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Radio frequency tempering uniformity investigation of frozen beef with various shapes and sizes

Yulin Li[a,b,c], Feng Li[a,b,c], Juming Tang[d], Ruyi Zhang[a,b,c], Yifen Wang[a,b,c,e], Tony Koral[f], Yang Jiao[a,b,c,*]

[a] College of Food Science and Technology, Shanghai Ocean University, Shanghai 201306, China
[b] Engineering Research Center of Food Thermal-processing Technology, Shanghai Ocean University, Shanghai 201306, China
[c] National R&D Branch Center for Freshwater Aquatic Products Processing Technology (Shanghai), Shanghai 201306, China
[d] Department of Biosystems Engineering, Washington State University, Pullman, WA 9164-6120, USA
[e] Department of Biosystems Engineering, Auburn University, Auburn, AL 36849-5417, USA
[f] Koral Associates, Woodcote, South Oxfordshire RG8 0QE, United Kingdom

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ABSTRACT

Radio frequency (RF) energy generates fast and volumetric heating as it penetrates food materials and converts electromagnetic energy to heat. With these advantages, RF heating is considered as a promising technology for tempering and thawing processes in the meat and fishery products industry. However, non-uniform heating problems hinder its further application to meat products due to their various sizes and irregular shapes. This study utilized representative frozen beef samples to investigate the parameters of varying sample thickness (40 mm; 50 mm; 60 mm), base area (small:$160 \times 102 \times 60\ \text{mm}^3$; medium: $220 \times 140 \times 60\ \text{mm}^3$; large: $285 \times 190 \times 60\ \text{mm}^3$) and shape (cuboid; trapezoidal prism; step) and their influence on tempering uniformity in a parallel-plate RF system. A computer simulation model was established, verified by experiments and then was utilized to evaluate the volumetric temperature distribution in food samples. Results show that the heating rate increases and heating uniformity decreases with increasing sample thickness and decreasing sample base area. As sample thickness increased from 4 cm, 5 cm to 6 cm, the simulated temperature uniformity index (*STUI*) increased from 0.093, 0.117 to 0.194. Sample base area increases from small to large decreased the *STUI* from 0.229 to 0.194 and 0.090. Among all three shapes, the cuboid shape has the best heating uniformity (*STUI* 0.194), followed by the trapezoidal prism (*STUI* 0.209) and the step shape (*STUI* 0.282). The step shape has the worst tempering uniformity because the RF energy focuses mainly on the vertical section and results in severe regional heating. Strategies to improve the step-shape frozen beef tempering uniformity by decreasing the input power to 1/3 and enlarging the electrode gap by 40 mm only reduced the hot spot temperature from 88 to 78 °C. Further research is needed in order to develop methodologies or suitable equipment for irregular shape food RF tempering in the future.

Industrial relevance: In industrial radio frequency thawing/tempering, the raw materials are usually presented in various irregular shapes and sizes. Thus, analyzing the non-uniformity severity influenced by sample size, shape and thickness to determine the capability and throughput of the equipment is necessary. Results in this study could be utilized in pre-evaluation of a protocol design and process optimization for irregular-shape food tempering.

1. Introduction

In recent decades, the amount of imported beef to China has been rising significantly to satisfy the local consumers' need of high-quality protein sources (Wu-Sheng & Cao, 2015). Before beef is exported, cows are slaughtered, cleaned, cut, and frozen to a temperature below −18 °C. After arrival, the beef parts are usually tempered for the purpose of easy cutting, either for sale or further processing. Traditional tempering processes usually allow meat products staying in a refrigeration room at 4 to 10 °C with proper air circulation. However, it typically take around 10 to 20 h to thoroughly temper large meat trunks since the natural convection heat transfer between air and frozen food material and the thermal conduction inside frozen food materials is slow (Brown & James, 2006; Uyar et al., 2015). During this lengthy

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[*] Corresponding author at: College of Food Science and Technology, Shanghai Ocean University, Shanghai 201306, China.
E-mail address: yjiao@shou.edu.cn (Y. Jiao).

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tempering, the beef surfaces are exposing to relatively high temperature that would allow microbe multiplication (Manios & Skandamis, 2015; Xia, Kong, Liu, Diao, & Liu, 2012), water drip loss (Eastridge & Bowker, 2011) and meat quality deterioration. Novel fast and uniform tempering techniques are therefore needed to shorten the time and prevent food quality degradation and nutrition loss.

Radio frequency (RF) has been applied in the food industry as a novel heating technology for many years with its advantages of fast and volumetric heating characteristics. Within the 21st century, much research has been conducted on RF drying (Wang et al., 2011, 2013; Zhang, Zheng, Zhou, Huang, & Wang, 2016), tempering (Bedane, Chen, Marra, & Wang, 2017; Farag, Duggan, Morgan, Cronin, & Lyng, 2009; Llave, Terada, Fukuoka, & Sakai, 2014), sterilization (Liu, Zhang, Xu, Fang, & Zheng, 2015), and pasteurization (Gao, Tang, Villa-Rojas, Wang, & Wang, 2011; Geveke, Kozempel, Scullen, & Brunkhorst, 2002; Li, Kou, Cheng, Zheng, & Wang, 2017; Zheng, Zhang, & Wang, 2017) etc. in food industry. The principle of RF heating is that the RF generator produces a high frequency alternating electromagnetic field, and the polar molecules and charged ions in foods are agitated in the alternating field. This high speed agitation results in frictional energy loss and heat is generated within the food matrix. Research into applying RF technology to frozen food tempering and thawing started in the middle of the 20th century. Experiments have been conducted for vegetables, meat, and aquatic products on experimental and pilot scale RF heaters (Bedane et al., 2017; Llave et al., 2014; Sanders, 1966). Researchers have found that RF tempering can save 90% of the processing time comparing with traditional methodologies, and it also preserves most of the quality attributes (Farag et al., 2009; Llave et al., 2014). These research exercises have been mostly conducted with regular-shaped (normally cuboid) samples in order to simplify those experiments. However, together with the fast heating characteristic, problems of uneven heating have been found at the edges and corners of the cuboid-shape samples processed in a parallel-plate RF equipment. In order to elevate the center temperature of the frozen products to −4 °C, the edges and corners are normally over-heated to above 10 °C or even higher, which causes severe quality degradation to final tempered products (Bedane et al., 2017; Kim et al., 2016). The reasons for edge heating or non-uniform heating of RF technology has been discussed by many researchers in various applications (Alfaifi, Tang, Rasco, Wang, & Sablani, 2016; Jiao, Tang, & Wang, 2014). The established principle is that when the food material is placed in an electromagnetic field, the electromagnetic waves tend to penetrate into food materials perpendicularly to their surfaces, and the energy carried by the wave decays as it penetrates further into the food material. Since sharp edges and corners are where many surfaces converge, the electromagnetic field intensity at these locations is higher than in the rest of the sample and causes more severe heating. Edge heating also causes thermal-runaway due to the fact that dielectric loss increases as temperature increases. Compared with regular shapes such as cuboids and cylinders, irregular shapes usually have more curved surfaces, cavities and are of uneven thickness, which gives rise to the non-uniform heating patterns observed in RF heating experiments. Therefore, for irregular-shaped food products such as meat and aquatic products, the non-uniform heating problem needs to be analyzed systematically and quantitatively to allow safe industrial processing protocols to be established.

Computer simulation has the ability to solve coupling equations and demonstrate the 3D distribution of the desired parameters, which gives rise to considerable time and labor savings and reduces the need for excessive experimental work. COMSOL Multiphysics® has been utilized in RF heating process simulation in many published works (Alfaifi et al., 2014; Chen, Lau, Chen, Wang, & Subbiah, 2017; Erdogdu, Altin, Marra, & Bedane, 2017; Jiao et al., 2014; Marra, Lyng, Romano, & McKenna, 2007; Uyar et al., 2015; Zhu, Li, Li, & Wang, 2017). After being validated by practical experiments, the established model is able to demonstrate the volumetric distribution of temperature and electromagnetic fields in RF treated products, and analysis of the tempering uniformity can be made according to a developed temperature uniformity index (TUI) (Jiao, Shi, Tang, Li, & Wang, 2015).

The thickness, volume, position and orientation of the food sample can influence its heating behavior in the RF field, and the effects had been investigated by several researchers (Ferrari-John et al., 2016; Marra et al., 2007; Romano & Marra, 2008; Tiwari, Wang, Tang, & Birla, 2011a; Uyar, Erdogdu, & Marra, 2014; Uyar, Erdogdu, Sarghini, & Marra, 2016). However, most of these studies have focused on regular shaped products and not many of them have been verified experimentally (Alfaifi et al., 2016; Huang, Zhu, Yan, & Wang, 2015; Tiwari et al., 2011a; Uyar et al., 2016). The effect of sample sizes and shapes on RF tempering results has not been explored and validated systematically. A thorough understanding of all the geometrical factors including shapes and sizes and their influence would help further design RF tempering processes and improve the uniformity of RF tempering.

The purpose of this study is to (1) build up an RF tempering computer simulation model based upon a 50-ohm RF system using the COMSOL Multiphysics® software package to simulate the tempering process of frozen beef samples with selected sizes and shapes; (2) verify the accuracy of the simulation model by pilot-scale RF tempering experiments; (3) apply the model to analyze the heating uniformity index of various beef samples, and (4) explore the effect of varying the electrode gap and the RF power input in order to improve heating uniformity with a representative-shaped food sample.

2. Materials and methods

2.1. Frozen food sample preparation

A quantity of fresh lean beef was purchased from a local grocery store in Lingang, Shanghai, China. The beef samples were minced with an automatic mincer (JR-12 800W, Shangxichu, Guangzhou) and then homogenized by hand mixing before filling into cuboid polypropylene containers. The size and specific dimensions of the samples are shown in Fig. 1. Specifically, (a) (b) (c) are frozen beef samples with the same base surface area but of three different thicknesses: (a) 40 mm; (b) 50 mm; (c) 60 mm. (d) (c) (e) are samples with the same height but different base surface areas: (d) small 160 × 102 mm^2; (c) medium 220 × 140 mm^2; (e) large 285 × 190 mm^2. (c) (f) (g) are samples with different shapes: (c) is cuboid, (f) is a trapezoidal prism shape with a corner (1/8 volume) cut off from (c), and (g) is a step shape with a corner (1/4 volume) cut from (c). It needs to be mentioned here that sample (c) was depicted three times in Fig. 1 as control since it represents “60-mm thickness”, “medium base area” and “cuboid shape” in each category, respectively.

To prepare samples (a) to (e), the minced beef was filled into containers, pressed to avoid air cavities inside samples, and then scraped flat. To prepare samples (f) and (g), clay material was firstly softened and modeled to the shape of the missing portion of the beef samples. When the clay had cooled down, it was put into the container bottoms, and then the minced beef was filled into each container to a controlled thickness and scraped flat. All beef samples with clay and containers together were placed in a freezer (BCD-610 W, SIMENS, Germany) at −30 °C for at least 24 h until the center location reached −30 °C. After freezing, the clay and frozen beef were removed from the containers and separated manually.

2.2. Computer simulation

2.2.1. Physical model

A 3D computer model was built for the test set-up, a 12 kW, 27.12 MHz, 50-ohm RF system (Labotron 12, Sairem, France). To simplify the modeling process, only the RF heating cavity and the food sample were considered in the computation process. The RF wave generation and transmission process was simplified to a voltage value assigned to the top electrode as the energy source. The system layout