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Effect of load volume on power absorption and temperature evolution during radio-frequency heating of meat cubes: A computational study

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ABSTRACT

During radio frequency (RF) processing, the size of sample between RF electrodes has certain effect on power absorption and heating rates. Hence, certain load sizes might be required for effective RF processes for temperature evolution. Therefore, the objective of this study was to evaluate the effect of sample size on power absorption and heating rate during RF heating. For this purpose, a 3-dimensional multi-physics model was used for various load volumes in two configurations. In the first configuration, distance between RF electrodes was fixed while air gap between sample's surfaces and electrodes was fixed in the second configuration. The smaller the load volume, the larger the air gap and the slower the heating rate of sample due to the behavior of electric field in the first case. The smallest volume in the second case, however, was heated much faster via the deflection of electric field by top–bottom edges increasing net electric field in the sample with the effect of shorter air gap distance. The results indicated that the sample load volume is rather important, and it might be possible to obtain optimal tuning of RF cavities to allow a high heating efficiency by changing the distance between electrodes.

Keywords: Meat processing; Multi-physics modeling; Radio-frequency heating; Load volume; Temperature evolution; Power absorption

1. Introduction

Research in novel heating of food products has focused on evaluating process time, determining heating uniformity and predicting energy efficiency and impact on quality attributes (McKenna et al., 2006; Olivera et al., 2013). Among novel processes, radio frequency (RF) and microwave (MW) heating have many advantages, and they differ from conventional heating since heat is generated volumetrically within materials by electromagnetic radiation formed by conversion of electric energy at high frequencies of 1–300 MHz for RF and 300 MHz–300 GHz for MW (Marra et al., 2009). In MW heating, magnetrons emit microwaves transferred by a waveguide into a cavity where target materials are placed. In RF heating, however, use of parallel plate electrodes is the most common application, and radio-wave generators create electric field alternating between electrodes (one of them grounded to set up a capacitor storing electrical energy) (Farag et al., 2010). When an alternating electric field is applied, positive ions in the material move toward negative regions of the electric field while negative ions move toward positive regions (Buffler, 1993). Heating occurs due to the non-static field, with polarity continuously changing at high frequencies (e.g., 27.12 MHz for RF – 2450 MHz for MW). In addition, continuous reversal of polarity leads to oscillation of ions in the product resulting in heat generation by friction while polar molecules (e.g., water) attempts to align themselves with changing polarity of electric field–dipole rotation (Buffler, 1993; Marra et al., 2009). Heating rate due to electromagnetic field effects is a function of its dielectric loss factor, applied frequency and square modulus of electric field (Ryynanen, 1995) while the electric field inside the material is determined by its dielectric properties, geometry, location in the cavity and cavity configuration (Venkatesh and Raghavan, 2004). Jones and Rowley (1997) gives a comprehensive explanation of physical theory on RF heating. One of the characteristics of MW heating compared to RFis

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its limitation by its relatively short penetration depth. This leads MW technology convenient for small sized materials. In fact, wavelength at RF frequencies is up to 90 times greater than the wavelength corresponding to the commonly used MW frequency. This allows RF energy to penetrate dielectric materials more deeply than MWs (Wang et al., 2003). Besides this advantage of RF, non-uniform heating is a major problem for commercial applications for both methods. Factors, such as material dielectric properties, size and shape and its location between RF electrodes with electrodes ‘configuration, might affect temperature uniformity in the RF treated materials.

Based on this background, various studies focused on simulation of RF processes (Yang et al., 2003; Marra et al., 2007) to improve heating uniformity (Chan et al., 2004; Birla et al., 2008; Petrescu and Ferariu, 2008; Wang et al., 2012). Farag et al. (2010) studied tempering of block-shaped beef blends to analyze heating rates, power absorption and power efficiency. Romano and Marra (2008) analyzed load geometry effects on heating rate and temperature uniformity. Orsat et al. (2001) studied RF treatment for ready-to-eat fresh carrots where 8 cm distance between electrodes resulted in a non-optimal RF coupling (carrots with 1–2 cm in thickness) due to the loss of absorbed power. Considering the product size in this study, distance between electrodes was too large influencing power absorption and hence heating rates. Birla et al. (2004) underlined that larger fruits such as citrus and apples compared to cherries face to a non-uniform heating during RF process due to the variations in the electric field. Tiwari et al. (2011a) also investigated the influence of sample size, shape, relative position between RF electrodes and dielectric properties on RF power distribution in dry food materials. It was concluded in this study that RF heating uniformity could be improved using larger sample sizes due to the behavior of electric field. With rather large volumes inside the cavity, electric field is deflected by edges and corners increasing the net electric field at the outer sections (Marra et al., 2007; Birla et al., 2008). Liu et al. (2013), however, reported the presence of an optimum gap between the electrodes to achieve a uniform heating in the vertical direction of the product located in the RF cavity. In addition, smaller distances between the sample and bottom or upper electrode were also reported to result in edge heating (Liu et al., 2013). As demonstrated in the literature, sample size and its orientation between RF electrodes had a certain effect on power absorption and heating rates. However, effects of the electrode gap and vertical location of loads in the RF cavity were not considered in these previous studies (Liu et al., 2013). Hence, loading of a certain size might be required to lead to an effective process. In this manner, Sisquella et al. (2013) reported a more efficient RF treatment in large size fruits compared to the smaller sizes in terms of controlling the brown rot problem in stone fruits.

Therefore, the objective of this study was to evaluate the effect of sample size with respect to the distance between the electrodes on heating rate and power absorption during RF heating. For this purpose, a 3-dimensional multi-physics model was prepared with COMSOL (Comsol V3.5, Comsol AB, Stockholm, Sweden) and applied for various sample load sizes with different distances between electrodes in a parallel-electrode RF system to compare power absorption and heating rate.

2. Materials and methods

2.1. *Methods*

RF heating simulations were performed considering a parallel plate RF system consisting of a cubic chamber with electrically insulated walls and of two parallel rectangular electrodes. Samples with different volumes were considered symmetrically located between electrodes at the center of the system.

Two cases were planned to simulate the effect of sample load with respect to the position of the electrodes on power absorption and heating rate of the material:

1. The distance between electrodes was fixed at (Fig. 1a) – in this case various sample volumes located symmetrically between the electrodes.
2. The gap between sample surfaces (top and bottom) and electrodes was fixed while various sample volumes were located (Fig. 1b).

Tiwari et al. (2011a) also carried out simulations to determine the effect of sample load where the distance between electrodes was fixed. They modified the dimensions of the cubic geometry to obtain various volumes by changing sample‘s location in the cavity. The results confirmed that reducing electrode gap by increasing the load volume improved the RF power uniformity in the sample load.

Table 1 summarizes the different sizes of applied sample volumes in the RF cavity based on the given configurations. A cubic geometry was preferred since it exhibits a fast and

Table 1 – Geometrical parameters versus sample volume located symmetrically between the electrodes during radio frequency heating: Case 1. Various sample volumes located symmetrically between the electrodes with a fixed distance (78.557 mm); Case 2. Fixed gap (2.5 mm) between electrodes and surfaces (top and bottom) of the sample load for different volumes.

Sample volume [L]	Case 1		Case 2	
	% of reference volume	Distance between electrodes and sample surfaces (top and bottom) [mm]	Chamber volume [L]	Distance between electrodes [mm]
3.9800E−01[a]	100	2.5000	4.8479E−01	78.557
3.5820E−01	90	3.7689	4.3891E−01	75.996
3.1840E−01	80	5.1356	3.9323E−01	73.263
2.7860E−01	70	6.6215	3.4729E−01	70.291
2.3880E−01	60	8.2565	3.0104E−01	67.021
1.9900E−01	50	10.0085	2.5440E−01	63.364
3.9800E−03	1	31.346	9.0535E−03	20.842

[a] Reference sample volume.