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Experimental study of radio frequency (RF) thawing of foods with movement on conveyor belt

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ABSTRACT

Thawing of frozen food products without affecting quality attributes at reasonable processing time is a crucial step in developing industrial-scale processing equipment. Radio frequency (RF) thawing of frozen lean beef meat blocks was experimentally studied under batch (static sample between electrodes) and continuous (sample moving between electrodes along the RF system) conditions. The objectives of the study were to investigate the processing parameters and conditions influencing the heating uniformity during RF thawing under moving conditions. A pilot scale RF system with 27.12 MHz and 6 kW was used to thaw lean beef meat block under static and moving conditions. Prior to run thawing experiments, dielectric properties of lean beef meat at different frequencies and temperatures were measured. An optimum electrode gap of 10 cm was chosen based on the thawing time and temperature distribution of the product to investigate effects of different conveyor belt speed in moving condition. The experimental results revealed that thawing of frozen lean beef meat blocks on moving conveyor belt slightly improved the heating uniformity across the food product. Average temperatures of −0.2 °C ± 1.5 and 0.4 °C ± 0.7 were achieved at 17 min of thawing time using static conditions and moving on conveyor belt at 3 m/h, respectively. The experimental results could be used for further studies using simulations to optimize and design process parameters.

1. Introduction

In food-processing industries, freezing is an effective way to preserve products either before or after processing operations. In meat (beef, pork, and poultry) and seafood processing industries, freezing preservations are highly applicable and have been widely used for long time. Those frozen products need to be tempered or thawed to an acceptable temperature for further processing. Perishable food items, such as military operational rations that are kept in cold chain storage and transportation, require thawing for further consumption (Karthikeyan et al., 2015). Most food processing operations involving large blocks of frozen fish and meat require tempering or thawing for further processing or cutting into small pieces. During thawing of those food products, conditions for microbial growth are highly favorable because of high water activity (Pham, 2006). Conventional thawing systems such as air impingement (Anderson and Singh, 2006) or cold and hot water thawing (James and James, 2002) have been applied in food processing industries. However, the drawbacks related to long thawing times, unexpected increases in surface temperature and possibilities of microbial growth on the surfaces of food have been the main concern. Rapid thawing methods are therefore required to avoid problems related to long thawing times and changes in quality attributes. Recently, the use of dielectric heating systems, such as radio frequency (RF) energy, has become the choice of many processing industries due to their shorter processing times.

The advantages of reduced thawing time are to avoid deterioration of food product quality, inhibit microbial activities and control water loss from dripping (Chamchong and Datta, 1999; Taher and Farid, 2001). Moreover, dielectric assisted heating methods provide volumetric heating, ability to penetrate deep and possibilities to heat food products in packaging. RF assisted thawing of food products has been explored and reported for various

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products, such as lean beef meat (Farag et al., 2010; 2011; Uyar et al., 2015) and tuna fish (Llave et al., 2015). Farag et al. (2011) studied RF thawing of different meat blends (lean, lean/fat and fat) using 27.12 MHz RF systems and reported that RF thawing is 85 folds faster than conventional air thawing. Uyar et al. (2015) also developed a mathematical model and validated the model with experimental data using different sizes of meat blocks. They reported that thawing times and power absorption within the food products were affected by sample size. However, a number of problems remain to be addressed due to non-uniformity of temperature distribution in the food product, and possible ways to mitigate higher temperature encountered on the surfaces and corners of the product.

Most of previous researches in RF thawing were focused on batch processes, while continuous treatment method is demanded in food industry for the advantages of handling large quantities of products, and reducing handling costs. Especially in meat products processing industries, the most common processes like tempering and thawing of frozen products involve larger sized frozen food products to be processed at the same time and hence require fast and continuous processing methods. This remains an open research area to extend the applications of continuous methods to practical industrial processing technologies.

RF heating systems work both in batch and continuous modes. However, the application of continuous mode (considering a food product moving on conveyor belt) in industrial systems is more desirable than the batch ones because the continuous operation improves the process cost of mass production and quality level of products. In meat processing, emulsion type of sausages for manufacturing of heated meat products uses continuous processing. Houben et al. (1991) reported that sausage products heated in continuous RF system had a good appearance, smooth surface and did not show moisture or fat release. An industrial RF heating system has been used for postharvest treatments of insect control in walnuts (Wang et al., 2007a, 2007b), lentils, (Wang et al., 2010; Jiao et al., 2012), chestnuts (Hou et al., 2014), and rice (Zhou and Wang, 2016). In continuous RF processing, the heating uniformity was influenced by physical parameters, such as speed of belt conveyor and, consequently, the residence time. Wang et al. (2010) also used a pilot scale RF system to investigate postharvest treatment of legumes, such as chickpea, green pea, and lentil, and reported that heating uniformity was improved using back and forth movement of products on belt conveyors. The same approach followed by Zhou et al. (2015) to develop a treatment protocol for achieving 100% mortality in postharvest insect control in milled rice. The heating uniformity is still a major concern in developing a large-scale industrial RF treatment.

Various techniques have been proposed to improve heating uniformity during RF processing. Recently, Huang et al. (2016) investigated the effects of using polystyrene container to improve heating uniformity for low-moisture agricultural products. For industrial large scale RF heating systems, the uses of hot air and mixing have been applied to agricultural products to improve the uniformity of heating (Wang et al., 2013; Chen et al., 2015a). Zhou et al. (2015) also investigated the effect of RF heating combined with hot air and product movement on conveyor belt and reported that heating uniformity could be improved without affecting product quality parameters. To date, there are no published studies on the factors affecting heating uniformity during continuous RF thawing of frozen food product. Investigation on the most influencing parameters and processing conditions will help to scale up the RF assisted thawing systems for industrial applications. Therefore, the objectives of this work were to experimentally study the continuous thawing of lean beef meat block using RF systems and to investigate the processing parameters affecting the heating uniformity and thawing time.

2. Material and methods

2.1. Radiofrequency thawing

Thawing of frozen products involves the transfer of heat to melt the ice that is formed within the product during freezing process. Thawing process is accomplished when the temperature of the cold spot (mostly at the center) is treated to a temperature just above the freezing point of the food product (Farag et al., 2008). During the thawing process, the surface temperatures may indicate that thawing is accomplished but the center part remains frozen or needs more time to be thawed. RF thawing method offers rapid thawing of frozen food products with minimal degradation and quality loss with respect to conventional processes (Uyar et al., 2015). The heating during RF thawing is generated due to the interaction between high alternating electric field molecules in food products when a food product is placed between two electrodes. The heat generation depends on the constituents and properties of the food. However, due to the different constituent and nature of food products, thawing is a complex process.

In continuous RF thawing system using conveyor belt to move the products along the RF system, the amount of heat generated inside the product and the thawing time are controlled by means of the voltage applied, which is adjusted by using different electrode gaps, and by means of the speed of the conveyor belt.

2.2. RF thawing method

Frozen lean beef blocks were thawed using a 6 kW, 27.12 MHz parallel electrode plate, free running oscillator RF equipment (COMBI 6-S, Strayfield International Limited, Wokingham, UK). The RF equipment consists of adjustable gap between electrodes from 9 cm to 19 cm and adjustable speed of conveyor belt from 1 m/h to 60 m/h for continuous heating operations. Schematic description of the used RF system and its detailed dimensions can be found in Chen et al. (2015b). Thawing of the lean beef blocks was performed using batch (static sample between electrodes) and continuous (sample moving between electrodes along the RF system) conditions. In batch case, the sample block was placed at the center of the bottom electrode; while for continuous case, the frozen meat block was placed on the belt conveyor and transferred through the tunnel from right to left side passing through two electrodes. The sample was placed at the entrance under the top electrode edge.

2.3. Sample preparation

Lean beef meat was purchased from local commercial market in Yangling, Shaanxi, China. The meat was cut into smaller size and fatty parts were removed manually. After selection, the lean beef meats were minced to a smaller size (average size 0.04 mm) in a kitchen meat-grinding machine working at 200 V and 200 rpm. 1.2 kg lean beef meat blocks were prepared in a polypropylene container having external dimensions of 20 × 13.5 × 6.5 cm^3 and internal dimensions 19 × 12.5 × 5.5 cm^3. The polypropylene container was filled using stage-by-stage tamping to exclude entrapped air: the minced meat used to fill the plastic container was divided in two layers, 19 cm long, 12.5 cm wide and 2.75 cm thick; between the two layers of meat, a cellophane plastic film was placed. The separation of meat layers by the cellophane plastic film allowed to quickly capture the thermal image of the top surface of the bottom layer with an infrared (IR) camera discussed in section 2.5. Then, the meat blocks were frozen in refrigerator at −20 °C for 24 h prior to thawing experiments.

2.4. Dielectric properties measurement

The dielectric properties of lean beef meat are the most important parameters used to understand the behaviors of RF heating. The study of these properties provides information on how the materials interact with electromagnetic energy and the rate at which energy is absorbed by the material (Marra et al., 2009). The dielectric properties of interest are dielectric constant and dielectric loss factor, which can be described by complex relative permittivity form in equation (1) below:

$$\varepsilon^{*} = \varepsilon^{'} - j\varepsilon^{''} \tag{1}$$

in which real part (ε') referred to dielectric constant and an imaginary part (ε'') referred to dielectric loss factor and $j = \sqrt{-1}$.

To study the behavior of heating and the factors affecting heating rate of the product during RF thawing of lean beef meat, it is necessary to measure the dielectric properties within range of temperature and frequency. These properties could also be used in designing an efficient industrial scale RF thawing systems.

The dielectric properties of frozen lean beef samples were measured using the most common method, the open-ended coaxial-line method. The impedance analyzer (E4991B, Keysight Technologies Co., LTD, California, USA) located in College of Food Science and Engineering (Northwest A&F University, Yangling, China) was used for measuring dielectric properties. The system consists of E49991B-300 model impedance analyzer (Keysight Technologies Co., LTD) with a calibration kit (E49991B-010), a high temperature coaxial cable, dielectric probe kit (85070E-020), a custom-built sample holder and a SST-20 oil circulated cooling system (Guanya Constant Temperature Cooling Technology Co., LTD, Wuxi, China). The analyzer had a measurement frequency range of 1 MHz–3 GHz. The sample holder used was an oil-jacketed cylindrical holder constructed of two coaxial stainless steel tubes designed and constructed in Yangling. Details of the equipment can be found in Wang et al. (2003).

At the beginning, the analyzer was warmed up for 30 min and a calibration was performed for the probe using three-calibration data acquisition procedures with open, short and 50Ω resistance in order. The open-ended coaxial system was then calibrated using air, short circuit and deionized water at 25 °C. Twenty grams of minced lean beef meat samples were placed in a stainless steel cylindrical holder (23 mm diameter and 56 mm height). The sample holder was attached to a liquid cooling system that was used for freezing the sample to a lower temperature prior to dielectric measurement. A thin 1.02 mm rigid stainless thermocouple was inserted into the center of the sample to monitor the temperature of the sample. Four replicated measurements were performed between the temperature range of −15 °C and 65 °C and the dielectric properties data were recorded and calculated using computer and software.

2.5. Temperature measurement

The heating behavior and temperature-time histories measured at desired points are very important to evaluate heating uniformity and to allocate the points or surfaces with hot and cold spots within the product. The thawing time required for the meat blocks was determined based on the end point temperature required by meat processing industries (−1 to +5°C). Temperature-time histories of lean beef meat were recorded during RF treatment at desired points across the sample. Measurement was performed in two different ways, one for detecting the surface temperature distribution and the other to follow the temperature evolution in particular points in the investigated domain. Surface temperatures on the top and middle surfaces of the sample were recorded using IR camera (DM63-S, DaLi Science and Technology Co., LTD, Zhejiang, China) with an accuracy of ±2.0°C. Recordings were performed instantly (in 20 s) when the sample was removed from RF equipment after thawing. The surface temperatures were collected and analyzed using image analysis system (V1.0, DaLi Science and Technology Co., LTD, Zhejiang, China). To detect temperature inside the block of meat undergoing the RF assisted thawing, small holes of size 2 mm were drilled using laboratory drilling machine at different points of the sample. Previous works (Uyar et al., 2015) demonstrated that RF assisted thawing of block shaped foods are characterized by warmer areas located in the proximity of block corners while colder areas are located in the central portion of the block (points 3 and 6). As shown in Fig. 1 the holes were located close to corners (as in case of measurement points 1, 2, 4 and 5) and in the central portion (points 3 and 6).

A six-channel fiber-optic temperature sensor system (HQ-FTS-D120, HeQi Technologies Inc, Xi'an, China) was used with an accuracy of ±0.5°C and the temperature-time histories were recorded by the connected data logger (FTS-P104, Xi'an HeQi Opo-Electronic Technology Co, LTD, Shaanxi, China).

The average and standard deviation values of the temperatures recorded at six points (two points each on top, center and bottom sections) using fiber optics were used for evaluation of heating uniformity index.

2.6. Electrode gap and conveyor belt speed selection

Electrode gap is the most important parameter among processing ones that highly affect the power absorption and hence temperature distribution across the food sample subjected to RF heating. It is also reported that the voltage of the top electrode is affected by the gap between the top and bottom electrodes (Zhu et al., 2014). To determine the optimum gap between electrodes, a range of gaps were selected between 9 cm and 12 cm at interval of 1 cm. This experiment was performed first in stationary case (the sample placed on the static conveyor belt between two electrodes) to obtain the general relationship between the electrode gap and the temperature-time histories measured at the center of the sample. The thawing time needed to reach 0°C and the surface temperature measured on the top and middle of the sample block were used to compare the heating uniformity and to choose the best electrode gap. After the right electrode gap was chosen, subsequent experiments were carried out using conveyor belt movement at different speeds. The speed of the conveyor belt was calculated using the length of the top electrode and the thawing time obtained from stationary thawing.

RF heating with moving conveyor belt is claimed to improve the heating uniformity and increase production excluding mixing to

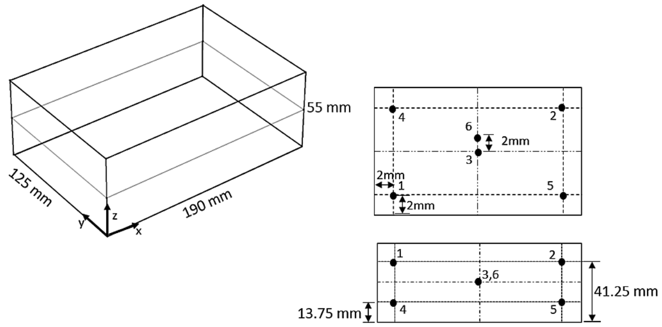

Fig. 1. Size of lean beef meat block used in the experiment and position of thermocouples within the sample.

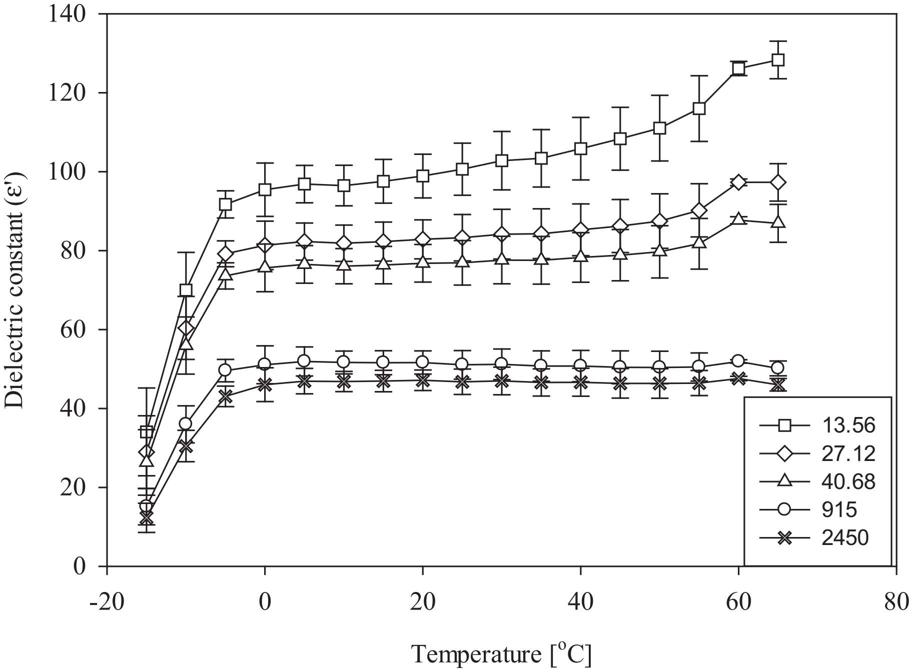

Fig. 2. Dielectric constant of lean beef meat for selected frequencies (in MHz).

achieve high throughput for industrial applications (Wang et al., 2007a,b; Zhou et al., 2015; Zhou and Wang, 2016). During continuous RF thawing, the parameter, which affected the heating behavior, was the speed of the conveyor belt. The residence time (time required by the product to stay fully under the top electrode) could be decided by the speed of the conveyor belt. The faster the speed of the conveyor belt, the shorter the residence time and the faster the block leaving the heating region. Relationship between the top electrode length and time required to thaw lean beef block at stationary condition was used to determine the speed of electrode conveyor. Using length of top electrode, 0.83 m, and thawing time of 17 min, speed of conveyor belt was calculated to be 2.93 m/h. Three different speeds (2.5, 3.0 and 3.5 m/h) were selected and the effect of varying conveyor belt speeds on heating behavior was investigated. In this study, one representative food block was used to study the effect of conveyor belt speed and residence time on heat uniformity and thawing time.

2.7. Heating uniformity index

The determination of one or more parameters capable of quantifying the heating uniformity has been discussed in the recent

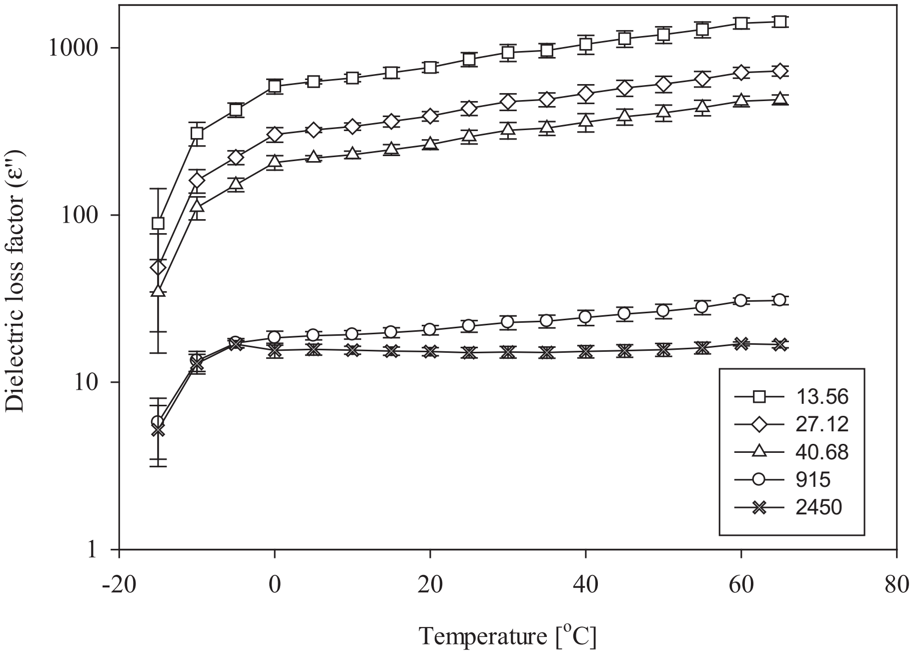

Fig. 3. Dielectric loss factor of lean beef meat for selected frequencies (in MHz).

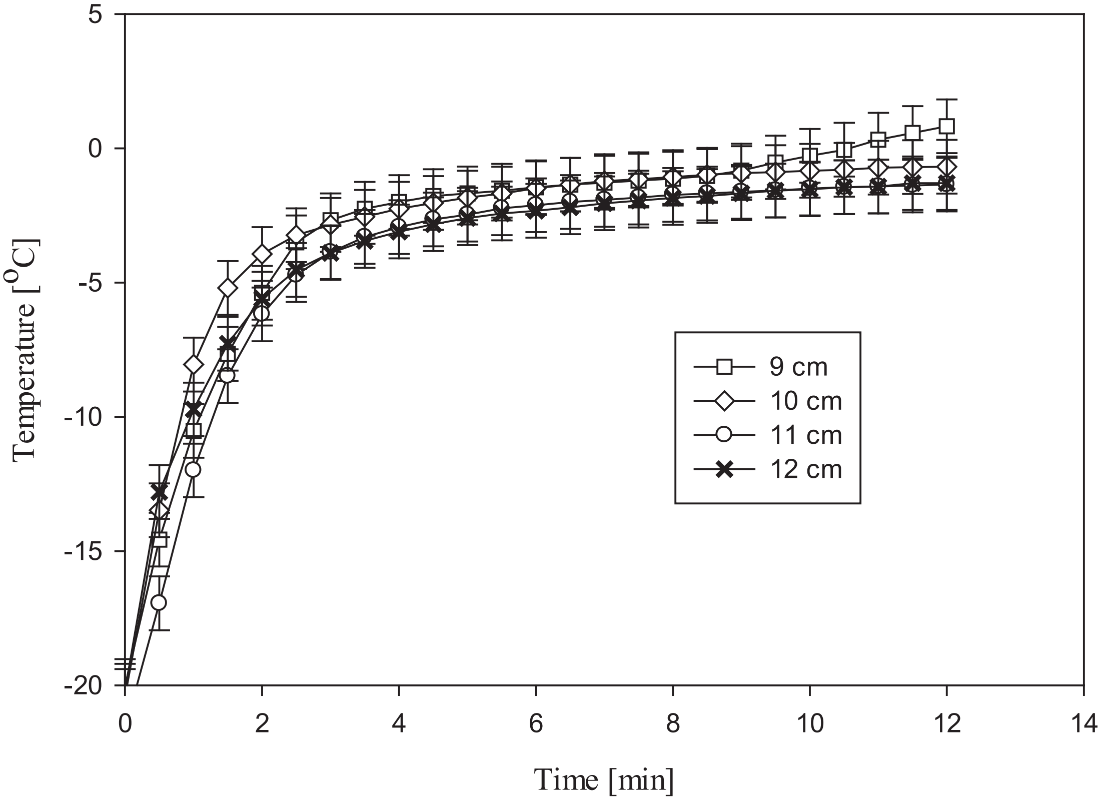

Fig. 4. Temperature-time histories at the center of the lean beef thawed using stationary RF system under different gaps between electrodes.

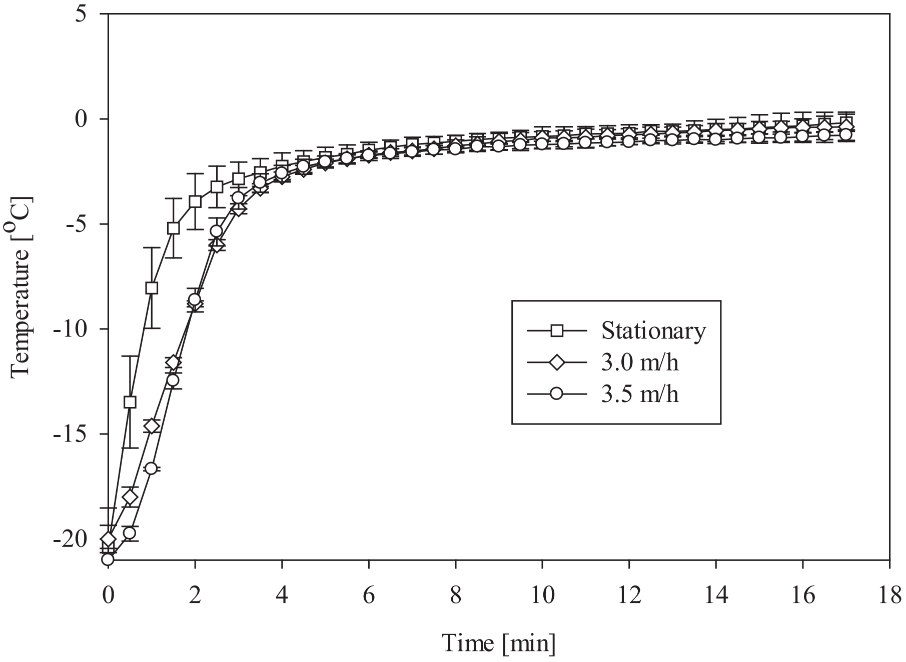

Fig. 5. Comparison of temperature-time histories between stationary and moving on conveyor belt using 10 cm electrode gap.

literature (Uyar et al., 2016). In this work, heating uniformity index (λ), as proposed by Wang et al. (2005), was used to evaluate the uniformity of RF heating, according to the following equation:

$$\lambda = \frac{\Delta\sigma}{\Delta\mu} \tag{2}$$

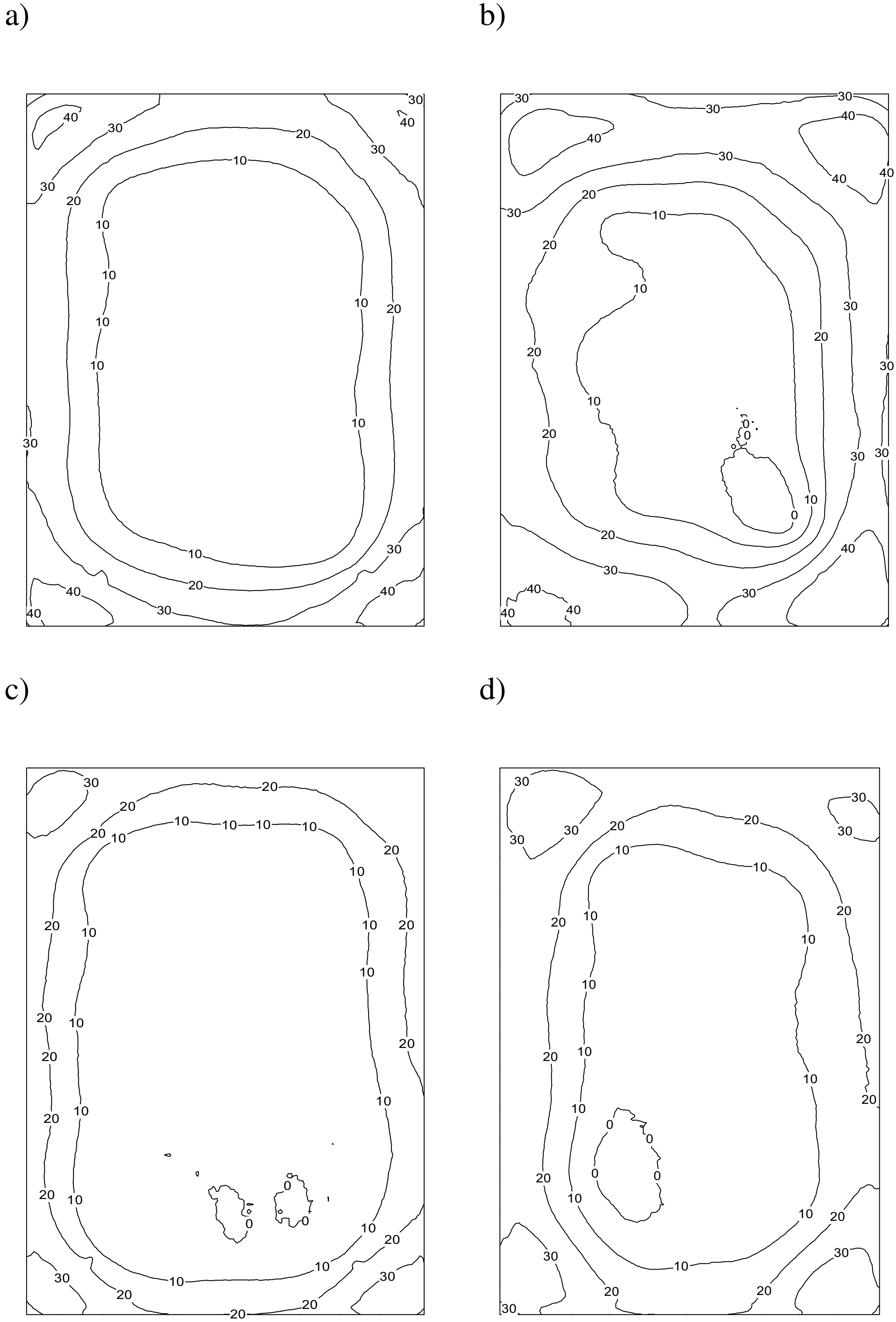

Fig. 6. Temperature distributions (°C) on top and middle surfaces of RF thawed lean beef meat block at 10 cm electrode gap after 17 min treatment. Stationary: top surface (a) middle surface (b), moving at 3 m/h: top surface (c), middle surface (d).

where λ, is uniformity index, $\Delta\sigma$, is the rise in standard deviation and $\Delta\mu$, is the rise in mean values from the initial to final temperatures. Better heating uniformity is described by smaller value of uniformity index. Various researchers have been successfully used this method to evaluate the heating uniformity in agricultural products (Wang et al., 2007a,b, 2010; Zhou et al., 2015). Uniformity index at the top, middle and bottom parts of the lean beef block were calculated for different electrode gaps and speed of the conveyor belt.

3. Results and discussions

3.1. Dielectric properties of lean beef meat

3.1.1. Dielectric constant (ε')

The dielectric constant of lean beef meat measured at the range of temperature from −15°C to 65°C and selected five frequencies of 13.56, 27.12, 40.68, 915 and 2450 MHz was shown in Fig. 2. The values indicated that increasing in temperature resulted in increasing dielectric constant for all frequencies. In the temperature range between −15°C and -1°C, the increase of dielectric constant with respect to temperature was higher compared to the behavior exhibited after initial thawing temperature. In the thawing region, between −5 °C and −1°C, significant increasing was observed at all frequencies. This could be due to the increased concentrations of liquid water and mobile ions as a result of phase change occurring in that temperature range. As reported also by Farag et al. (2008), the dielectric constant exhibited higher values at lower frequency (13.56 MHz) and relatively smaller value at higher frequency (2450 MHz). At higher frequencies (microwave frequencies) dielectric constant shows very small change as temperature increases from 0°C to 60°C and tends to decrease after 60°C. For instance, at frequency of 915 MHz, the dielectric constant of lean beef meat at 0°C and 60°C were observed to be 51.05 ± 4.80 and 51.89 ± 0.45, respectively, which is changed by a value of 0.84.

3.1.2. Dielectric loss factor (ε'')

Fig. 3 shows that the dielectric loss factor of lean beef meat measured for various frequencies at a temperature range of −15°C to 65°C. At lower frequencies (radio frequency), the values of dielectric loss factor increased significantly while very small increase was observed at higher frequencies (microwave). For instance, the average value of dielectric loss factor at 20°C for 27.12 MHz and 2.45 GHz were 390.16 and 15.27, respectively. The results agree with the data reported by Farag et al. (2008) at frequency of 27.12 MHz. In microwave frequency range (915 and 2450 MHz), the values of dielectric loss factor increased insignificantly as the temperature increases. In RF heating, high values of dielectric loss factor imply that high amount of energy can be generated throughout the product. At 27.12 MHz, dielectric properties of meat result in higher penetration depth with respect to microwave heating and for this reason, RF assisted heating is more suitable for thicker products. Similar results were reported by Llave et al. (2016) for model food (tylose) undergoing microwave thawing.

3.2. Stationary thawing

Temperature-time histories of RF thawing of lean beef meat measured at the center of the sample using different electrode gaps are shown in Fig. 4. The temperatures measured at the corners were higher than those at the center of the sample. This could be due to increased electric field distribution as a result of deflection of electric fields at the corners and edges of the products (Marra et al., 2009; Tiwari et al., 2011). At the beginning of the thawing process, the temperatures of the samples raised very quickly. It must be considered that, under frozen conditions, thermal conductivity is 4–5 times higher than in thawed conditions: so, while the food sample is still frozen, thermal conduction definitely helps to transfer the heat around the zone more subjected to heat generated by the interaction of the food sample with the electromagnetic field displacement.

3.3. Selection of gap between electrodes

The influence of electrode gap on the heating rate during RF thawing of lean beef meat under static condition is shown in Fig. 4. Electrode gaps of 9, 10, 11 and 12 cm were tested in this experiment based on the thawing time required to raise the temperature of the lean beef sample from frozen condition to a thawing temperature. It is possible to understand that larger electrode gap results in longer thawing time while the shortest time resulted in uneven distribution of temperature in which corners were heated to a high temperature (for instance 39.6°C for 9 cm electrode gap and 14 min heating time). Smaller electrode gap of 9 cm resulted in arching and higher temperature on the corners and edges while 12 cm gap resulted in longer thawing time. In the range of electrode gaps used in RF thawing of lean beef meat, the electric current increased with decreasing electrode gap. Zhou et al. (2015) reported that decreasing electrode gap increased electric current, as a result increased the heating rate during RF heating of milled rice. Similar results were reported by Jiao et al. (2015), Uyar et al. (2014) and Zhou and Wang (2016). To obtain relatively acceptable heating uniformity at reasonable thawing time, an electrode gap of 10 cm was chosen and consecutive experiments were performed using moving conveyor belt at different speed.

3.4. Thawing on the moving conveyor belt

Fig. 5 shows the comparison among average temperature-time evolution in the lean block for both the static and the continuous cases, at different speeds. Rise in temperature was faster in stationary than in moving conditions, since frozen sample blocks were not initially placed under the top electrode with moving conditions, resulting in less total electromagnetic power absorbed by the sample.

Comparison between temperature distribution on the top and middle surfaces of the lean beef meat block treated using both stationary and moving conditions under 10 cm electrode gap and after 17 min treatment is shown in Fig. 6. Higher temperature distribution was observed on the corners and edges of the sample treated under stationary condition. Temperature difference of around 10°C between stationary and moving conditions can be appreciated. This implies that RF heating under moving condition may reduce overheating and increase uniformity of temperature distribution across the sample. Chen et al. (2015b) reported that movement of conveyor belt improved temperature uniformity at the middle layer of a food load undergoing RF heating. Thawing

Table 1
Average temperature and standard deviation of lean beef meat thawed using stationary and moving RF systems.

Position	Stationary	Average Temperature (°C) ± Standard deviation (SD)		
		2.5 m/h	3.0 m/h	3.5 m/h
Top	28.0 ± 5.5	28.2 ± 8.0	18.6 ± 3.9	12.8 ± 7.5
Middle	−0.2 ± 1.5	0.7 ± 1.1	−0.4 ± 0.7	−1.0 ± 0.2
Bottom	28.4 ± 8.4	24.8 ± 12.6	20.7 ± 12.1	13.1 ± 10.1

Table 2
Uniformity index for stationary thawing at different electrode gaps and thawing on moving conveyor belt at different speeds.

Electrode gap (cm)	Uniformity index (λ)			Speed (m/h)	Uniformity index (λ)		
	Top	Middle	Bottom		Top	Middle	Bottom
9	0.52	0.09	0.62	2.5	0.18	0.01	0.30
10	0.12	0.03	0.18	3.0	0.11	0.02	0.33
11	0.21	0.01	0.34	3.5	0.25	0.01	0.33
12	0.13	0.01	0.32				

lean beef meat block under moving condition resulted relatively in uniform temperature distribution and reduced overheating on the corners of the sample.

3.5. *Heating uniformity index*

The average temperature-time histories on top, middle and bottom sections of the lean beef block thawed by RF system indicated that heating rates were faster on top and bottom sections while gradually increase at the middle or center section. This could be due to the fast melting of ice crystals covered the surface of the meat blocks. During thawing of lean beef block on stationary condition, the heating uniformity improved as the gap between electrodes increased. The comparison of final average temperatures on top, middle and bottom sections of the meat block were shown in Table 1. The results indicated that thawing on moving conveyor belt reduced the difference between hot and cold spot temperatures. Increasing the speed of conveyor belt slightly changed the heating behavior. Fast speed of conveyor belt resulted in lower heating performance. For example, the temperature differences between average hot and cold spots of 27.5°C, 20.3°C and 14.1 °C were observed at conveyor belt speed of 2.5, 3.0 and 3.5 m/h, respectively. Using hot air assisted heating or holding, the temperature difference between hot and cold spots could be minimized and heating uniformity could be improved.

The uniformity index was calculated for both stationary and moving conditions at three different positions, top, center and bottom sections of the meat block. The results showed that (Table 2) uniformity of heating on the top section reasonably improved at increased electrode gap and speed of conveyor belt. The uniformity index values were 0.52, 0.12, 0.31 and 0.32 for the top section while 0.09, 0.03, 0.01, and 0.01 for the middle section under electrode gaps of 9, 10, 11 and12 cm, respectively. Similar results have been reported for RF heating of agricultural products (Zhou et al., 2015; Zhou and Wang, 2016).

4. Conclusions

Dielectric properties of lean beef meat, with related information on behavior of RF heating, were measured at different frequencies and range of temperature between frozen and unfrozen states. The experimental RF thawing of lean beef meat blocks under static (batch) and moving (continuous) conditions on conveyor belt was performed. The results indicated that the gap between electrodes affected heating uniformity in static condition and speed of conveyor belt played great role in moving condition in addition to gap between electrodes. The results also revealed that RF thawing on moving conveyor belt slightly improved the heating uniformity. The experimental results could be further used to optimize processing parameters and conditions through modeling and simulations.

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