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Radio-frequency thawing of food products – A computational study

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ABSTRACT

Main goal of optimal thawing is to minimize thawing time with least damage to the quality of frozen food products. Microwave (MW) and radio frequency (RF) applications have potential for their use in industrial thawing. Higher penetration depths of RF contribute to a better distribution of energy generated by the interaction between food and electromagnetic field, and thus help to improve the heating uniformity and to minimize runaway heating. Modeling is one way to design and to optimize such process where complexities due to coupling the heat transfer with phase change and the solution of electric field are faced. Therefore, the objectives of this study were to develop a computational model to determine temperature distribution in frozen lean beef during thawing and experimentally validate the model. For this purpose, a commercial software, based on finite element method, was used to solve coupled heat conduction and electric field in a 3D domain with temperature dependent thermo-physical and dielectric properties. Experimental data used to validate the model referred to a 50 Ω and a free-running oscillator RF systems with various sized samples. Comparison of simulation results agreed well with experimental data, and the mathematical model was reported to be used for designing RF systems to mitigate the effect of overheating at the surfaces of the sample.

1. Introduction

Freezing and thawing are important food processing operations. Freezing is one of the key unit operations for preservation of foods. With notable exceptions such as ice cream, frozen foods must be thawed before further use or consumption. In a number of food processing operations, it is a common practice to begin with frozen foods as raw material. For example, in manufacturing sausages, frozen meat is used as the raw material. Similarly, large blocks of frozen fish are processed into fillets for further processing. Different thawing and tempering methods are used for preparing frozen foods for further processing, and each method has its own advantages and disadvantages (e.g., thawing in air or in water, use of impingement systems, microwave thawing). The main goal of a thawing process is to keep thawing time to a minimum so that the least damage is caused to quality. However, a number of quality attributes might be adversely affected during thawing by moisture (drip) loss, change in the structure of proteins, microbial growth and textural changes. Thawing of large-size frozen foods such as big chunks of meat or fish takes excessively long time in conventional processes like use of still-air or low-velocity moving air environment. This is due to the fact that thawing involves a conduction mode of heat transfer within the product, and upon thawing of surface, frozen parts are being surrounded by a low thermal conductivity layer. This slows down the process with inevitable losses in the quality like excessive water loss due to dripping or evaporation and increased microbial growth on the food surface.

Conventional methods remains widely used in industrial practice primarily because they are economical and applicable to a wide range of products. However, there is a critical need to develop procedures that would reduce thawing time without incurring microbial growth or other adverse physical or chemical changes in the product. As noted by Farag et al. (2008a), industry is always interested in fast and compact systems while maintaining the quality during thawing. Besides conventional thawing systems of using air, microwave (MW) and radio frequency (RF) applications appear to have the potential for industrial use (Farag et al., 2008a) to overcome the various problems faced during thawing. In these systems, heat generation is carried out by dipole rotation and ionic polarization through the movement and friction of dipoles and/or ions under alternating electric field (Buffler, 1993).

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In dielectric heating, dipole rotation is major contributor at higher frequencies (MW – 915 or 2450 MHz) whilst ionic displacement is more pronounced at the lower frequencies of RF (e.g., 27.12 MHz) (Jones, 1992). MW heating is more accepted for rapidly heating small sized food products but found to be less satisfactory for heating larger sized ones (Taher and Farid, 2001). This is due to the problem of runaway heating (occurring with melting of ice since water heats faster due to its high dielectric loss factor) leading to a non-uniform heating (some parts might be cooked with still some unfrozen parts) and limited penetration depth compared to RF heating (Buffler, 1993). Higher penetration depths of RF and less generated energy to convert heating help improve heating uniformity and minimize the runaway heating problem. Besides experimental studies, mathematical modeling is another way to design and optimize an RF thawing process.

Modeling RF processes is a multi-physics problem that involves the solution of electromagnetic equation coupled with heat transfer equation with a generation term as a function of electric field. Various studies in the literature focused on modeling of RF processes to improve heating uniformity (Chan et al., 2004; Yang et al., 2003; Marra et al., 2007; Romano and Marra, 2008; Birla et al., 2008; Petrescu and Ferariu, 2008; Wang et al., 2012). The coupled electro-thermal problem of modeling an RF process becomes more complicated for simulation of thawing since the phase change process requires dealing with evolving large latent heat over a small range of temperature. Moreover, variations in thermo-physical and dielectric properties in the phase change region also increase the complexity of RF thawing simulation. To deal with this difficulty, apparent specific heat, enthalpy and quasi-enthalpy methods are suggested (Pham, 2006). Then, simulation of an RF thawing process becomes a multi-physics problem where the coupled heat transfer with electrical field distribution should be solved including the phase change process. There are not many studies for modeling RF thawing carried out in the literature for this purpose while modeling MW thawing has been practiced numerous times (Basak and Ayappa, 1997; Chamcong and Datta, 1999a,b; Taher and Farid, 2001; Rattanadecho, 2004; Tilford et al., 2007; Campanone and Zaritzky, 2010). Therefore, the objectives of this study were to:

– develop a computational model to determine the electrical field distribution in a RF system and temperature distribution in the frozen product during thawing, and
– validate the thawing model with experimental results.

2. Materials and methods

2.1. Experimental studies

This study was completed in two parts. First, two computational 3D multi-physics models for modeling RF thawing were developed using COMSOL (Comsol V4.3b, Comsol AB, Stockholm, Sweden): one for a parallel-electrode RF systems and another one for a free-running oscillating system, and the models were validated with two various sets of experimental data. The first set of experimental data used to validate the parallel-electrode RF model was obtained from previous works published by some of the authors, such as Farag et al. (2008a,b, 2011, 2010), in which a custom built RF system (50 Ω) was used to thaw a large size sample of frozen lean beef meat (≈3.84 kg), shaped as a parallelepiped (20 × 20 × 10 cm). Farag et al. (2008a and 2011) extensively described the experimental set-up and the methodology used to measure, off-line, the temperature at 25 different locations (Fig. 1). The RF system related to the studies published by Farag et al. (2008a,b, 2010, 2011), is a custom built 50 Ω system (manufactured by C-Tech Innovation, Chester, UK) using a low power (in the considered study, 400 W) generator with an automatic impedance matching network and controller at a frequency of 27.12 MHz was used. The boxed frozen lean beef sample (20 × 20 × 10 cm) was placed at the center of the bottom electrode (Fig. 1) during the experiments carried out in this system. The distance between top of sample and upper electrode was 1.4 cm as demonstrated in Fig. 1.

Subsequently, a series of experiments was carried out in the laboratories of the Mersin University (Turkey) for the second data set in a free-running oscillator RF system for thawing smaller samples of frozen ground lean beef. The system was a 2 kW pilot scale free-running oscillator RF system (Sonar, Izmir, Turkey), sketched in Fig. 2. It was used to generate the experimental data. For this purpose, minced lean beef was purchased from a local store. Samples shaped as blocks of various dimensions (width × length × thickness) were prepared for RF thawing studies: one block (A) was 12.0 × 17.2 × 3.8 cm – with a mass of 0.8 kg; the other block (B) was 12.0 × 17.2 × 5.5 cm – with a mass of 1.2 kg. These samples were placed in a poly-propylene (PP) container, then two fiber-optic probes (Fiso Technologies, Inc., Quebec, Canada) were inserted in the samples (Fig. 3), and they were frozen in a freezer (some samples at −13 °C, some other at −18 °C) prior to the thawing experiments. For the block A, the distance between sample surface and upper electrode was 12 cm while it was 13 cm

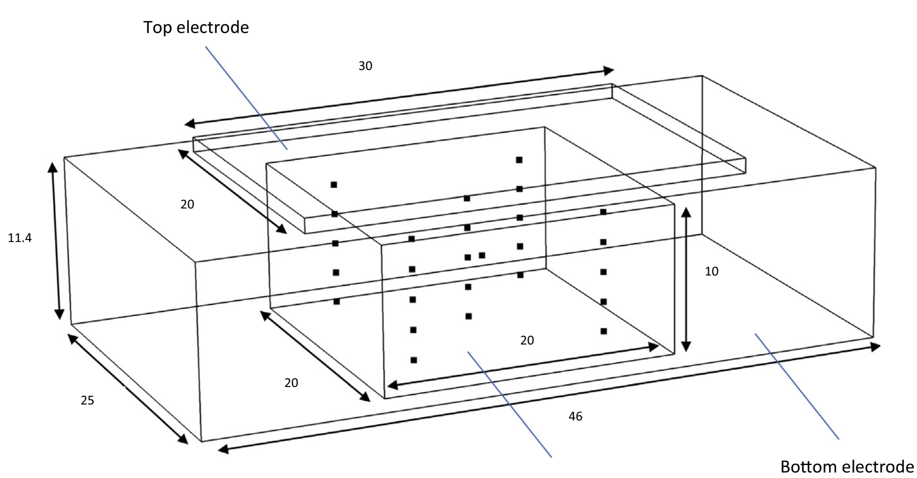

Fig. 1. Sketch of the experimental set up by Farag et al. (2008a,b, 2010, 2011) and position of 25 locations (black spots) in the sample where the temperature data were recorded. All measures in cm.