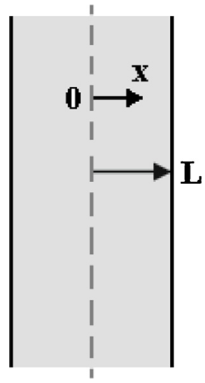

Fig. 1 – Symmetric scheme for osmotic dehydration of an infinite slab of thickness 2L.

remain constant during osmotic dehydration. This condition could be obtained by selecting a high solution to solid mass ratio. Also, constant equilibrium moisture and solute concentrations at the surface (negligible external resistance to mass transfer) of the material are considered. In these conditions, the unsteady-state one-dimensional mass transfer in the solid material can be described by the following general equation (Crank, 1975):

$$\frac{\partial C}{\partial t} = D_e \frac{\partial^2 C}{\partial x^2} \quad (1)$$

and the following initial and boundary conditions are taken:

$$C(x, 0) = C_o \quad \text{at} \quad t = 0 \quad (2)$$

$$\frac{\partial C}{\partial x} = 0 \quad \text{at} \quad x = 0 \quad (3)$$

$$C(L, t) = C_e \quad \text{at} \quad x = L \quad (4)$$

where x is the spatial coordinate, as illustrated in Fig. 1, and $C = C(x,t)$.

Average dimensionless concentrations (space-mean concentrations), $\varphi(t)$, could be obtained by applying the method of separation of variables to Eq. (1), to yield concentration distribution, $C(x, t)$ and then taking the spatially average, arriving at:

$$\varphi(t) = \frac{\overline{C}(t) - C_e}{C_0 - C_e} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left[-\frac{\pi^2 (2n+1)^2 D_e}{4L^2} t\right] \quad (5)$$

In which C is the mass of water (W) or solute (S) per volume of the drying material ($C_w = W/V$ & $C_s = S/V$). Equation (5) can be simplified by considering only the first term in its series expansion and written in logarithmic form as:

$$\ln(\varphi) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_e}{4L^2}\right) t \quad (6)$$

Then by using the definition of water loss and solid gain as a function of initial mass of fruit (m_0), initial mass of moisture (W_0) and solute (S_0) in the fruit as:

$$WL_t = \frac{W_0 - W_t}{m_0} \quad (7)$$

$$SG_t = \frac{S_t - S_0}{m_0} \quad (8)$$