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Computer simulation of radio-frequency heating applied to block-shaped foods: Analysis on the role of geometrical parameters

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ABSTRACT

During radio frequency (RF) processing, geometrical factors such as distance between electrodes and projection of top electrode on the samples' exposed surface area (area that electric field passes through the sample) have a certain effect on power absorption, temperature distribution, heating rates and heating uniformity in the samples. Knowing the role played by these factors can be helpful for further studies in optimization of design parameters of an RF heating process. Therefore, to evaluate effect due to distance between electrodes and projection area during RF heating process, samples of same volume but exhibiting different projection areas were used to determine the variability in their power absorption, temperature change and heating rates. RF electrodes in this system were positioned with a fixed gap between samples' top–bottom surfaces and the electrodes and, case by case, at different distance between electrodes. The results indicated that both parameters have strong effect on power absorption, temperature distribution, heating rates and heating uniformity in the samples, which is further amplified when it is combined with the change of dielectric properties with temperature. In the investigated range, wider projection area and shorter distance between electrodes led to faster heating, in terms of average temperature, but less uniform temperature distribution, at least in the early stage of the RF heating process, before the changes in dielectric properties of the heated load started modifying the trend of the loss tangent and penetration depth. The results of this study are expected to be used in planning geometrical configuration and design parameters of RF systems and sample dimensions for further optimization studies.

1. Introduction

As a novel food processing method radio frequency heating (RF, in the frequency range of 1–300 MHz) introduces many advantages over conventional heating since heat is generated volumetrically within materials by electromagnetic radiation. Volumetric heating usually provides a higher heating rate compared to traditional methods (hot air or hot water heating), saving processing time and potentially improving product quality (Jiao et al., 2014). However, one significant problem encountered during RF processing is the possibility of non-uniform heating.

Sample dielectric properties, sample size – geometry, sample position between RF electrodes and electrode

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configuration affect power absorption of the processed sample and hence the temperature and uniformity of thermal field.

A relevant number of studies have been published in the literature about the temperature uniformity in RF heating of food products. Wang et al. (2005) developed a mathematical model to study the influence of the number of RF units and the effect of stirring on heating uniformity of walnuts. Marra et al. (2007) modeled temperature distribution and heating uniformity inside a cylindrical meat roll processed in a RF heating system. Romano and Marra (2008) analyzed the effects of sample shape (sample foods regularly shaped as cube, cylinder and sphere) and orientation on heating rate and temperature distribution in RF heating system using a multi-physics model. Wang et al. (2008) simulated and validated a computer model to study the influence of dielectric properties of mashed potato and circulating water on the electric field distribution, heating rate and temperature distribution in a RF system reporting the results to demonstrate the ability of computer simulation on constructing and modifying RF systems. Tiwari et al. (2011) investigated the effects of sample size and shape on RF power distribution in dry food materials in a parallel plate RF system using a validated model. In their work the authors compared the effect on heating due to the different sizes and positions of the samples, computed the power uniformity index (PUI), and the effects of electrode gap and top electrode configuration were also demonstrated.

Wang et al. (2014) analyzed the effectiveness of polyurethane foam sheets to improve RF heating uniformity, and the influence of different foam locations in an RF cavity were investigated in terms of heating uniformity. Uyar et al. (2014) evaluated the effect of sample size and distance between the electrodes on power absorption and heating rate during RF heating. In this study, the effect of a decreasing sample volume was demonstrated to have a negative effect on the temperature evolution if the electrodes were maintained at a constant distance.

Moreover, sample shape, its orientation in an RF cavity and cavity configuration introduce a further effect on temperature evolution and distribution besides the effects of the distance between electrodes, sample to cavity volume ratio and the distance between the electrodes and the sample. Romano and Marra (2008) demonstrated the significant influence of sample shape and orientation on heating rates and temperature distribution.

Due to the view of the RF electrodes towards the sample, the projection of top electrode is expected to have an effect on the temperature distribution and heating rates of the processed samples. Therefore, products with the same volume but different dimensions (i.e. a regular hexahedral geometry of 4 cm × 4 cm × 4 cm vs a parallelepiped geometry of 2 cm × 4 cm × 8 cm) might heat at different rates. An important parameter for this effect is the area where the electric field formed between the two electrodes of the system passes through the sample plane, and it is called projection area.

The studies quoted above mostly aimed to discuss and to improve heating uniformity of the processed samples. Huang et al. (2016) and Hou et al. (2016) claimed that computer modeling represents a powerful tool to analyze the strategies leading to a better heating uniformity in RF processing of foods. At same time, in the available literature there is still a lack of understanding on the relationship among RF heating uniformity, load shape and projection area. Hence, the objectives of this study was to use a virtual tool, based on computer modeling, to analyze power absorption, temperature distribution, heating rates and heating uniformity in processed food material during RF heating when different projection areas and different distances between electrodes were considered.

2. Materials and methods

2.1. Materials

Four block-shaped samples made of a meat batter, as the one described by Marra et al. (2007), were considered as load placed between the electrodes in a RF cavity (50 ohm) as the one described by Marra et al. (2007) and Farag et al. (2010). All blocks are characterized by the same volume and by different relative dimensions, available in Table 1. The distance between the upper electrode and the top surface of the samples was 2.5 cm. An equal distance was maintained between the lower electrode and the bottom surface of the samples. In this way, four configurations (A1, A2, A3 and A4, all described in Table 1) were obtained.

The placement of the samples from A1 to A4 to obtain various projection areas of the same volumes are shown in Fig. 1. The sample volume was set equal to 10^{-3} m^3 (10^{-1} m × 10^{-1} m × 10^{-1} m in case of sample configuration A1) while the projection areas of the samples were (in m^2) A1: 1.00 × 10^{-2}, A2: 1.25 × 10^{-2}, A3: 1.67 × 10^{-2} and A4: 2.5 × 10^{-2}. Other data on sample dimensions and distance between electrodes are reported in Table 1.

As described by Uyar et al. (2014), a cubic shape was preferred as reference geometry for the load, as it exhibits a faster and more uniform heating with a good rate of power absorption (Romano and Marra, 2008). Besides, a considerable number of food products are processed in boxes during RF heating (Huang et al., 2015; Llave et al., 2015). Romano and Marra (2008) also demonstrated that cubic geometry shows a possible uniformity in temperature distribution since it reflects a full view of its planar surfaces exposed to the electrodes in an RF cavity while a partial view is obtained for the case of round objects. Tiwari et al. (2011) also modified the dimensions of a cubic geometry and its location in an RF cavity to determine the effect of sample load to the power uniformity achieved.

For the numerical simulations to determine the temperature changes of these samples during an RF processing, the RF cavity, as described by Farag et al. (2008, 2010) was used (Fig. 2), with the thermal–physical and dielectric properties of a meat sample reported by Marra et al. (2007).

2.2. Key definitions

In this work, the “projection area” is defined as the area where the electric field formed between the two electrodes of the system passes through the sample plane. Projection area of a 3-dimensional geometry, for example, shows a 2-dimensional area obtained by projecting the external shape of the considered geometry onto an arbitrary plane (surface A), Fig. 3 demonstrates the projection area of a 3-dimensional geometry on a surface. As mentioned in the introductory section, the uniformity of temperature distribution in an RF processed sample is a significant parameter, and it is especially affected by the absorbed power of the sample. To analyze the temperature uniformity and absorbed power, various parameters have been introduced in the literature.