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Influence of dielectric properties on the heating rate in free-running oscillator radio frequency systems

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ABSTRACT

The heating behavior of a food product in a radio frequency (RF) heater with a free-running oscillator largely depends on the dielectric properties of the food material in processing. In this study, heating rate was mathematically derived as a function of its influencing factors in a RF system. This relationship was validated by experiments using conditioned salt solutions and peanut butter samples in a 27.12 MHz, 6 kW RF system. The dielectric properties of the materials used to validate the model ranged from 3.3 to 91.6 for dielectric constant and from 0.1 to 1577.0 for dielectric loss factor. The comparison between theoretical and experimental results showed a good agreement for the tested samples. Both dielectric constant and loss factor influenced the heating rate under a fixed electrode gap and frequency. When the values of dielectric constant and loss factor were close to one another, the maximum heating rate can be reached.

1. Introduction

Radio frequency (RF) is an electromagnetic wave with a frequency range of 3 kHz to 300 MHz. The US Federal Communications Commission (FCC) allocates 13.56, 27.12 and 40.68 MHz in the RF range for industrial, scientific and medical (ISM) application (Wang and Tang, 2001). RF heating has been applied in the food industry as an efficient dielectric heating method for years. Because of its volumetric heating, adjustable heating rate and high energy efficiency, RF heating is already showing its advantages in thawing and in conditioning of biscuit post baking (Farag et al., 2011; Palazoglu et al., 2012). Wide applications have also been explored in disinfestation, enzyme inactivation, pasteurization and sterilization (Rice, 1993; Wang et al., 2003b,2010; Luechapattanaporn et al., 2005; Guo et al., 2006, 2011; Manzocco et al., 2008). The 50 ohm technology and free-running oscillators are two different designs of RF heating systems. Although 50 ohm systems use modern methods to control the frequency and power, the free-running oscillator design is still the most commonly used in the food industry because of the low cost, simple structure and flexibility. In a free-running oscillator RF heater, the portion of power converted to useful heat depends mainly on the properties of the material (Rowley, 2001).

For a free-running oscillator RF system, "parallel plates" are the most commonly used electrode configuration for bulk material heating (Jones and Rowley, 1996). The food material is placed in-between the two parallel plate electrodes of the applicator, which act as a capacitor. When energized, the generator provides high voltage, high frequency power to the electrodes in the applicator, and the food material with certain dielectric properties is heated up in the high density alternating electric field. In dielectric heating, the dielectric properties of food products are important intrinsic properties that directly influence the energy conversion rate. The complex dielectric property ε^* is the sum of the real part – dielectric constant ε', and the imaginary part – loss factor ε''. Due to the nature of the free-running oscillator RF system, the dissipated power could not be measured directly because of the varying voltage and electric field. Therefore, the only way to estimate the dissipated power in food is to calculate from theoretical equations. The power conversion in the material is described as (Choi and Konrad, 1991):

$$P = 2\pi f \varepsilon_0 \varepsilon'' |\overrightarrow{E_m}|^2 \tag{1}$$

where P is the power conversion in food material from electromagnetic to thermal energy, (W/m^3); f is the frequency of the RF generator, (Hz); ε_0 is the permittivity of vacuum (8.854×10^{-12} F/m); ε'' is the loss factor of the material; $\overrightarrow{E_m}$ is the electric field intensity in the food sample (V/m) (Fig. 1).

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The dielectric properties of various food materials over the RF frequency band have been reported over the past 40 years (To et al., 1974; Nelson, 1981; Calay et al., 1994; Sosa-Morales et al., 2010). The dielectric properties are usually functions of temperature, frequency, density, moisture content, and other compositions of the food. Thus, for a given material, the dielectric properties may vary during heating, and the heating behavior may also change accordingly. Therefore, knowing the dielectric properties as a function of temperature, moisture content and other properties before running experiments may help to predict possible thermal run away and temperature distribution in the bulk food.

It has been a general belief that the power absorption in food is positively related to the loss factor of a food material (Piyasena et al., 2003). However, Birla et al. (2008a) found that in a free-running oscillator RF system, the maximum heating rate was reached when the loss factor of a load is 180 in the studied range between 80 and 350. But the conclusion was derived through theoretical analysis without experimental validation. Wang et al. (2008) reported a reverse relationship between ε'' and heating rate in mashed potato samples of different salt contents based on both experimental and simulation results. A theoretical equation was developed to explain the phenomena, but the simple assumptions in this study limited its application only to a narrow range of dielectric properties, i.e.: ε': 83.3–84.7; ε'': 78.7–173.2. Tiwari et al. (2011a) conducted a computer simulation on RF heating of dry food with COMSOL Multiphysics® software to analyze the influence of dielectric properties on power distribution. In their results, the maximum power distribution and better heating uniformity were reached when the values of dielectric constant and loss factor were small and comparable. But no adequate explanation was given for this phenomenon. So far, there is no systematic research showing in details how the dielectric properties influence heating behavior in free-running oscillator RF systems.

The general goal of this study was to better understand the influence of dielectric properties on RF heating, and further assist experiment design to guide the development of industrial RF heating processes. The specific objectives of this study were to: (1) theoretically analyze the influencing factors of RF heating rate, and use a mathematical model to estimate the heating rate as a function of material properties for a given condition of a RF heater; (2) validate the mathematical model with salty water when only dielectric loss factor changes as a function of salt concentration; and (3) validate the model with conditioned peanut butter samples when both dielectric constant and loss factor change as a function of moisture content and temperature.

2. Materials and methods

2.1. Theoretical model

The power conversion in a food material during RF heating depends on the working frequency, loss factor and the electric field density inside the material (Birla et al., 2008b). When heat loss to the ambient is negligible, the heating rate in a food after absorbing RF power can be described as:

$$P = \rho c_p \frac{\partial T}{\partial t} = 2\pi f \varepsilon_0 \varepsilon'' |\overrightarrow{E_m}|^2 \tag{2}$$

where ρ is the density of the load, (kg/m^3); c_p is the heat capacity of the load, (J/kg K); $\partial T/\partial t$ is the transient heating rate of the load during RF heating (°C/s).

When air is the only surrounding media between the electrodes other than the food sample, the continuity boundary condition of the electric flux density can be applied at the interface of the load and air for a simplified case shown in Fig. 1 (Metaxas, 1996; Birla et al., 2008a,b). The continuity equation can be written as:

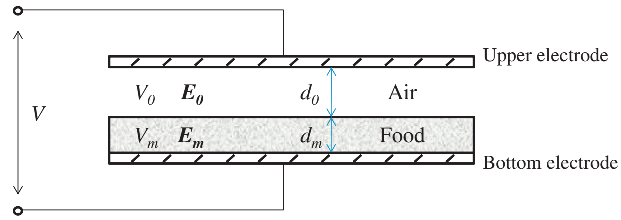

Fig. 1. Scheme of RF heating system with parallel plate electrodes.

$$\overrightarrow{D_n} = \varepsilon_0 \overrightarrow{E_0} = \varepsilon_0 \varepsilon^* \overrightarrow{E_m} \tag{3}$$

where $\overrightarrow{D_n}$ is the normal electric flux density, (C/m^2); $\overrightarrow{E_0}$ is the electric field intensity in the air gap, (V/m); ε^* is the relevant (to air) complex permittivity of the load, $\varepsilon^* = \varepsilon' - j\varepsilon''$, which leads to:

$$\overrightarrow{E_0} = (\varepsilon' - j\varepsilon'')\overrightarrow{E_m} \tag{4}$$

Since the bottom electrode is normally grounded, the voltage on the upper electrode is the total electric potential between the two electrodes (V), which can be divided into voltage falls in the air gap (V_0) and the voltage falls in food material (V_m):

$$V = V_0 + V_m = |\overrightarrow{E_0} d_0 + \overrightarrow{E_m} d_m| \tag{5}$$

Substitute Eqs. (4) into (5), it becomes:

$$|\overrightarrow{E_m}| = \frac{V}{\sqrt{(\varepsilon' d_0 + d_m)^2 + (\varepsilon'' d_0)^2}} \tag{6}$$

Then substitute Eqs. (6) back into (2) yields:

$$P = \rho c_p \frac{\partial T}{\partial t} = 2\pi f \varepsilon_0 \varepsilon'' |\overrightarrow{E_m}|^2 = 2\pi f \varepsilon_0 V^2 \frac{\varepsilon''}{(\varepsilon' d_0 + d_m)^2 + (\varepsilon'' d_0)^2} \tag{7}$$

or:

$$\frac{\partial T}{\partial t} = 2\pi f \varepsilon_0 V^2 \frac{\varepsilon''}{\rho c_p [(\varepsilon' d_0 + d_m)^2 + (\varepsilon'' d_0)^2]} \tag{8}$$

Accordingly, for linear temperature increases, the final temperature after processing can be described as:

$$T_f = T_i + t \cdot 2\pi f \varepsilon_0 V^2 \frac{\varepsilon''}{\rho c_p \left[(\varepsilon' d_0 + d_m)^2 + (\varepsilon'' d_0)^2\right]} \tag{9}$$

where T_f is the final temperature of load (°C), T_i is the initial temperature of load (°C), and t is the total processing time (s).

Metaxas (1996) studied the voltage across the load of a free-running oscillator RF system and found there is only a 7% variation between empty and full load in a typical industrial scale system. Therefore, it is a valid assumption that there is a constant voltage at the upper electrode for a certain product during RF heating. The assumption has been used in many previous researches (Marra et al., 2007; Birla et al., 2008a; Tiwari et al., 2011a,b). Since $2\pi f \varepsilon_0 V^2$ can be seen as a constant when the electrode gap is fixed, the heating rate only depends on the value of $\varepsilon''/\{\rho c_p[(\varepsilon' d_0 + d_m)^2 + (\varepsilon'' d_0)^2]\}$.

It can be seen from Eq. (8) that as the d_0 is reduced to zero, the value of ε' does not influence heating rate any more, which means that ε'' is the dominating factor in heat production. In this case, the heating mechanism changes from dielectric heating to resistive heating, in which the power conversion is dominated by the electric conductivity of the food (Metaxas, 1996):

$$P = 2\pi f \varepsilon_0 \varepsilon'' |E_m|^2 = \sigma |E_m|^2 \tag{10}$$