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Mathematical modeling of ohmic heating of two-component foods with non-uniform electric properties at high frequencies

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ABSTRACT

The ohmic heating (OH) of two-component foods (consisting of mashed potato and mashed potato with 1% NaCl) configured using four different filling patterns (parallel, series, and two concentric patterns) was investigated experimentally and by modeling. The electrical conductivities of the samples at 50 Hz and 20 kHz were obtained in the range of 20–85 °C. The differences between the thermal behaviors of the two-component foods were analyzed using internal thermal images and temperature profiles from four positions. A three-dimensional OH model for high frequencies was developed based on electric field analysis using Maxwell's equations. The model agreed sufficiently with the measured results and was able to confirm that the current applied to the sample follows the path that presents minimum electrical resistance, which is independent of the filling pattern configuration. Analysis of the heat flux density provided a better understanding of the heating behavior of two-component foods during OH.

Industrial relevance: Although several mathematical approaches used to simulate the OH process of solid foods have been published in recent years, the simulation of temperature and electric field distributions using simplified methods, such as by the solution of Laplace's equation, is still a problem for two-component solid foods with special configurations of the internal components treated using an OH process at high frequencies. This problem can be solved using a more fundamental solution based on Maxwell's equations and electric field analysis via computer simulation. A comprehensive mathematical simulation of the thermal behavior and the effect of the orientation of the current within the two-component foods can be used to accurately predict the heat during OH. Therefore, the modeling of heating patterns of complex foods can assist in the design of food sterilization and pasteurization processes. Moreover, it will contribute in industrial applications for a better design of OH systems and electrode configurations for rapid and uniform heating.

1. Introduction

Recently, several thermal and non-thermal technologies were proposed for food processing with the objective of contributing to producing safer and higher-quality food products. Ohmic heating (OH) is one of these technologies that is defined as a process wherein electrical current is passed through food and the resistance it offers generates heat inside it. OH provides rapid and uniform heating, resulting in lower thermal damage than that caused by conventional heating (Simpson, Carevic, Grancelli, & Moreno, 2014).

A number of factors affect OH performance during the treatment of foods. These factors include food composition; their electric and physical properties such as the electrical conductivity (EC), density, specific heat capacity, thermal conductivity, and viscosity; and the parameters of the OH system such as features of the food (single phase or food mixture), electrical field intensity, and configurations of the ohmic heater and electrodes (Li & Zhang, 2010). Additionally, for solid foods, the EC behavior depends to a large extent on whether a cellular structure exists within the material, the fiber orientation, and the size and shape of the solid food (Liu et al., 2016; Sastry & Kamonpatana, 2014). In recent years, several studies focusing on the OH process for solid foods (Engchuan, Jittanit, & Garnjanagoonchorn, 2014; Ito, Fukuoka, & Hamada-Sato, 2014; Lyng, 2014; Marra, Zell, Lyng, Morgan, & Cronin, 2009; Shynkaryk, Ji, Alvarez, & Sastry, 2010; Zell, Lyng, Morgan, & Cronin, 2009, 2011) were reported. In these studies, efforts were made to improve the uniformity during OH applications and pretreatment methods such as increasing the electrolytic content in solid food, salt infusion via soaking and blanching of solids in salt solution were evaluated.

Computational work is also required for understanding the OH process. Recently, some relevant computer simulation models (Choi, Lee, Kim, & Jun, 2015; Engchuan et al., 2014; Içier, 2014; Jun & Sastry, 2007; Marra, 2014; Marra et al., 2009; Shim, Lee, & Jun, 2010) were

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Notation

A	electrode surface area [m^2]
C_p	specific heat [$J\ kg^{-1}\ K^{-1}$]
E	electric field intensity [$V\ m^{-1}$]
H	magnetic field intensity [$A\ m^{-1}$]
I	intensity of current [A]
k	thermal conductivity [$W\ m^{-1}\ K^{-1}$]
L	length between the two electrodes [m]
Q_v	volumetric internal heat generation [$W\ m^{-3}$]
R	electrical resistance of the component food [Ω]
rms	root mean square
t	time [s]
T	temperature [°C]
V	voltage [V]
ε_0	permittivity of the free space [$F\ m^{-1}$]
ε_r	relative permittivity [−]
ε''	dielectric loss factor [$J\ s^{-1}$]
σ	electrical conductivity [$S\ m^{-1}$]
ρ	density [$kg\ m^{-3}$]
ω	angular frequency [$rad\ s^{-1}$]
∇	gradient [−]
Δ	increment [−]

Subscripts

0	initial value
a	mashed potato sample
b	mashed potato with 1% NaCl sample
J	based on Laplace's equation
m	based on Maxwell's equations
p	parallel
s	series
amb	ambient

published. These models attempted either to model the OH process predicting the heating patterns of treated foods or to characterize the effect of EC on the heating performance. Although the use of many factors influencing the EC of foods, such as the heating rates, temperature distribution, and electric field was reported for modeling (Li & Zhang, 2010), the determination of electric field is one of the most challenging subjects in the modeling effort in OH technology.

The electric field was predicted based on semi-empirical models or traditional models based on the Laplace's equation. The Laplace's equation, which includes Joule's law and Ohm's law, is widely used because it is useful in determining the voltage drop and reduces the computation time involved in the whole-field simulation (Li & Zhang, 2010). However, Laplace's equation assumes that the current is approximately proportional to the electric field for most materials. Therefore, estimating the heat generated based purely on EC and its temperature dependence relationship (by the Laplace's equation method) may not deal with the distortion of the electric field efficiently because of the differences of ECs in the anisotropic tissues of some foods such as meat products. The geometry and orientation of these foods within the OH device causes different rates of heat generation because the orientation of the vascular fibers to the electric field strongly influences the EC or impedance of the biological tissues. The Laplace's equation method is less fundamental than Maxwell's equations and is not always obeyed. Therefore, a more apt determination of the electric field intensity within the OH system conducted at high frequencies, even for anisotropic foods, can be obtained through a more appropriate calculation, e.g., using Maxwell's equations and electric field analysis (Choi et al., 2015).

The electric field analysis calculated by Maxwell's equations was used to predict the thermal behavior of foods in dielectric heating such as radio frequency (RF) heating (Llave, Liu, Fukuoka, & Sakai, 2015) and microwave (MW) heating (Liu, Fukuoka, & Sakai, 2013); however, this method was not used in OH applications to the best of the authors' knowledge. Even though simulations were conducted using Maxwell's equations and electric field analysis, reports suggest that extreme computational effort is required, which increases the computational cost. However, this method is believed to provide a more accurate simulation performance of OH applications, especially at high frequencies, because it can deal with the independence of the sample position within the OH system and predict large-scale variations in the electric field intensity when the voltage is applied along the current flow.

According to Pain and Muller (2014), a "second generation" of ohmic processing equipment was developed recently, characterized by a new high-frequency power supply commercially available in Europe and Japan. In earlier applications, the use of low alternating current frequencies in the range 50–60 Hz was found to be disadvantageous because it increased electromechanical reactions and electrode erosion, particularly in conjunction with metallic electrodes. Direct contact of the food with the electrodes is regarded as a critical aspect of the application. Alternating current is used at frequencies >20 kHz to reduce oxidation reactions and metallic contamination of the product because in this frequency range, electrode erosion is reduced because of the inhibition of Faraday reactions (Jaeger et al., 2016). The use of high frequencies instead of low frequencies during OH showed some advantages, e.g., minimization of the texture degradation of the peach tissue (Shynkaryk et al., 2010), reduced effect of resistance on the EC of yellowtail (*Seriola quinqueradiata*) fillets (Jin, Cheng, Fukuoka, & Sakai, 2015), and improved quality of ohmically heated chicken breast samples as compared to that of the retort-heated samples (Ito et al., 2014). However, there is a lack of computer simulation models of OH at high frequencies.

In this study, Maxwell's equations and electric field analysis were used to analyze the temperature distribution and heat flux density of the electric fields of two-component foods undergoing OH at a high frequency by using a three-dimensional (3D) model. Mashed potatoes were chosen as the model food because of their highly homogenous nature. The electrical behavior of the solid model food was modified by adding 0% and 1% of NaCl. The ECs of the samples at 50 Hz and 20 kHz were estimated in the temperature range of 20–85 °C. The dielectric loss factor (ε'') used in modeling was estimated based on its relationship with the EC. The effects on the thermal behavior and the current flow of the orientation of the two-component foods using four different filling pattern configurations within the OH system were evaluated using the 3D model. Results were compared and validated with the measured thermal profiles and temperature distributions.

2. Materials and methods

2.1. Sample preparation

The two-component foods were filled using two solid model foods:

(1) A mashed potato prepared by mixing instant mashed potato flakes (20% wb) (Mashed Potato Tokuyo 1201, Marukyu Co. Ltd., Japan) and distilled water (80% wb). The mashed potato flakes have a crude protein content >4.8%, crude fat content <0.9%, crude ash content <2.7%, and carbohydrate content approximately equal to 95.2%.
(2) A mashed potato prepared by mixing instant mashed potato flakes (19% wb) with 1% (wb) of sodium chloride-NaCl and distilled water (80% wb).

Each sample was stirred for 10 min to form a homogeneous mixture. The samples were sealed with cling film in order to prevent moisture loss due to evaporation and were kept at 20 °C for about 3 h before experimentation. In this study, the electrical behavior of the samples was