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A generalized approach on microwave processing for the lateral and radial irradiations of various Groups of food materials

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ABSTRACT

Numerical studies have been carried out for microwave heating of food samples. It has been shown that the food materials can be divided into four groups based on the values of f_p and f_w and the microwave heating characteristics remain same for the materials in each group. The heating characteristics of each group of materials have been presented based on the heating front, heating rate and heating nonuniformity (thermal runaway). These characteristics are shown to be strongly dependent on sample size, which can be classified as thin (uniform heating), intermediate (localized heating fronts driven be resonances of microwave power absorption) and thick (exponential attenuation of heating rate from the exposed surface). The analysis shows that the localized heating in intermediate and thick samples can lead to significant thermal runaway, which can be efficiently avoided by selecting radial irradiation over lateral irradiation but at the expense of higher processing time.

1. Introduction

Studies of the microwave food processing have gained attention over the years due to its wide applications in food processing including drying, pasteurization, sterilization, thawing, tempering, baking of food materials etc. (Metaxas & Meredith, 1983; Baik, Marcotte, & Castigne, 2000; Guzmán, Dorantes, Hernández, Hernández, Ortiz, & Mora, 2002; Vattem & Shetty, 2003; Gentry & Roberts, 2005; Knoerzer, Regier, & Schubert, 2008; Souraki & Mowla, 2008; Picouet, Landl, Abadias, Castellari, & Viñas, 2009; Al-Muhtaseb, Hararah, Megahey, McMinn, & Magee, 2010; Lombraña, Rodríguez, & Ruiz, 2010; Basak & Rao, 2011; Ben-Lalli, Meot, Collignan, & Bohuon, 2011; Brody, 2012; Xia, Kong, Liu, Diao, & Liu, 2012; Chandrasekaran, Ramanathan, & Basak, 2013; Fazaeli, Yousefi, & Emam-Djomeh, 2013; Benlloch-Tinoco, Igual, Rodrigo, & Martínez-Navarrete, 2013; Ruiz-Ojeda & Peñas, 2013). Advantages of the microwave food processing include the volumetric heating effect that leads to the faster heating rate, reduction in processing time, operational cost, product uniformity, ease of operation, low maintenance, very less change of flavor and nutritional change of food and protection from the surface browning and crusting due to heating from inside (Fakhouri & Ramaswamy, 1993; Guan, Zhang, Hui, Yin, Qiu, & Liu, 2011; Litvin, Mannheim, & Miltz, 1998; Tajchakavit, Ramaswamy, & Fustier, 1998; Taher & Farid, 2001; McMinn, 2004; Basak & Meenakshi, 2006; Zhang, Tang, Mujumdar, & Wang, 2006; Samanta & Basak, 2008; Durairaj & Basak, 2009; Vadivambal & Jayas, 2010; Benlloch-Tinoco, Igual, Rodrigo, & Martínez-Navarrete, 2013).

Microwave heating characteristics are largely dependent on material dielectric properties and sample dimension. Dielectric properties ($\kappa = \kappa' + i\kappa''$) of a material are the combined effect of (i) dielectric constant (κ') and (ii) dielectric loss (κ''). Dielectric constant (κ') determines the ability of a material to store the electromagnetic energy, while dielectric loss (κ'') determines the ability to convert the stored energy to heat. These two factors give rise to two characteristic length scales associated with the electromagnetic wave propagation within the sample. The first length scale is the wavelength (λ_m),

$$\lambda_m = \frac{c\sqrt{2}}{f\left[\sqrt{(\kappa')^2 + (\kappa'')^2} + \kappa'\right]^{1/2}}, \quad (1)$$

and the second length scale is the penetration depth (D_p),

$$D_p = \frac{c}{\sqrt{2}\pi f\left[\sqrt{(\kappa')^2 + (\kappa'')^2} - \kappa'\right]^{1/2}}, \quad (2)$$

where c is the velocity of light and f is the frequency of incident radiation. The wavelength determines the number of waves which can be

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formed within a sample, while the penetration depth determines the distance at which microwaves can penetrate without loosing more than 35% (1/*e* times) of the incident energy. The penetration depth of a material can vary between 0 to ∞, while the wavelength for a given frequency of radiation can vary from 0 to the free space wavelength ($\lambda_0 = c/f$). Instead, these two length scales can be grouped in the following manner

$$f_p = \frac{\lambda_m}{2\pi D_p}, f_w = \frac{\lambda_m}{\lambda_0}, \quad (3)$$

such that the resulting dimensionless numbers vary between 0 to 1 (Bhattacharya & Basak, 2006a). Here, f_p measures the relative magnitude of the wavelength with respect to the penetration depth within the material, while f_w measures the magnitude of the wavelength within the sample compared to that in the free space. Based on these two parameters, entire food materials can be classified into four Groups — (i) low f_p, low f_w ($f_p \leq 0.1, f_w \leq 0.1$), (ii) low f_p, high f_w ($f_p \leq 0.1, f_w \gg 0.1$), (iii) high f_p, low f_w ($f_p \gg 0.1, f_w \leq 0.1$) and (iv) high f_p, high f_w ($f_p \gg 0.1, f_w \gg 0.1$). Classifications of food in the above four Groups are shown in Tables 1–4, which list κ', κ'', λ_m, D_p, f_p and f_w for those food materials. Note that, κ', κ'' and hence λ_m, D_p, f_p and f_w are functions of frequency, temperature and composition such as moisture and salt content. Here, Tables 1–4 show the representative values of each material at room temperature and 2450 MHz frequency unless specified in the tables. Tables 1–4 show that the most of the food materials belong to Group 1, which were widely studied by earlier researchers (Ayappa, Davis, Barringer, & Davis, 1997; Hossan, Byun, & Dutta, 2010).

Studies on the microwave heating of food materials have been conducted by various researchers and it has been shown that the heating features, position of hot spots, non-uniformity etc. depend on the material size, shape and dielectric properties (Zhou, Puri, Anantheswaran, & Yeh, 1995; Ryynanen & Ohlsson, 1996; Van Remmen, Ponne, Nijhuis, Bartels, & Kerkhof, 1996; Ayappa, Davis, Barringer, & Davis, 1997; Oliveira & Franca, 2002; Pandit & Prasad, 2003; Zhang & Datta, 2005; Bhattacharya & Basak, 2006a; Basak, 2007; Bhattacharya & Basak, 2008; Basak, 2008; Samanta & Basak, 2009; Hossan, Byun, & Dutta, 2010). Ryynanen and Ohlsson (1996) found that the uniformity of the microwave heating is a strong function of the arrangement and geometry of the component and type of the hay for various food materials such as meat, sauce, mashed potato, and carrot. Ayappa, Davis, Barringer, and Davis (1997) studied the microwave heating of the cylindrical and slab shaped cooked beef, raw beef, carrot, potato, gravy etc. and studied the position of the maximum power absorption of each food sample. They found that the maxima can be characterized by the dimensionless position defined with respect to λ_m. Hossan, Byun, and Dutta (2010) studied the heating characteristics of beef samples and Basak (2007) studied the heating characteristics of beef and oil cylinders. Hossan, Byun, and Dutta (2010) observed that the variation of temperature largely depends on the sample size and frequency and the heating efficiency showed the highest value due to the occurrence of resonances. Basak (2007) studied the microwave heating behavior due to the lateral and radial irradiations and it was shown that the radial irradiation gives more uniform heating than the lateral irradiation irrespective of materials. Bhattacharya and Basak (2006a, 2008) studied the microwave processing for potato, marinated shrimp, beef, bread slabs and they found that the heating rate and patterns largely depend on the material size. It was also found that food samples with small length scales give uniform heating and samples with large length scales give non-uniform heating which can be characterized in terms of f_p, f_w and the dimensionless length scale. Zhou, Puri, Anantheswaran, and Yeh (1995) and Pandit and Prasad (2003) studied the microwave heating pattern of rectangular and cylindrical potato samples and it was found that, the hot spot occurs at corners whereas the cold spot occurs at the center for the rectangular sample. On the other hand, the hot spot occurs at the center and the cold spot occurs between the center and surface of the cylindrical sample. Samanta and Basak (2009) studied the microwave heating of oil water emulsions and they found that, the hot spot formation within a sample depends strongly on the lateral/radial irradiation for various emulsion compositions.

The review of previous studies shows that the majority of materials involving the microwave heating is confined in Group 1 (see Tables 1–4). Although a few studies exist on the power distribution for Group 2 [e.g. pizza (Ayappa, Davis, Crapiste, Davis, & Gordon, 1991)] and Group 3 [e.g. ham (Zhang, Lyng, Brunton, Morgan, & McKenna, 2004)] food materials, the power absorption characteristics within Group 4 materials are yet to appear in the literature. Moreover, the majority of earlier studies considered only a few specific sample dimensions to analyze the power absorption and temperature distribution. This led to the main objective of this work to characterize the power absorption for all four Groups of materials over the entire range of sample dimensions.

This work is aimed to present the analysis of the power absorption within circular cross sections of few representative materials from each Group. It may be noted that, although food materials occur with different shapes, the majority of food materials can be well represented by the circular cross-section (e.g. fish/meat rolls, vegetables, sandwiches, burgers, and bread). The power absorption characteristics within circular cross sections have been analyzed based on two aspects (i) the average power absorption (which determines the overall processing rate of a material) and (ii) spatial distribution of the power absorption (which determines the non-uniformity of the power absorption and probable hot spot formation). Both lateral and radial microwave radiations are considered based on the application in industrial processing. It has been shown in an earlier work (Bhattacharya & Basak, 2006a, b) that the entire range of the sample dimension can be divided in three distinct classes with respect to the power absorption characterization: thin (samples dimension ≪ wavelength of microwave within sample), thick (samples dimension ≫ penetration depth) and intermediate (samples dimension in between thin and thick). Here, we have presented the comparative analysis on the power absorption characteristics of the four Groups of materials for thin, intermediate and thick regimes. The analysis also presents heating characteristics in terms of the temperature distribution, hot spot formation, evaluation of temperature non uniformity and heating rate with time.

2. Theory and governing equations

The heating configurations are shown schematically in Fig. 1a and b. Fig. 1a illustrates that TM^z polarized uniform plane microwaves (propagating along *x*-direction) of intensity I_0 are laterally incident on the semi-infinite food cylinders of radius *R*, whose axis is aligned along the direction of the electric field (*z*-direction). Fig. 1b depicts that microwaves are assumed to be incident radially, which may be realized if the sample of Fig. 1a rotates with the sufficiently large speed (Kostoglou & Karapantsios, 2006; Basak, 2007). The microwave power absorption for both the cases of Fig. 1a–b is given by the following expression:

$$q = \frac{1}{2}\omega\varepsilon_0\kappa'' E_m E_m^*, \quad (4)$$

where, $\omega = 2\pi f$ is angular velocity, ε_0 is the free space permittivity and E_m and E_m^* are the induced electric field within the sample and its complex conjugate, respectively. During the lateral incidence, the electric field within the medium, E_m, can be obtained from the solution of the following two-dimensional Helmholtz equation (Balanis, 1989) and associated boundary conditions (Ayappa, 1997),

$$\nabla^2 E_m(r,\phi) + \kappa_m^2 E_m(r,\phi) = 0, \quad (5)$$