FOOD AND BIOPRODUCTS PROCESSING 97 (2016) 88–99

Contents lists available at ScienceDirect

Food and Bioproducts Processing

journal homepage: www.elsevier.com/locate/fbp

Mass transfer modeling in osmotic dehydration: Equilibrium characteristics and process dynamics under variable solution concentration and convective boundary

H. Pacheco-Angulo[a], E. Herman-Lara[b], M.A. García-Alvarado[a], I.I. Ruiz-López[c,*]

[a] Unidad de Investigación y Desarrollo en Alimentos, Departamento de Ingeniería Química y Bioquímica, Instituto Tecnológico de Veracruz, Av. M.A. de Quevedo S/N. Col. Formando Hogar, C.P. 91860 Veracruz, Veracruz, México
[b] Coordinación de Posgrado e Investigación, Departamento de Ingeniería Química y Bioquímica, Instituto Tecnológico de Tuxtepec, Av. Dr. Víctor Bravo Ahuja S/N. Col. 5 de Mayo, C.P. 68350, Tuxtepec, Oax. , México
[c] Facultad de Ingeniería Química, Benemérita Universidad Autónoma de Puebla, Av. San Claudio y 18 Sur. Ciudad Universitaria, Puebla, Puebla, México

ARTICLE INFO

Article history:
Received 22 April 2015
Received in revised form 10 November 2015
Accepted 25 November 2015
Available online 8 December 2015

Keywords:
Interfacial resistance
Mass Biot number
Mass transfer
Osmotic dehydration
Variable solution concentration
Equilibrium distribution

ABSTRACT

The aim of this study was to model both the dynamic and equilibrium mass transfer periods for water, osmotic solute and food solids interchange between product and solution during an osmotic dehydration (OD) process. The OD model is able to represent situations where concentration of osmotic media changes during the process or where interfacial resistance to mass transfer cannot be neglected. Water and solute are considered to move within the product by a diffusion mechanism based on Fick's second law, while external convective mass transfer is considered in the fluid. The state-space form of the model is analytically solved for one-dimensional mass transfer in products with flat slab, infinite cylinders and sphere geometries. The developed theory was applied to the analysis of equilibrium and OD dehydration curves of carrot slices obtained at 40 °C in sodium chloride solutions with and without stirring and different ratios between solution volume and product mass. Water and NaCl diffusivities were identified in the narrow ranges of $6.0–7.6 \times 10^{-10}$ m^2/s and $3.5–4.1 \times 10^{-10}$ m^2/s, respectively, demonstrating the applicability of the proposed model under a wide range of operating conditions.

1. Introduction

Osmotic dehydration is a solid–liquid contact operation involving the immersion of food products, especially fruits and vegetables, in hypertonic solutions such as brines or syrups. When the food is immersed in the solution, an osmotic pressure gradient is developed between the involved phases originating a dynamic mass transfer period in which water is removed from food toward the liquid media with a simultaneous solute gain by the product (Khan et al., 2008; Goula and Lazarides, 2012; Herman-Lara et al., 2013; Souraki et al., 2013, 2014). If processing is performed for a long enough time, then both water loss and solute gain reach a stationary state, where the driving potential for mass transfer between food and solution becomes zero (Sablani and Rahman, 2003; Herman-Lara et al., 2013). This operation involves several mass

---

[*] Corresponding author. Tel.: +52 222 2295500x7250.
E-mail addresses: irving.ruiz@correo.buap.mx, irvingisrael@hotmail.com (I.I. Ruiz-López).

http://dx.doi.org/10.1016/j.fbp.2015.11.002

Nomenclature

A	surface area available for mass transfer (m^2)
$\mathbf{A}$	state-space matrix
a_w	water activity
Bi	mass Biot number (dimensionless)
C	concentration (g/L)
d	maximum inner diameter of flask (m)
D	diffusion coefficient (m^2/s)
F	Faraday constant (96485.34 C/mol)
Fo	Fourier number for mass transfer (dimensionless)
g	gravitational constant ($9.81\,m^2/s$)
Gr	mass Grashof number (dimensionless)
k_c	convective mass transfer coefficient (m/s)
K_e	equilibrium partition coefficient (kg product/kg osmotic media)
L, L_c	characteristic lengths for diffusion and convection, respectively (m)
m	solute molality (mol solute/kg solvent)
m	mass in product (kg)
M	mass in osmotic media (kg)
n	number of nodes
N	number of components
n_+, n_-	valences of cation and anion, respectively (dimensionless)
R	gas constant (8.314 J/mol K)
Re	Reynolds number (dimensionless)
Sc	Schmidt number (dimensionless)
Sh	Sherwood number (dimensionless)
t	time (s)
T	temperature (K)
u	axial or radial coordinate (m)
U	food solids-to-(osmotic solute + water) mass ratio in product (kg/kg)
v	orbital velocity (1/s)
V	volume (m^3)
X	mass fraction of a given component in product (kg/kg product)
X^*	mass fraction in product free of food solids (kg/kg osmotic solute + water)
$\mathbf{X}$	state-space vector
Y	mass fraction of a given component in solution (kg/kg solution)
Y^*	mass fraction in solution free of food solids (kg osmotic solute + water)
x_1, x_2	coded temperature and time, respectively
W	food solids-to-(osmotic solute + water) mass ratio in osmotic media (kg/kg)

Greek letters

α	parameter defining product geometry
δ	mass ratio between osmotic media and product
ε	volume fraction occupied by osmotic media (m^3 solution/m^3 solution + product)
φ	thermodynamic factor (dimensionless)
Γ	dimensionless concentration in solution
$\gamma_\pm$	mean ionic activity coefficient of solute (dimensionless)
λ_+°, λ_-°	limiting (zero-concentration) ionic conductances of cation and anion, respectively ($S\,m^2/mol$)
η	dynamic viscosity (Pa s)
Θ	dimensionless group related with product-to-osmotic media mass ratio
ρ	density (kg/m^3)
μ	chemical potential (J/mol)
ξ	dimensionless coordinate
ψ, Ψ	dimensionless concentration in product: local and average, respectively

Subscripts

0	at beginning of the process
$\circ$	at infinite dilution
f	denotes food solids
e	at equilibrium
i	at the product–solution interface
j	denotes either water or osmotic solute
k	denotes node numbering
o	denotes osmotic media
p	denotes product
s	denotes osmotic solute
t	at time t
w	denotes water

transfer mechanisms; however, diffusion of water and solute within product are usually considered the controlling factors, usually described by Fick's second law (Kaymak-Ertekin and Sultanoğlu, 2000; Rastogi and Raghavarao, 2004; Goula and Lazarides, 2012; Souraki et al., 2012; da Silva et al., 2013, 2014; Rodríguez et al., 2013).

Depending on modeling assumptions, non-steady-state diffusion equation may be solved under analytical or numerical techniques (Kaymak-Ertekin and Sultanoğlu, 2000; Porciuncula et al., 2013; Rodríguez et al., 2013); however, the use of analytical models remains widespread due to several practical advantages, including easier implementation and lower computational effort. Analytical solutions for OD process in well-stirred systems (*i.e.*, those with negligible external resistance to mass transfer) can be classified in two main groups based on the available amount of working solution (Crank, 1975). Most studies consider an infinite volume of osmotic media (*i.e.*, of constant concentration; Rastogi and Raghavarao, 2004; Rodríguez et al., 2013; Souraki et al., 2012, 2013, 2014), experimentally achieved by using mass ratios between solution and product of 10 and above (Herman-Lara et al., 2013). The use of lower ratios between osmotic media and product may result in an appreciable decrease of solute concentration during product impregnation, affecting water loss and solute gain rates as well as final dehydration and impregnation levels at equilibrium. Therefore, special analytical solutions considering a finite volume of osmotic media (*i.e.*, of variable concentration) should be applied in these cases (Singh et al., 2007; Bellary et al., 2011), or alternatively, resort to a numerical solution allowing the use of additional assumptions such as variable mass of involved phases (Kaymak-Ertekin and Sultanoğlu, 2000). As a diffusion-controlled process is presumed in the aforementioned models (Crank, 1975), these may not be applicable to describe experimental conditions where convective resistance to mass transfer may occur (for example, processes conducted without or with mild stirring), which may be required in products with fragile structures.