Innovative Food Science and Emerging Technologies 41 (2017) 244–250

Contents lists available at ScienceDirect

Innovative Food Science and Emerging Technologies

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

Analysis of thermal effect using Coupled Hot-air and Microwave heating at different position of potato

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ARTICLE INFO

Article history:
Received 27 November 2016
Received in revised form 15 January 2017
Accepted 25 March 2017
Available online 27 March 2017

Keywords:
Coupled Hot-air and Microwave (CTMW) heating
Electromagnetic field
Temperature field
Numerical- simulation

ABSTRACT

A 3D mathematical food model of Coupled Hot-air and Microwave (CTMW) heating was developed to understand complex microwave interactions in food. The heating process at different position of potato using CTMW heating was investigated numerically and experimentally. Simulated spatial temperature profiles were compared with experimental ones, and predict spatial temperature profiles were in good agreement with experimental ones. In this study, the effect of the potato's position inside cavity was studied. The simulation results were analyzed and evaluated. The results showed the loss power values& density distribution at different position of potato varied greatly, which directly led to the potatoes in the uneven distribution of temperature field. The results are useful in understanding complex microwave heating, designing CTMW heating systems.

1. Introduction

Microwave is a new heat source and more attractive than the conventional heating methods because electromagnetic wave can penetrate through the surface and is converted into thermal energy within the foods. High speed startup, selective energy absorption, non-pollution, high energy efficiency and high product quality are several advantages of microwave heating (Campañone, Bava, & Mascheroni, 2014). Coupled Hot-air and Microwave (CTMW) heating has been widely used in the field of food processing. Malafronte, Lamberti, and Barba (2012) simulated the heat and mass transfer process of potatoes under CTMW by COMSOL, and the simulated result was experimentally demonstrated. The mechanism of Hot-air and Microwave heating was detailed discussed in many published data (Schubert & Regier, 2005; Curet, Rouaud, & Boillereaux, 2014; Santos, Valente, Monteiroa, Sousab, & Costaa, 2011). There are many factors that influence CTMW Heating, such as equipment, microwave power, dielectric properties of heated food, heating time, hot air temperature and velocity (Klinbun, Rattanadecho, & Pakdee, 2011; Romano, Marra, & Tammaro, 2005). While, study on the influence of different positions about Coupled Hot-air and Microwave heating is seldom reported.

From the perspective of physical field, microwave heating is mainly involved in the electromagnetic field and temperature field of energy conversion and transmission. In order to discuss the influence of effect on CTMW heating at different position of food, the main parameter to be considered should be the values & density distribution of electromagnetic power loss at different position of heated food, so as the final temperature field distribution uniformity within the heated food.

With the rapid development of CAE (Computer Aided Engineering) technology, numerical simulation has become an important way of scientific research and product development, which avoid lots of repeated test and shorten the development time.

In this study, CTMW heating was used to heat a whole photo in the particular cavity. Change the position of the heated food on electromagnetic power loss, density distribution of electromagnetic field and uniformity of temperature distribution was discussed. The numerical simulation technique was used to analyze and evaluate the position change.

2. Mathematical CTMW heating

A successful algorithm of microwave heating is coupled between Maxwell's equations and the heat transfer equation. Maxwell's time harmonic equations in the heated food is(Santos et al., 2011; Kopyt & Celuch, 2007):

$$\nabla \times \left(\mu_r^{-1} \nabla \times \vec{E}\right) - k_0^2 (\varepsilon_r - j\sigma/\omega\varepsilon_0)\vec{E} = 0 \tag{1}$$

Where in Eq. (1), $\vec{E}, \mu_r, \varepsilon_r, \sigma$are respectively electric field intensity, relative magnetic permeability, relative permittivity, electric conductivity.

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http://dx.doi.org/10.1016/j.ifset.2017.03.014
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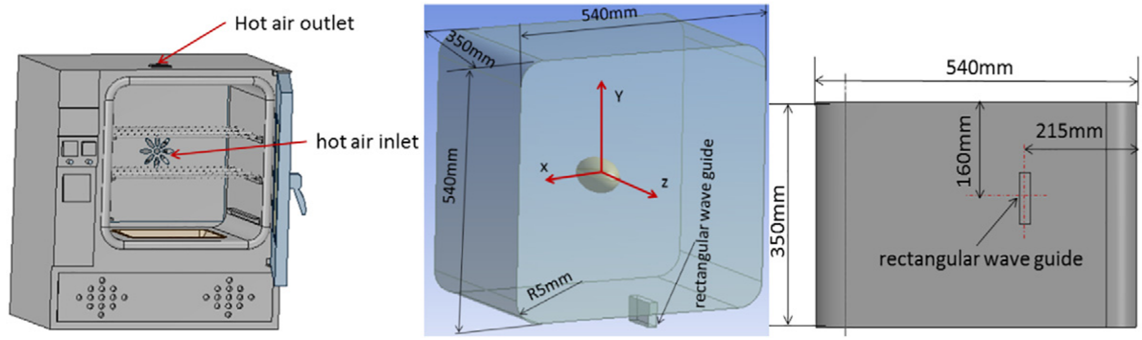

Fig. 1. Experimental device & 3D models.

ε_0 is vacuum permittivity ($\varepsilon_0 = 8.854 \times 10^{-12}$ F/m); ω is excitation angular frequency of electromagnetic wave; k_0 is wavevector in free space.

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r'' = \varepsilon_r'(1 - j\ \tan\delta) \tag{2}$$

Where in Eq. (2), ε_r', the real component, referred to as dielectric constant, describes the ability of a material to store electric energy; ε_r'', the imaginary component, referred to as loss factor, determines energy dissipation in the material or the conversion from electrical energy into heat. While the loss tangent coefficient of the heated foods can also be expressed as $\tan\delta = \varepsilon_r''/\varepsilon_r'$. In other words, $\tan\delta$ indicates the ability of the heated foods to absorb microwave energy.

When the heated food is linear isotropic properties.

$$\vec{D} = \varepsilon_r \varepsilon_0 \vec{E},\ \ \vec{B} = \mu_r \mu_o \vec{H},\ \ \vec{J} = \sigma \vec{E} \tag{3}$$

where in Eq. (3), $\vec{D}$, $\vec{B}$, $\vec{J}$, $\vec{H}$ are respectively electric flux density vector, magnetic flux density vector, electric current density, magnetic field intensity.

In the microwave heating process, absorbed microwave power by the heated food was the power loss of electromagnetic fields P, which is a local electromagnetic heat generation term, which is a function of the electric field and defined as:

$$P = \omega \varepsilon_0 \varepsilon_r'' \left|\vec{E}\right|^2 \tag{4}$$

Thermal conduction equation of the heated foods is determined as the following equation (Guangyi et al., 2015):

$$\rho C_p \frac{\partial T}{\partial t} = k \nabla^2 T + P \tag{5}$$

Where in Eq. (5), ρ, C_p, k are respectively the heated foods density, specific heat capacity and temperature thermal conductivity.

By power loss of electromagnetic fields P in Eqs. (4) and (5), two types of different physical field—electromagnetic field and temperature field were coupled together.

In the actual process of microwave heating, thermal fluid (such as hot air) and microwave was usually coupled together to improve the heating efficiency and enhance the uniformity of temperature field distribution of the heated food. In this situation, conjugate heat transfer analysis of fluid-solid can be used to analyzed, or a boundary conditions of convection heat transfer coefficient was added on to heat conduction equation of heated materials. In this paper, h, convective heat transfer coefficient is defined to simulate coupling process of the hot air and microwave heating.

$$-k \frac{\partial T}{\partial n} = h(T - T_a) \tag{6}$$

In Eq. (6), $\partial T / \partial n$ called temperature gradient, the negative sign indicates that the direction heat flux and temperature gradient is opposite, T is the surface temperature of the heated food, T_a is the hot fluid (e.g., hot air) temperature. h is the convective heat transfer coefficient, which is a physical quantity indicating the strength of the convective heat transfer process.

In microwave heating process, index λ of the cross-section was often used to evaluate the uneven heating (Vadivambal & Jayas, 2010; Wang, Tang, Johnson, & Cavalieri, 2013) the equation is as following:

$$\Delta\overline{T} = \sum_{i=1}^{n} T_i / n \tag{7}$$

$$\Delta T = T_{i\ max} - T_{i\ min} \tag{8}$$

$$\lambda = \Delta T / \Delta\overline{T} \tag{9}$$

T_i is the temperature of each node at the cross-section of the heated food, i is the corresponding node number.

3. Experiment setup & numerical solution

The self-made pilot-scale CTMW experiment apparatus was designed by the authors' department (Fig. 1). The dimensions of length, width and height of the multimode rectangular cavity are 540 × 400 × 550 mm, and the volume is 115 L. There is a certain interval of 10 cm between the three trays. Each layer tray had an area of 0.17 m^2 and was made of a glass fiber mesh grid. The heating feasibility of a material via microwave irradiation depends on dielectric properties (or permittivity); trays with a low dielectric constant almost do not absorb microwave energy and ensure it was absorbed by the working samples and allow

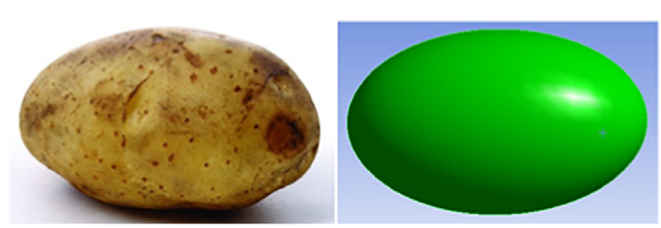

Fig. 2. Potato & 3D numerical models.