Radio frequency heating of corn flour: Heating rate and uniformity

Samet Ozturk a, Fanbin Kong a,⁎ Rakesh K. Singh a, Jesse Daniel Kuzy b, Changying Li b

a Department of Food Science and Technology, University of Georgia, Athens, GA, USA
b College of Engineering, University of Georgia, Athens, GA, USA

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ABSTRACT

Non-uniform heating is a major challenge for using radio frequency (RF) heat treatment in pasteurization of low moisture food products. The objective of this study was to evaluate the effect of different electrode gaps, moisture content (MC), bulk density and surrounding materials on RF heating uniformity and rate in corn flour. Additionally, the dielectric and thermal properties of corn flour were determined as affected by MC, temperature (°C), and frequency (MHz). Changes in MC, water activity (aw) and color in the sample after RF heating were measured to evaluate treatment effect on food quality. A precision LCR meter and a liquid test fixture were used to study DP of the sample at RF frequency ranging from 1 to 30 MHz. The RF heating uniformity and temperature profiles of corn flour as exposed to RF heating were obtained with an infrared camera and a data logger connected to a fiber optic sensor. The DP values increased with increasing MC and temperature, but decreased with frequency. The heating rate increased from 3.5 to 6.8 °C min⁻¹ with increasing MC from 10.4 to 16.7%, but decreased from 12.7 to 5.2 °C min⁻¹ with increasing electron gap (from 11 to 15 cm). The corner and edge heating were observed at all layers of the samples for all the distances, and the hottest and the most uniform layer were determined as the middle layer at an electrode gap of 15 cm. Glass petri dish provided better heating uniformity than those of polyester plastic petri dish. Covering by foam led to more uniform RF heating and better moisture and aw distribution. This study provided useful information to develop an effective RF process as an alternative of conventional thermal treatments for pasteurization of low-moisture products.

Industrial relevance: This paper describes a novel methodology based on Radio Frequency heating to pasteurize food powder while maintaining the quality. The study addresses the ever-increasing global demand from consumers for safe food products.

1. Introduction

Low moisture foods including dried spices, vegetable powders, whole milk powder, corn and wheat flour, are defined as food with water activity (a w) less than 0.7 or moisture content (MC) below 20% (Blessington, Theofel, & Harris, 2013). Although the low water activity environment is not suitable to grow microorganisms, low water activity foods are liable to be contaminated by microorganisms during harvesting, processing or transportation. A number of recent outbreaks of salmonellosis were associated with contamination of low moisture foods (CDC, 2007, 2010), leading to foodborne illness such as diarrhea, abdominal pain, mild fever, and chills (Baird-parker, 1990; Rhee, Lee, Dougherty, & Kang, 2003). The pasteurization of Salmonella contaminated low moisture foods is difficult because of the high heat resistance of Salmonella in low water activity environment. Different decontamination methods have been applied to reduce the microbial hazard of low moisture foods, such as steam, hot air and irradiation. However, conventional methods including steam and hot air require long processing time, which leads to severe quality degradation in low moisture foods, due to their low thermal conductivity. Vancauwenberge, Bothast, and Kwolek (1981) reported the inactivation effect of dry hot air on corn flour contaminated with eight different Salmonella serotypes. Their results showed that corn flour with moisture content 10 and 15% required 5.8 and 2.2 h for 99% log reduction at 49 °C, respectively. On the other hand, irradiated foods are not readily accepted by consumers due to health concerns (Farkas, 2006; Schweiggert, Carle, & Schieber, 2007). As a method of volumetric heating, radio frequency (RF) heating offers the possibility to rapidly pasteurize low moisture foods while maintaining the food quality. The RF covers a wide band of frequencies ranging from 1 to 300 MHz, but only 13.56, 27.12 and 40.68 MHz are used for industrial, scientific and medical applications (Wang and Tang, 2001). Studies were reported recently in using the RF treatments for postharvest disinfection (S. Jiao, Johnson, Tang, & Wang, 2012a; Lagunas-Solar, Pan, Zeng, Truong, & Khir, 2007), and pasteurization

⁎ Corresponding author.
E-mail address: f.kong@uga.edu (F. Kong).

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of low moisture foods (Gao, Tang, Johnson, & Wang, 2012; Jeong & Kang, 2014; Kim, Sagong, Choi, Ryu, & Kang, 2012). Compared to microwave (MW) heating which involves higher frequency (915 or 2450 MHz), RF heating ensures more uniform heating and deeper penetration depth in solid and semi-solid low moisture foods due to the lower frequency range and longer wavelengths (Luechapanaporn et al., 2005; Marra, Zhang, & Lyng, 2009). Despite of improved heating uniformity as compared to microwave heating, the non-uniformity and run-way heating are still major challenges to apply RF heating pasteurization system in food industry. The variation in temperature distribution of food during RF heating can lead to overheated hot area causing severe quality deterioration and under-heated cold spot. Several researches have been conducted to improve RF heating uniformity using different ways. Wang, Tiwari, Jiao, Johnson, and Tang (2010) reported that as legumes were heated by RF oven using combination of forced hot air and shaking container on a conveyor belt, a decrease between hot and cold spot temperatures was achieved. There are several factors affecting heating uniformity during the RF Heating including electron gap, power, packaging material and geometry, dielectric properties, and physical and chemical properties of heated sample (S. Wang, Monzon, Gazit, Tang, & Mitcham, 2005). Recently, it was reported that surrounding materials, moisture content and bulk density can also impact the RF heating uniformity (Huang, Zhu, & Wang, 2015; Y. Jiao, Tang, & Wang, 2014; Zhang, Zhu, & Wang, 2015). Jiao et al. (2014) studied the effect of surrounding material, which has low dielectric and thermal properties, on the RF heating uniformity in peanut butter and wheat flour. They found that covering the plastic container with PEI material resulted in decrease in the average temperature difference (from 13 to 7 °C) on the surface layer. Furthermore, the effect of polyurethane foam sheets on the RF heating uniformity in low moisture foods including walnut and bread have been studied by Liu, Wang, Mao, Tang, and Tiwari (2013) and Wang et al. (2010). However, there is no reported study on the effect of foam when used as surrounding material for corn flour. Further studies are needed to understand the effect of MC and bulk density, and different surrounding material on RF heating uniformity in order to develop optimized RF heating parameters and to minimize unfavorable effect on food quality.

This study aims to investigate the heating behavior of corn flour during RF treatment as affected by different factors during RF heating, and to explore methods to improve heating uniformity by using polyurethane foam and PEI plates as surrounding materials. The obtained information will help develop an effective RF pasteurization method for packaged low moisture foods.

2. Material and methods

2.1. Physical characterization of corn flour

Commercially processed corn flour was purchased from Georgia Spice Company (Atlanta, GA USA). The initial MC of the corn flour was determined by drying the sample in a vacuum oven at 105 °C for 16 h (AOAC, 1998). To study the effect of moisture on dielectric and thermal properties, and heating uniformity and rate, MC of the corn flour was adjusted by spraying distilled water to the samples which were then held in ziplock bags and shaken manually for 10 min. The water added corn flour samples were stored at 4 °C for two days, and shaken twice a day to obtain a uniform moisture distribution throughout the sample.

To determine the effect of bulk density on RF heating uniformity and rate, different bulk densities of corn flour with initial MC (10.2% w.b.) at room temperature (23 ± 2 °C) were obtained by a basic volume method using a polystyrene plastic petri dish (D × H = 100 × 15 mm). To obtain different bulk densities, the cylindrical petri dish was filled with different amounts of corn flour and then weighed. The bulk density was calculated as weight of flour/volume (g/cm³).

Thermal conductivity, diffusivity and specific heat of corn flour with three different MC at room temperature were measured with a KD2 Pro thermal analyzer (Decagon Devices, Inc., USA) using a T1 probe, which is suitable for solid and granule food materials. For each measurement, 20 g sample was placed into a plastic container and the measurement probe was inserted in the sample to determine thermal properties.

2.2. Determination of dielectric properties and penetration depth

The DP of the corn flour were determined using the parallel plate method with an Inductance Capacitance and Resistance (LCR) meter (4285A, Agilent Technologies, Palo Alto, CA) with a dielectric liquid test fixture (16452, Agilent Technologies, Palo Alto, CA). The LCR meter was calibrated manually to minimize the biased error and random error using a BNC cable before taking measurement. Dielectric properties of corn flour with various MC (10.4, 13.6 and 16.7% (w.b.)) at temperature range between 20 and 80 °C were measured at 13.56 and 27.12 MHz, as determined by the capacitance between electrodes of the test fixture (C_p) and resistance (R_p) values obtained from the LCR meter. The experimental procedure was described in Ozturk, Kong, Trabelsi, and Singh (2016). The corn flour sample (2 g) was placed into the test fixture. The fixture was then tightly closed and placed into a temperature chamber (625G, Thermo Fisher Scientific Inc., Waltham, MA, USA) and C_p and R_p values were measured with different frequencies (ranging from 1 to 30 MHz) and temperatures (ranging from 20 to 80 °C with 10 °C interval). The dielectric constant (ε′) and loss factor (ε″) of the corn flour were calculated using the following equations (Agilent Technologies, 2000; Halliday, Resnick, & Walker, 2001; Von Hippel, 1954).

\[
ε' = \frac{A}{C_p E_0} \quad (1)
\]

\[
ε'' = \frac{1}{2πfR_p E_0 A} \quad (2)
\]

where, \(t\) is the gap (m) between electrodes of the test fixture, \(C_p\) is parallel capacitance (F), \(R_p\) is the resistance (Ω), \(f\) is the frequency (Hz),
$\varepsilon_0$ is the permittivity of vacuum ($8.854 \times 10^{-12}$ F m$^{-1}$), and $A$ is the electrode area (m$^2$).

When exposed to an electromagnetic field, food materials, which have poor electric conductivity, are able to store and release electrical energy as heat energy (Buffler, 1993). The penetration depth of RF and MW can be defined as depth into a sample where the power has dropped to $1/e$ ($e = 2.718$) of the power value at the surface (Guan, Cheng, Wang, & Tang, 2004). The penetration depth is a function of dielectric properties of food material, and it can be calculated using the following equation (Buffler, 1993; Von Hippel, 1954)

$$d_p = \frac{c}{2\pi f \sqrt{2\varepsilon' (\tan \delta)^{-1}}}$$  \hspace{1cm} (3)

where, $c$ is the speed of light in air ($3 \times 10^8$ m s$^{-1}$), $f$ is the frequency (Hz) and $\tan \delta$ is defined as $(\varepsilon' - \varepsilon)/\varepsilon'$. $\varepsilon$ and $\varepsilon'$ are the measured dielectric constant and dielectric loss factor values of corn flour with various MC, respectively. Using obtained dielectric properties, $d_p$ (m) values of RF at frequencies of 13.56 and 27.12 MHz in corn flour were calculated at room temperature ($23 \pm 2$ °C) and target temperature of RF heating (80 °C).

### 2.3. Determination of heating uniformity and temperature time profile of corn flour during RF heating

Heating uniformity tests were conducted by placing corn flour in a rectangular polyetherimide (PEI) container (Inner dimension: 7 H × 24 W × 30 (L) cm$^3$) (Figs. 1 & 2) and treated in a 27.12-MHz, 6-kW RF system (COMBI 6-S, Strayfield International, Wokingham, UK). To develop an effective RF heating protocol for better RF heating uniformity, the optimal electrode gap was determined first. Prior to the RF treatment, the corn flour with MC of 10.4% (w.b.) were equilibrated at the room temperature ($23 \pm 2$ °C). The PEI container was filled with 3.2 kg corn flour, and placed in the middle of two parallel electrodes (Fig. 1) for RF heating at various electrode gaps including 11, 13 and 15 cm. In the view of previous studies, placing the sample in the middle of parallel electrodes during RF heating can provide better heating uniformity and rate (Tiwari, Wang, Tang, & Birfa, 2011). The sample in the PEI container was heated from room temperature ($23 \pm 2$ °C) to 80 ± 5 °C, which is in the range of lethal temperature required to kill most insects and microorganisms at all growth stages (Armstrong, Tang, & Wang, 2009; Johnson, Valero, Wang, & Tang, 2004). To obtain the temperature time history and calculate the heating rate in corn flour during RF heating, the change in temperature of the sample during heating was recorded at the geometric center of the PEI container using a fiber optic temperature sensor with accuracy of ± 1 °C (Fiso Tech. Inc., Quebec, Canada) connected to a data logger. When the center temperature reached 80 °C, the sample was taken out immediately and their thermal images were taken. The samples in the PEI container were divided into three different interior layers (Fig. 2) separated by a thin cheese cloth (with mesh opening of 1 mm). After RF treatment, the top surface and interior layer images were taken by an infrared camera (FLIR T440, FLIR Systems, Inc., North Billerica, MA, USA) to analyze the surface temperature distribution. To determine the effect of the cheese cloth on RF heating uniformity, the interior temperature distribution of each layer at 13 different locations (Fig. 3) was also measured by using T type thermocouples (Model 91,100–20, Cole-Parmer Instrument Company, Vernon Hill, IL, USA) with an accuracy of ± 2 °C collected to portable data loggers (Model RDXL4SD, OMEGA Engineering Inc., Norwalk, CT, USA). All the treatments were replicated three times. The average and standard deviation (SD) values of the surface and interior sample temperatures were used to evaluate the RF heating uniformity. The mapped temperature distribution for different layers and locations were used to determine hot and cold spots in corn flour after RF heating.

The RF heating uniformity in corn flour of four different layers with different distances from surface and bottom (Fig. 2) at the target temperatures was evaluated using the heating uniformity index (UI), which has been used to evaluate RF heating uniformity for many studies (Hou, Ling, & Wang, 2014; S. Jiao, Johnson, Tang, & Wang, 2012b; Pan, Jiao, Gauz, Tu, & Wang, 2012; S. Wang, Luechapattanaporn, & Tang, 2008; S. Wang, Monzon, M., Gazit, Y., Tang, J., Mitchan, E.J., Armstrong, J.W., 2005; S. Wang et al., 2010). S. Wang, et al. (2005) defined the uniformity index as the ratio of the rise in standard deviation of sample temperatures to the rise in the average sample temperatures during the RF heating. It can be calculated using the following equation (S. Wang, Monzon, M., Gazit, Y., Tang, J., Mitchan, E.J., Armstrong, J.W., 2005):

$$\lambda = \frac{\Delta \sigma}{\Delta \mu}$$  \hspace{1cm} (4)

where $\Delta \sigma$ is the rise in the standard deviation (SD) of sample
temperature (°C), and Δμ is the rise of the mean temperature (°C) over the RF heating time. The smaller UI values indicate better RF heating uniformity in the sample.

As a comparison, the corn flour filled PEI container was placed in a temperature chamber (625G, Thermo Fisher Scientific Inc., Waltham, MA, USA) with 85 °C temperature until the center temperature reached the target temperature (80 °C) in the middle of container. The change in the temperature of the sample during heating was recorded using a data logger with a fiber optic temperature sensor (Fiso Tech. Inc., Quebec, Canada). The time required to reach the target temperature were compared with RF heating. The color of the samples from the two methods was also compared to show the effect of the heating process on food quality.

2.4. Effect of surrounding material, moisture content and bulk density on heating uniformity

Based on the recent studies, surrounding materials with similar dielectric properties to treated sample can help improve heating uniformity during the RF heating (Y. Jiao et al., 2014). In this study, the effect of four surrounding materials, including glass, polystyrene, polyurethane foam and polyetherimide were studied. It was reported that the squared, sphere, and cylinder shape containers commonly used in RF heating systems for different foods had similar heating uniformity pattern during RF heating (Alfaifi et al., 2014; Birla, Wang, & Tang, 2008). In this study, to investigate the influence of surrounding materials on heating uniformity and heating rate in corn flour during RF heating, polystyrene and glass cylindrical petri dishes (D × H = 100 × 15 mm) were used to hold sample. The dielectric properties of the surrounding materials, including glass, polystyrene, polyurethane foam and polyetherimide, are shown in Table 1. The polystyrene and glass cylindrical petri dishes were filled with 50 g corn flour before placed in the middle of two parallel electrodes at a gap of 15 cm. Samples were heated to reach 70 °C, and the change in temperature was recorded using a data logger with a fiber optic sensor, which was placed into the geometric center of cylindrical petri dishes. After RF heating, sample was taken off immediately from the RF oven, and the top surface image was taken by the infrared camera to evaluate the effect of different surrounding material on heating uniformity using the UI values. Furthermore, three different approaches were also tested to determine effect of surrounding material on RF heating uniformity and rate: 1) the polystyrene and glass cylindrical containers were covered all around with polyurethane foam sheet (5 mm thickness), 2) the petri dish containers was covered by PEI cylindrical blocks with different thickness (diameter × thickness: 100 × 10 or 20 mm) on both top and bottom surface, and 3) only one side of the sample container was covered by PEI block to determine the position of PEI blocks on the heating uniformity. In the view of recent studies, the foam box and PEI cylindrical blocks helps to enhance the electromagnetic field uniformity around the food sample which can absorb more electrical energy during RF heating (Y. Jiao et al., 2014; S. Wang et al., 2010; Y. Y. Wang, Zhang, Gao, Tang, & Wang, 2014)

To evaluate the effect of moisture content and bulk density on RF

<table>
<thead>
<tr>
<th>Thermal conductivity and dielectric properties of glass, polystyrene (PS), polyetherimide (PEI) and polyurethane foam.</th>
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<tbody>
<tr>
<td>Glass(^a)</td>
</tr>
<tr>
<td>Thermal conductivity (W m(^{-1})K(^{-1}))</td>
</tr>
<tr>
<td>Dielectric constant</td>
</tr>
<tr>
<td>Dielectric loss factor</td>
</tr>
</tbody>
</table>

\(^a\) (Bansal & Doremus, 1986).
\(^b\) (Lampman, 2003).
\(^c\) (Domeier & Hunter, 1999).
heating uniformity and heating rate, corn flour with various moisture contents and bulk density levels (0.42, 0.53 and 0.61 g cm\(^{-3}\)) were heated in the polystyrene plastic petri dish. The thermal images of the top surface and temperature time profiles were used to determine uniformity index values and heating rate in corn flour.

2.5. Evaluation of color and moisture distribution in RF treated samples

RF treated corn flour samples prepared with foam covered PEI container were used to evaluate the influence of heating on the quality of final products. Color was selected as the quality parameter to evaluate corn flour quality before and after RF heating. \(L^*, a^*,\) and \(b^*\) values were obtained from five different locations in the PEI container (Fig. 2), and analyzed using a Minolta colorimeter (model CR300, Minolta Co., Osaka, Japan). \(L^*, a^*,\) and \(b^*\) values indicate the lightness, whiteness, and yellowness of the sample, respectively. The average of the five locations was used to represent color change in sample caused by RF heating. In addition, MC and \(a_{ commem.} of the corn flour were also used to evaluate the effect of RF heating. To determine moisture distribution, samples were obtained from selected locations (Fig. 2) throughout the PEI container, and MC were determined by the vacuum oven drying method. Water activity at different locations was also measured using a water activity meter (Aqualab serious 3TE, Decagon Devices Inc., Pullman, WA, USA) at room temperature.

2.6. Data processing and analysis

All measurements, including MC, bulk density, thermal properties, dielectric properties and heating rates, were done in triplicate. The mean value and standard deviation (SD) were reported. Excel (Microsoft office, Redmond, WA, USA) was used to process and analyze data.

3. Results and discussion

3.1. Dielectric and thermal properties of corn flour as influenced by moisture content, temperature and frequency

The dielectric properties of corn flour with various moisture levels (10.4, 13.6 and 16.7% w.b.), and two different temperatures at frequency of 13.56 and 27.12 MHz are listed in Table 2. Both \(\varepsilon'\) and \(\varepsilon''\) of corn flour increased with increasing MC and temperature, but decreased with increasing applied frequencies. The increase in both \(\varepsilon'\) and \(\varepsilon''\) can be explained with increased amount of free and bound water in corn flour, and the increase in mobility of water molecules as temperature increased. Furthermore, the effect of frequency on the decrease of both \(\varepsilon'\) and \(\varepsilon''\) in corn flour can be explained by the changes in ionic conduction in the samples. Byynänen (1995) reported that dielectric heating below 300 MHz is based on the ionic conduction, which decreases as frequency increases, resulting in decrease in dielectric constant (Shrestha & Baik, 2013). On the other hand, the penetration depth of RF in corn flour decreased with increasing MC, temperature, and frequency (Table 2). It means that lower frequencies (1–300 MHz) provide deeper penetration than those of high frequencies (915 or 2450 MHz), which means that high frequency could cause more surface heating than that of RF frequencies. Other researchers also reported decreases in penetration depth as frequency increased for various food powders including wheat flour (Nelson & Trabelsi, 2006), soybean flour (Guo, Wu, Zhu, & Wang, 2011), and broccoli powder (Ozturk et al., 2016). The penetration depth is an important parameter to evaluate efficiency of RF heating in low moisture foods, and to design an effective RF heating system. The results indicate that it is important to consider the moisture content of low moisture foods to obtain desired penetration capacity in the RF heating system.

Table 2 also shows the thermal property values including thermal conductivity, diffusivity and specific heat of corn flour with various MC at room temperature. Thermal conductivity of corn flour lies in range of 0.123–0.166 (W/m °C) as MC increased from 10.4 to 16.7% (w.b) at room temperature (23 ± 2 °C). It is important to know the thermal properties of corn flour since as RF heating generates heat in the food, heat transfer happens as conduction throughout the sample and convection between container surface and surrounding air, which affect heat distribution. Bozikova (2003) reported a linear relationship between moisture content and thermal conductivity for corn and wheat flour, and low moisture foods has low thermal conductivity and thus requires a long heating time for conventional thermal treatment.

3.2. Determination of RF heating rates in the corn flour at three different electrode gaps

Fig. 4 shows the temperature change in corn flour with MC 10.4% (w.b) and 0.501 \(a_{ commem.}\) at the geometric center of container placed in the middle of two parallel electrodes during RF heating for three selected electrode gaps of 11, 13 and 15 cm, with heating times required to raise the temperature from 23 °C to 80 °C for each gap being about 4, 9 and 13 min, respectively. A linear increase in the temperature of corn flour was shown for all the electron gaps during RF heating (Fig. 4). The heating rate in corn flour during the RF heating decreased from 12.71 to 5.2 °C min\(^{-1}\) as the electron gap increased. High heating rates correspond to high throughputs and short processing times, which are desired, but adversely affect the heating uniformity in the sample during the RF heating because of rapid and run away heating. Similar temperature time profiles to corn flour as heated by RF heating were also reported for other low moisture foods including almond, lentil,
chickpea, and green peas (Gao, Tang, Wang, Powers, & Wang, 2010; S. Wang et al., 2010). To compare the efficiency of RF heating with conventional heating system, sample was also heated by hot air in a temperature chamber, and it took almost 210 min with 0.28 °C min\(^{-1}\) heating rate to reach target temperature because of poor heat conduction in corn flour, which has a low thermal conductivity (0.13 W/m °C) at 10.4% (w.b.) MC (Table 2). Although RF heating was much faster than hot air heating, its heating uniformity is a major challenge to achieve safe products with high food quality. Therefore, the electron gap of 15 cm corresponding to a relatively longer heating time (13 min) was selected for RF pasteurization of corn flour, as it has better heating uniformity than those of smaller electron gaps.

3.3. Radio frequency heating uniformity in the corn flour

Fig. 5 shows the experimental temperature distribution of the corn flour in top and middle layers after RF heating for each electrode distance. The overheating of corner and edge were observed in both top and middle layers of the sample for all distances, and cold spots were located at center area for each layer. Similar observations were reported for RF heated coffee bean (Pan et al., 2012), rice (Zhou, Ling, Zheng, Zhang, & Wang, 2015), and wheat flour (Tiwari et al., 2011). A detailed comparison of temperature distribution, and uniformity index values in RF heated corn flour for each layers at different electrode gaps are shown in Table 3. The UI was used to compare heating uniformity in corn flour for different distances after RF heating. The average temperature in middle layer was higher than in top layer at each electrode gap (Table 3), which could be caused by high electromagnetic fields in the middle of two parallel electrodes, and heat dispersion on top surface to the surrounding air. The most uniform layer, which corresponds the smallest UI value, was observed in the middle layer of each treatment at different electrode gaps. The RF heating uniformity in corn flour was gradually improved as the electrode gap increased from 11 to 15 cm due to reduced over-heating and run-away energy. Heat conduction may have also helped improve the heating uniformity throughout the PEI container due to the slow heating rate at 15 cm

![Fig. 4. A typical temperature–time curve of corn flour subjected to RF heating at three different electrode gaps.](image)

![Fig. 5. Top and middle surface temperature distribution (°C) of corn flour in a PEI container heated in the middle of two parallel electrodes of a RF oven with three electrode gaps (11, 13 and 15 cm).](image)
and the longer heating time. On the other hand, the thermocouple measured RF heating uniformity index and average temperature of each layer were only slightly different than those from the infrared camera. For example, the uniformity index and average temperature of the layer with 1 cm depth at 15 cm electrode gap were determined as 0.042 ± 0.019 and 68.37 ± 1.65 °C, respectively, using type T thermocouples, as compared to 0.044 ± 0.011 and 70.36 ± 1.88 °C, measured by the infrared camera. The results show that the cheese cloth did not affect significantly temperature distribution and heating pattern in the PEI container.

3.4. Effect of surrounding material on the RF heating uniformity

Fig. 6 shows the top surface temperature distribution in polystyrene
and glass cylindrical petri dishes with two MC levels, and with and without foam sheet. As seen in Fig. 6, glass cylindrical petri dish with filled corn flour provides a better heating uniformity (UI = 0.036) than those (UI = 0.051) of polystyrene after RF heating. The average temperature in top surface of corn flour (10.4% (w.b.)) with bulk density (0.42 g cm\(^{-3}\)) in glass petri dish was higher than that of polystyrene. It may be explained by higher dielectric property values of glass which results in higher energy absorption and dispersion as heat energy to the sample. Furthermore, RF heating rates in glass and polystyrene cylindrical petri dishes with filled corn flour were 4.52 °C min\(^{-1}\) and 3.85 °C min\(^{-1}\), respectively. On the other hand, polyurethane foam sheet helped improve RF heating uniformity and rate in both glass and polystyrene cylindrical containers (Fig. 6). The uniformity index values of top surface in glass and polystyrene cylindrical petri dishes were decreased by covering foam sheet (5 mm thickness) from 0.036, 0.051 to 0.023, 0.039, respectively. The smaller uniformity index values correspond to a better temperature distribution, and small variations between hot and cold spots after RF heating.

The heating uniformity index, average temperature and heating rate in top surface of corn flour in polystyrene petri dish as sandwiched by a pair of PEI blocks are shown in Table 4. As seen in Table 4, the UI increased as the thickness of PEI blocks increased, which means that PEI blocks improved the heating uniformity. When the thickness of PEI block increased from 1 to 2 cm, the average temperature increased from 62.3 ± 2.3 to 64.3 ± 2.7 °C. That is probably because the thicker PEI block can absorb more electrical energy, which results in increase in heating rate with better heating uniformity as compared to uncovered polystyrene container. Y. Jiao et al. (2014) also came up a similar effect of PEI block on the heating uniformity of peanut butter. Although the PEI cylindrical blocks provided more uniform RF heating and higher average temperature on top surface than those of uncovered polystyrene container, the hot and cold spots still stay at the same locations (Fig. 7). Furthermore, other approaches were also tried including covering only one side (bottom or top surface) of polystyrene cylindrical container to determine the best position for PEI blocks to have a better heating uniformity and rate in corn flour. As the PEI block with 1 cm thickness was placed only on bottom side, the UI increased from 0.0435 to 0.078, which means worse heating uniformity, and the average temperature decreased from 60.9 to 49.9 °C on top surface (Fig. 8). This indicates less energy absorption on the top surface area during RF heating. The average surface temperatures of corn flour (10.4% (w.b.)) as placing PEI blocks placed at bottom were 60.9 and 62.5 °C for 1 and 2 cm thicknesses, respectively (Fig. 8). In this case, covering both side of polystyrene cylindrical container by PEI blocks provides better heating uniformity and higher energy absorption, which results in increase in average surface temperature, than those of covering only one side. Result showed that heating uniformity and average temperature on top surface in polystyrene container could be improved by adding PEI blocks on both sides of container. However, average temperature in top surface is still lower than center temperature of corn flour in polystyrene container. Other methods like hot air heating may be used as in combination with RF heating to further improve the heating uniformity in order to determine the effect of foam on heating rate and uniformity. Furthermore, the PEI container was surrounded by the foam sheet (5 mm thickness). The average temperatures of corn flour in different layers increased slightly, and the heating uniformity was improved with reduced standard deviations (Table 3). The reason of that might be the enhanced electromagnetic field around the container when foam sheet was used (S. Wang et al., 2010). Additionally, heating rate in PEI container by covering foam sheet increased from 5.52 to 5.91 °C min\(^{-1}\). Thus, PEI container covered with foam sheet (5 mm thickness) as a surrounding material seemed to be an effective strategy to improve RF heating effects.

### Table 4

<table>
<thead>
<tr>
<th>Petri dish</th>
<th>1 cm PEI Lid covered both side</th>
<th>2 cm PEI Lid covered both side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>59.5 ± 3.3</td>
<td>62.3 ± 2.3</td>
</tr>
<tr>
<td>Heating uniformity index (%)</td>
<td>0.051 ± 0.02</td>
<td>0.044 ± 0.01</td>
</tr>
<tr>
<td>Heating rate (°C min(^{-1}))</td>
<td>3.85 ± 0.6</td>
<td>5.58 ± 0.8</td>
</tr>
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</table>

*a* Reported are average and standard deviation of three measurements.

3.5. **Effect of moisture content and bulk density on the RF heating uniformity**

The effect of MC and bulk density on heating uniformity in top surface of corn flour as heated in polystyrene petri dish are shown in Table 5. As MC increased the UI also increased, which results in worse temperature distribution and uniformity. It may be explained with increase of run-away energy due to the increased dielectric properties of corn flour. The heating pattern with edge and corner effects obtained for three moisture samples in the polystyrene cylindrical petri dish were similar to the sample with initial MC heated in PEI container. The average surface temperatures in higher moisture (16.7% (w.b.)) corn flour were higher than those of lower moisture samples (10.4 and 13.6% (w.b.)) (Table 5). The heating rate also increased as MC increased. The relationship among the heating rate, dielectric loss factor and MC of the corn flour is shown in Fig. 9. The effect of moisture content on dielectric loss factor of various foods were reported (Guo, Wang, Tiwari, Johnson, & Tang, 2010; S. Jiao, Johnson, Tang, Tiwari, & Wang, 2011; Ozturk et al., 2016). It is possible to adjust RF heating rate in food by controlling the moisture content (S. Jiao et al. (2011). Furthermore, the heating uniformity was also gradually increased with increasing bulk density (from 0.42 to 0.61 g cm\(^{-3}\)) of the
samples in polystyrene petri dish based on reduced UI values (Table 5). The hot spot and cold spot after RF heating were located in edges and center of the cylindrical petri dish. Similar results were reported in RF heated wheat flour (Tiwari et al., 2011), lentil (S. Jiao et al., 2011), coffee bean (Pan et al., 2012), chestnut (Hou et al., 2014) and rice (Zhou et al., 2015). These results suggest that a greater bulk density would help achieve a better temperature distribution which results in a better RF heating uniformity.

### 3.6. Effect of RF heating on color and moisture distribution in corn flour

The change in color, MC, and $a_w$ of corn flour along the PEI container with and without foam sheet at five different locations, which cover hot and cold spots, is presented in Table 6, for three electron distances. There were slight changes in color before and after RF treatments. The results showed that RF heating had no significant impact on corn flour color for all treatments, which is also in good agreement with literature for other RF treated low moisture foods including lentil (Jiao et al., 2011), coffee bean (Pan et al., 2012), and legumes (Wang et al., 2010). The slight change of color values ($L^*$, $a^*$, and $b^*$) after RF heating was probably because of different temperature distributions along the treated sample. Furthermore, moisture migration occurred during the RF heating. The highest MC and $a_w$ of RF heated samples were determined in the center of container, which is the coldest part of sample. As the PEI container was covered with foam sheet, the water migration in corn flour during the RF heating was reduced and moisture distribution throughout the container was more uniform which helps to maintain food quality. These results indicate that a foam layer can be used to cover corn flour container during RF heating treatment that can not only improve heating uniformity but maintain good product quality.

### Table 5

Effect of MC and bulk density on the RF heating uniformity and rate, and average temperature of the corn flour in polyester petri dish.

<table>
<thead>
<tr>
<th>Moisture content (w.b.%)</th>
<th>Surrounded material</th>
<th>Temperature (°C)</th>
<th>Heating rate (°C min⁻¹)</th>
<th>Heating uniformity index (λ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.42</td>
<td>Surface layer in polystyrene (PS) petri dish</td>
<td>59.5 ± 2.4</td>
<td>3.85 ± 0.07</td>
<td>0.051 ± 0.05</td>
</tr>
<tr>
<td>0.53</td>
<td></td>
<td>62.8 ± 3.1</td>
<td>4.46 ± 0.45</td>
<td>0.0416 ± 0.01</td>
</tr>
<tr>
<td>0.61</td>
<td></td>
<td>64.7 ± 3.3</td>
<td>3.16 ± 0.81</td>
<td>0.0377 ± 0.25</td>
</tr>
<tr>
<td>13.6</td>
<td></td>
<td>63.85 ± 2.1</td>
<td>0.0691 ± 0.015</td>
<td>5.16 ± 0.91</td>
</tr>
<tr>
<td>16.7</td>
<td></td>
<td>68.7 ± 2.9</td>
<td>0.094 ± 0.03</td>
<td>6.28 ± 1.2</td>
</tr>
</tbody>
</table>

* Reported are average and standard deviation of three measurements.
**Table 6**

Effect of RF heating and hot air heating on moisture (M.C.) and water activity (a_w) distribution and color values (L, a, and b) of the corn flour at five different locations of a PEI container as influenced by electron gap and foam coverage.

<table>
<thead>
<tr>
<th>L</th>
<th>a</th>
<th>b</th>
<th>T1</th>
<th>a_w</th>
<th>T2</th>
<th>a_w</th>
<th>T3</th>
<th>a_w</th>
<th>T4</th>
<th>a_w</th>
<th>T5</th>
<th>a_w</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>93.5 ± 0.16</td>
<td>4.22 ± 0.07</td>
<td>32.37 ± 0.14</td>
<td>10.4</td>
<td>0.509</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Hot air</td>
<td>95.41 ± 0.36</td>
<td>3.32 ± 0.04</td>
<td>28.70 ± 0.36</td>
<td>5.62</td>
<td>0.201</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>11 cm</td>
<td>92.7 ± 0.41</td>
<td>4 ± 0.08</td>
<td>32.6 ± 0.26</td>
<td>8.12</td>
<td>0.337</td>
<td>8.59</td>
<td>0.383</td>
<td>8.42</td>
<td>0.375</td>
<td>8.38</td>
<td>0.397</td>
<td>9.47</td>
</tr>
<tr>
<td>13 cm</td>
<td>92.5 ± 0.07</td>
<td>3.9 ± 0.11</td>
<td>32.4 ± 0.41</td>
<td>8.22</td>
<td>0.381</td>
<td>8.57</td>
<td>0.372</td>
<td>8.89</td>
<td>0.384</td>
<td>8.49</td>
<td>0.379</td>
<td>9.54</td>
</tr>
<tr>
<td>15 cm</td>
<td>93.1 ± 0.16</td>
<td>3.89 ± 0.07</td>
<td>32.1 ± 0.22</td>
<td>8.5</td>
<td>0.364</td>
<td>8.41</td>
<td>0.372</td>
<td>8.89</td>
<td>0.379</td>
<td>8.78</td>
<td>0.374</td>
<td>9.66</td>
</tr>
<tr>
<td>15 cm with Foam Sheet</td>
<td>93.24 ± 0.28</td>
<td>4.16 ± 0.07</td>
<td>32.21 ± 0.22</td>
<td>9.26</td>
<td>0.413</td>
<td>9.28</td>
<td>0.417</td>
<td>9.34</td>
<td>0.432</td>
<td>9.42</td>
<td>0.431</td>
<td>9.76</td>
</tr>
</tbody>
</table>

* Reported are average and standard deviation of three measurements.

4. Conclusions

RF heating of corn flour can be obtained with a heating rate of 5.52 °C min⁻¹ as compared with hot air heating 12.71 °C min⁻¹. The dielectric and thermal properties of corn flour were influenced by MC, temperature and frequency, which are also influencing factor on the RF heating uniformity and rate. The heating uniformity was improved with increase in bulk density, but decreased with increase in moisture content. For the sample heated at the central position between the two parallel electrodes, the middle layers were hotter than bottom and top layers, and the hot spot and cold spot were located in edges and center of the sample for all experimental setup, respectively. Adding and increasing the thickness of cylindrical PEI blocks on top and bottom of polystyrene container increased RF heating uniformity, rate and average temperature of corn flour. RF heating uniformity was also improved by addition of surrounding polyurethane foam sheet leading to decreased difference between hot and cold spot temperatures. The results showed that the RF heating offers an effective pasteurization method for corn flour with fasted heating rate and improved product quality as compared to hot air heating. Further research will be conducted to confirm the effectiveness of the RF heating in reduction of Salmonella inoculated in the corn flour.

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References


