Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Food Engineering 66 (2005) 329–338
JOURNAL OF FOOD ENGINEERING
www.elsevier.com/locate/jfoodeng

Mathematical modeling for immersion chilling and freezing of foods. Part I: Model development

Susana E. Zorrilla *, Amelia C. Rubiolo

Instituto de Desarrollo Tecnológico para la Industria Química, Consejo Nacional de Investigaciones Científicas y Técnicas, Universidad Nacional del Litoral, Güemes 3450, (3000) Santa Fe, República Argentina

Received 1 November 2002; received in revised form 2 September 2003; accepted 26 March 2004

Abstract

Mathematical equations for modeling immersion chilling and freezing of foods were developed. Solid foods were assumed as a porous media with an occluded solution. Three phases were considered, the rigid solid matrix, the liquid phase, and the ice phase. Transport equations for a continuous media were applied to each phase. The averaging-volume method developed by Whitaker [Adv. Heat Transfer 13 (1977) 119] was used for obtaining comprehensive equations to predict solute concentration and temperature as a function of space and time. The thermodynamic relation between temperature and solute concentration in presence of ice is critical to complete the mathematical formulation. Moreover, the thermal properties and enthalpy depend on the initial depression of freezing point. This work contributes with a simple model for predicting heat and mass transfer phenomena during immersion chilling and freezing of foods.

Keywords: Immersion freezing; Mathematical modeling; Heat transfer; Mass transfer; Food

1. Introduction

Immersion chilling and freezing (ICF) consists of direct soaking of foods in aqueous fluids maintained at low temperature. ICF has recognized advantages, it is one of the fastest chilling and freezing techniques, and it is associated to lower costs and to higher quality of the final product. However, the main disadvantage that reduces ICF use is the uncontrolled solute uptake from the refrigerated solution into the product (Lucas & Raoult-Wack, 1998).

Several experimental results improved the knowledge about different aspects of ICF process. Lucas and Raoult-Wack (1996) observed clearly the two different stages during ICF. Using gelatin gel cylinders and NaCl immersion solutions, they studied cross-sections of the cylinders and showed that a formation of an ice barrier at a first stage hindered salt transfer and that peripheral thawing at a secondary stage after thermal equilibrium became evident. Moreover, temperature, concentration and agitation of a NaCl immersion solution affected phase change and salt gain in the gel. Some studies were related to the reduction of salt impregnation in apple cylinders during ICF process. Lucas, Francois, and Raoult-Wack (1998) concluded that the formation of an ice barrier on product surface limited only partially salt impregnation, that solute transport can be efficiently reduced by freezing quickly and by working at the lowest possible solution temperature, and that the addition of sucrose to the immersion solution as well as the pre-coating of food pieces in cold water prior to ICF, led to a reduction of salt impregnation. Moreover, mass transfer was reduced during the secondary stage when immersion-solution temperature was lower and when sucrose was used in a biphasic mixture (Lucas, Francois, Bohuon, & Raoult-Wack, 1999).

Mathematical models may help to have a better understanding of the transport phenomena associated with ICF and to control or optimize the variables of the ICF process. A simplified model of heat and mass transfer in a porous medium, valid in the absence of phase change, allowed performing a dimensional analysis (Lucas, Flick, & Raoult-Wack, 1999). Authors

* Corresponding author. Tel.: +54-342-4559174/4559177; fax: +54-342-4550944.
E-mail address: zorrilla@intec.unl.edu.ar (S.E. Zorrilla).

0260-8774/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jfoodeng.2004.03.026

Nomenclature

A	area (m^2)
b	coefficient of Eq. (42)
c	coefficient of Eq. (42)
$C_{P\mathrm{eff}}$	effective specific heat ($J\,kg^{-1}\,°C^{-1}$)
$C_{P\mathrm{f}}$	specific heat of the completely frozen food ($J\,kg^{-1}\,°C^{-1}$)
$C_{P\mathrm{u}}$	specific heat of the unfrozen food ($J\,kg^{-1}\,°C^{-1}$)
d	coefficient of Eq. (42)
$\mathscr{D}$	diffusion coefficient ($m^2\,s^{-1}$)
D_{eff}	effective diffusion coefficient for the solute ($m^2\,s^{-1}$)
e_1	total initial mass fraction of freezable water
h	enthalpy per unit mass ($J\,kg^{-1}$)
h_{c}	heat transfer coefficient ($W\,m^{-2}\,°C^{-1}$)
$\bar{h}_i$	partial mass enthalpy for the ith species ($J\,kg^{-1}$)
ΔH_0	latent heat of fusion of ice ($kJ\,kg^{-1}$)
k_{eff}	effective thermal conductivity ($W\,m^{-1}\,°C^{-1}$)
k_{f}	thermal conductivity of the completely frozen food ($W\,m^{-1}\,°C^{-1}$)
k_{u}	thermal conductivity of the unfrozen food ($W\,m^{-1}\,°C^{-1}$)
L	half height of cylinder (m)
$\langle \dot{m} \rangle$	mass rate of water solidification ($kg\,m^{-3}\,s^{-1}$)
$\mathbf{n}$	outwardly directed unit normal
p	pressure ($N\,m^{-2}$)
$\mathbf{q}$	heat flux vector ($W\,m^{-2}$)
r	radial coordinate (m)
r_i	mass rate of production of ith species due to chemical reaction ($kg\,s^{-1}\,m^{-3}$)
R	cylinder radius (m)
t	time (s)
T	temperature (°C)
$\mathbf{T}$	total stress tensor ($N\,m^{-2}$)
T_0	freezing point of pure water (°C)
T_{f}	initial freezing point of the food (°C)
T_{ref}	reference temperature for the enthalpy calculation (°C)
$\mathbf{v}$	mass average velocity vector ($m\,s^{-1}$)
V	volume (m^3)
w	mass fraction
$\mathbf{w}$	velocity of the α–β interface ($m\,s^{-1}$)
z	axial coordinate (m)

Greek symbols

ε	volume fraction
ϕ	rate of heat generation ($J\,s^{-1}\,m^{-3}$)
η	variable defined in Eq. (45)
λ	unit tangent vector
ρ	density ($kg\,m^{-3}$)
τ	tortuosity
$\mathbf{\Omega}$	viscous stress tensor ($N\,m^{-2}$)
$\langle\psi\rangle$	spatial average of a function ψ
$\langle\psi_\delta\rangle$	phase average of a function ψ_δ
$\langle\psi_\delta\rangle^\delta$	intrinsic phase average a function ψ_δ
ζ	variable defined in Eq. (46)

Subscripts/superscripts

1	water
2	solute
i	ith species
α	ice phase
β	liquid phase
σ	solid phase
∞	at the bulk immersion solution

estimated theoretically that the thawed surface zone would not exceed one millimeter in thickness considering the solute impregnation levels in real food. Lucas, Flick, Chourot, and Raoult-Wack (2000) examined the mechanisms for thawing/impregnation of a food system and discussed two models, one solved numerically (Lucas, Chourot, Bohuon, & Flick, 2001) and the other analytically. The product was considered as a porous medium with an occluded medium in a liquid state or in a liquid + ice state. Three state variables were considered: temperature, solute mass fraction relative to the liquid phase, and the ice mass fraction relative to the liquid + ice mixture. Heat and mass transport were described by Fourier's and Fick's laws, respectively. The equations were solved for a one-dimensional system by a finite difference method to represent primary and secondary phases, while the analytical model represented only the secondary phase. The predicted time-course changes in the thawing front and solute gain agreed experimental values. However, a model that considers a simple approach for foods of regular geometries has not been yet developed.

Our objective was to develop a mathematical formulation to represent the transport phenomena involved in the ICF process.

2. Model development

Whitaker (1977) developed a theory of drying in porous media based on the transport equations for a continuous media. Those equations were volume averaged to provide a rational route to a set of equations describing the transport of heat and mass in porous media. A similar approach can be used for ICF to develop a comprehensive theory. A rigid porous media is