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A new strategy to improve heating uniformity of low moisture foods in radio frequency treatment for pathogen control

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ABSTRACT

Multistate *Salmonella* outbreaks in low moisture foods have created food safety concerns in recent years. Radio frequency (RF) heating could be applied to eliminate pathogens and reduce the damage to food quality. However, non-uniform heating in RF treatment is still a major problem for developing a food pasteurization process. In this study, commercial peanut butter in a cylindrical jar was used as a model of low moisture food for studying the RF heating uniformity. Polyetherimide (PEI) was placed around peanut butter samples to provide better heating uniformity. A computer simulation model was established with COMSOL Multiphysics®, and experiments with a RF machine (27.12 MHz, 6 kW) were performed to validate the effectiveness of the PEI assisting method. Top surface and vertical cross-sectional temperature distributions of peanut butter in a cylindrical container were obtained with an infrared camera, and temperatures at 18 locations inside the container were measured with T type thermocouples. The results showed that PEI assistance reduced the difference between maximum and minimum temperature of top surface from 13 to 7 °C and cross-sectional surface temperatures from 28 to 18 °C. The same strategy was used on wheat flour and heating uniformity was also improved. The computer model was then used with a group of 9 jars of peanut butter to RF processing, and PEI assistance was also found to be effective in improving heating uniformity. Thus, PEI assisted RF heating has potential as a pasteurization intervention for low moisture foods after optimization of this process by the food industry.

1. Introduction

Low moisture food is a large category of foodstuffs, including tree nuts, dried species, wheat flour, legumes, grains, and butter among others. Peanut butter is a popular food due to its appealing taste, smooth mouth feel, high protein content and a moisture content below 2% ($a_w < 0.3$ at room temperature). It is normally considered a shelf stable food since its low moisture environment usually prevents bacterial growth and multiplication (Beuchat, 1981). *Salmonella*, however, was found to survive in a low moisture environment for several months, even 1 cfu/ml can result in human illness or even death (Gelosa, 1984; Kapperud et al., 1990; Burnett et al., 2000). Several cases of peanut butter contamination with *Salmonella* have been reported by the Centers for Disease Control and Prevention in recent years (CDC, 2012). The main source of *Salmonella* implicated in the reported outbreaks was found as the cross contamination occurring during the multiple steps involved in processing of peanut butter. To ensure sufficient elimination of *Salmonella* in peanut butter products, a pasteurization step could be added after packaging. However, peanut butter has a relatively low thermal diffusivity, which makes traditional heating technologies insufficient for inactivating *Salmonella* without causing severe food quality degradation (Shachar and Yaron, 2006; Ma et al., 2009). Therefore, novel heating technologies need to be developed to explore their effectiveness in pathogen control for peanut butter.

Radio frequency (RF) heating involves utilizing electromagnetic energy at a frequency range of 1–300 MHz. This electromagnetic energy can be converted into heat in foods. The volumetric heating usually provides a much faster heating rate than traditional hot air or hot water heating, which saves processing time and potentially improves product quality. A parallel plate RF heater with a free-running oscillator is a popular design, which has been widely used in the food industry, e.g. drying (Jumah, 2005), thawing (Farag et al., 2011), and post-baking (Palazoglu et al., 2012). The thermal effect of RF was also found to be effective in food pasteurization (Geveke and Brunkhorst, 2004; Gao et al., 2011) and sterilization (Luechapattanaporn et al., 2005; Kim et al., 2012; Wang et al., 2012).

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Although the relatively longer wavelength of RF (comparing to microwave) usually results in more predictable temperature distributions in foods, edge over-heating is still a problem for foods heated in containers (Tiwari et al., 2011a,b). This is caused by the different dielectric properties of food and the surrounding medium (usually air), which results in an unevenly distributed electric field (Birla et al., 2004). Severe non-uniform heating may result in a losses of quality at high temperatures, e.g., oil rancidity of nuts (Wang et al., 2005, 2007) or thermal damage in fruits (Birla et al., 2004). Several methods have been reported to improve uniformity in RF heating of fruits and nuts. These methods include: rotation and water immersion for apples (Birla et al., 2004), intermittent stirring for walnuts (Wang et al., 2005), hot water preheating for apples (Wang et al., 2006) and persimmons (Tiwari et al., 2008), and hot air assistance for almonds and white bread (Gao et al., 2011; Liu et al., 2011). Tiwari et al. (2011b) used computer simulation to comprehensively study the effect of shape, size, position, dielectric properties of low moisture foods, and the shape of bent upper electrode in RF cavities on heating uniformity. Their results showed that when the dielectric constant and loss factor of the load are relatively close, the shape of the load is spherical, and the food sample is placed in the middle of the electrodes, the sample may achieve good heating uniformity. The upper electrode bent to a certain angle also helped improve heating uniformity. However, these methods all have some limitations when applied to peanut butter processing. Firstly, the water immersion method is only effective for high moisture foods. Secondly, intermittent stirring and hot air assisting methods work well for porous materials or particles, such as grains or nuts, but would not be practical and effective for pre-packaged paste foods, such as peanut butter. Moreover, not many food containers can be made in a spherical shape. Also, bending the electrode to suit the geometry of a specific food cannot be performed in all cases.

To reduce the edge over-heating and obtain a relatively uniform temperature distribution in foods, a uniform electric field needs to be generated throughout the treated food sample. Theoretically, the dielectric constant determines the electric field distribution when the loss factor is far smaller than the dielectric constant (Metaxas, 1996; Jiao et al., 2014). The uniformity of the electric field in the food could be improved by minimizing the difference between the dielectric constant of the food and the surrounding material.

The objectives of this study were to (1) conduct computer simulation studies on the effectiveness of using a plastic material – polyetherimide (PEI) – to assist improvement of RF heating uniformity in peanut butter in cylindrical plastic jars; (2) conduct experiments in a pilot scale RF unit to validate simulation results; (3) use the validated model to further analyze the heating uniformity of different spatial arrangements of multiple peanut butter jars with and without PEI sheets for potential high-throughput industrial processes; and (4) conduct further experiments with wheat flour to assess possibilities of extending the method for other products.

2. Materials and methods

2.1. Sample preparation

Commercial creamy peanut butter was purchased from a local grocery store (IGA Inc., Pullman, WA). The compositions of peanut butter as reported by the manufacturer were: 50 g/100 g fat, 25 g/100 g protein, 1.19 g/100 g salt, and 21.9 g/100 g carbohydrates (including 6.3 g/100 g fiber and 9.4/100 g sugar). Moisture content of the peanut butter sample was 1.3 g/100 g sample. Peanut butter was filled into a plastic cylindrical container (made of polypropylene, inner-diameter d = 10 cm, height h = 5 cm, wall thickness l = 1 mm) and covered with a lid for all treatments.

Wheat flour (Gold Medal, General Mills, Minneapolis, MN, USA) with a moisture content of 11.0% (w.b.) was purchased from a local grocery store (IGA Inc., Pullman, WA). The same plastic cylindrical container and lid used for the peanut butter samples was used for the wheat flour samples in RF heating experiments.

2.2. Physical properties of food material

Dielectric properties of peanut butter were determined with an open-ended coaxial probe connected to a network analyzer (Agilent E5071C, Agilent Technologies, Inc., Santa Clara, USA). Before measurement, the network analyzer was warmed up for 30 min and calibrated with open/short/low lossy capacitance/50 Ω load in sequence. The probe was then calibrated with air/short block/25 °C deionized water following standard procedures. Agilent software 85070D (Agilent Technologies, Inc., Santa Clara, CA, USA) was used to trigger measurement and record data. The peanut butter sample was placed into a cylinder sample holder (d = 20 mm, h = 94 mm), with oil circulating through the jacket of the sample holder. The sample temperature was then raised up to the target temperature by the heated oil. Detailed design of the measurement system and procedure can be found elsewhere (Wang et al., 2003). Triplicate measurements were performed at 20–80 °C with 10 °C intervals at frequencies of 1–1800 MHz. The density and thermal properties of peanut butter were from Jiao et al. (2014).

2.3. Surrounding material selection

Plastic materials were chosen based on their similarity in dielectric properties to peanut butter. Dielectric properties of common plastic materials at a frequency of 1 MHz, which is close to the RF heating frequency, were taken from the literature (Table 1). Comparing all the listed materials, Polyetherimide (PEI) has the closest dielectric constant to that of peanut butter (Table 2) and a lower dielectric loss factor. PEI is an amorphous plastic material with high heat resistance, high mechanical strength, high electric strength and known dielectric properties which meets all the requirements of this study (Karasz, 1972). Therefore, PEI was chosen as the surrounding material for heating uniformity improvement of peanut butter in RF heating.

2.4. Temperature profiles of peanut butter in hot water and RF heating with and without PEI assistance

A 6 kW 27.12 MHz free-running oscillator RF machine with parallel-plate electrodes (COMBI 6-S, Strayfield International, Wokingham, UK) was used for RF treatments. Scheme and dimensions of

Table 1
Dielectric properties of common plastic materials at 1 MHz and room temperature.

Plastic material	Dielectric constant ε'	Dielectric loss factor ε''
Polytetrafluoroethylene (PTFE)	2.1	0.00063[a]
Polyethylene terephthalate (PET)	3.0	0.048[b]
Polypropylene (PP)	2.1	0.0001[a]
Polyvinyl chloride (PVC)	3.1	0.017[b]
Polyvinylidene chloride (PVDC)	3.0	0.15[b]
Polyetherimide (PEI)	3.2	0.003[c]
Polycaprolactam (Nylon)	3.0	0.108[b]

[a] Mark (1999).
[b] Modern Plastics Encyclopedia (1991).
[c] Zhu et al. (2011).

Table 2
Properties of peanut butter, polyetherimide and air for mathematical modeling (dielectric properties of peanut butter averaged at temperature 20–80 °C at 27.12 MHz).

	Peanut butter	Polyetherimide (PEI)[b]	Air[c]
Density (kg/m^3)	1115[a]	1270	1.2
Heat capacity (J/kg K)	2030[a]	2000	1000
Thermal conductivity (W/m K)	0.209[a]	0.122	0.026
Dielectric constant	4.03	3.15	1
Dielectric loss factor	0.04	0.0025	0

[a] Jiao et al. (2014).
[b] Kelly and Zweben (2000).
[c] COMSOL material library, 2012.

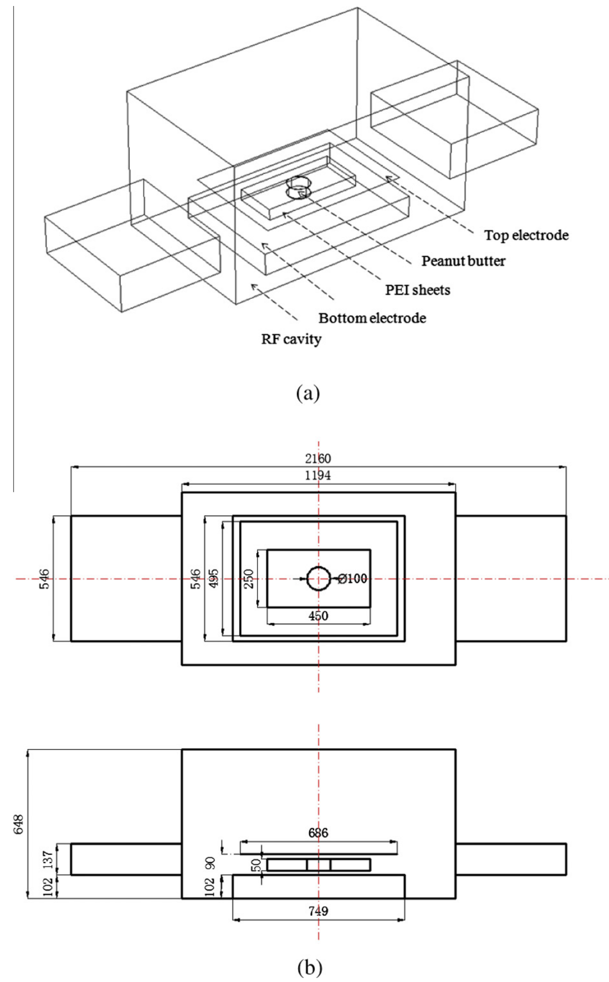

Fig. 1. 3-D Scheme (a) and dimensions (b) of the 6 kW 27.12 MHz RF system and a food load (peanut butter) with PEI sheets (dimensions are in mm).

the RF machine are presented in Fig. 1. Peanut butter (460 g) was fed into a plastic container (d = 10 cm, h = 5 cm). Two PEI sheets (l = 45 cm, w = 25 cm, h = 2.5 cm) were stacked together as one piece, and a hole with a slightly larger diameter (d = 10.4 cm) than that of peanut butter container was cut in the center of the PEI sheets. The sample container was inserted into the PEI sheets which were in turn placed between the two electrodes of the RF system. Only the side surface of the food sample was covered by PEI sheets, with the top and bottom left uncovered and exposed to air (Fig. 1). The peanut butter sample underwent RF heating with an electrode gap of 9 cm. The gap was selected based on preliminary experiments to obtain an appropriate heating rate. RF treatments were conducted individually for peanut butter with and without PEI assistance.

For hot water treatments, another peanut butter sample in the same size container was prepared and placed in a preheated water bath (Humboldt deluxe water baths H-1390, Humboldt Mfg. Co., Schiller Park, IL, USA). The water temperature of the water bath was set as 72 °C.

In all treatments, a fiber optical sensor (UMI, FISO Technologies, Inc., Saint-Foy, Quebec, Canada) with an accuracy of ±1 °C was calibrated and placed in the center of the sample to monitor temperature change versus time. The time–temperature history was recorded by the connected data logger (FOT-L, FISO, Quebec, Canada). The initial sample temperature for both RF and hot water treatments was 23 ± 1 °C.

2.5. Computer simulation

2.5.1. Physical model

The RF system with a free-running oscillator included a generator and an applicator. The generator provided electromagnetic energy to the applicator. The applicator had two parallel metal plate electrodes. The space between the two electrodes formed a cavity filled with an electromagnetic field when the system was in operation. The food material in the cavity was heated through conversion from electromagnetic energy to thermal energy.

The amount of power conversion from electromagnetic energy to thermal energy is related to the dielectric properties of the food, working frequency, and the electric field intensity in the food (Metaxas, 1996):

$$P = 2\pi f \varepsilon_0 \varepsilon'' |\vec{E}|^2 \quad (1)$$

where P is the power conversion in foods per unit volume (W m^{-3}), f is the working frequency of the RF equipment (Hz), ε_0 is the permittivity of electromagnetic wave in free space (8.854×10^{-12} F m^{-1}), ε'' is the loss factor of food material, and $\vec{E}$ is the electric field intensity in the food material (V m^{-1}).

2.5.2. Governing equations

The electric field intensity in the electromagnetic field can be obtained by solving the Maxwell's equations. The RF field is a time-harmonic field so that the Maxwell's equation can be simplified to the Laplace equation with a quasi-static assumption (Choi and Konrad, 1991; Birla et al., 2008):

$$-\nabla \cdot ((\sigma + j2\pi\varepsilon_0\varepsilon')\nabla V) = 0 \quad (2)$$

where σ is the electrical conductivity of the food material (S m^{-1}), $j = \sqrt{-1}$, ε' is the dielectric constant of food material, and V is the electric potential across the electrode gap (V).

The heat transfer inside the food material is described by Fourier's equation:

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T + \frac{P}{\rho c_p} \quad (3)$$

where $\partial T/\partial t$ is the instant heating rate in food material, (°C s^{-1}); α is the thermal diffusivity (m^2 s^{-1}); ρ is the density (kg m^{-3}); and c_p is specific heat (J kg^{-1} K^{-1}).

By simultaneously solving Eqs. (1)–(3), the temperature profile in a peanut butter jar within a certain time period can be obtained.

2.5.3. Initial and boundary conditions

The initial temperature was set at room temperature (23 °C). In the case of peanut butter surrounded by PEI, the outer surface of the peanut butter container was in direct contact with the vertical,

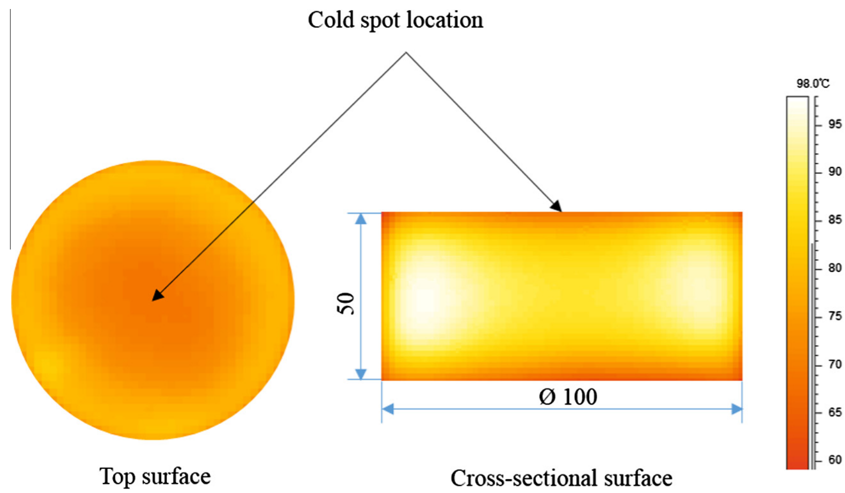

Fig. 2. Typical thermal images for top and cross-sectional surface of peanut butter samples after RF treatment (dimensions are in mm).

cylindrical surface of the PEI sheets (Fig. 1b). The other surfaces of the PEI sheets were exposed to still air and the convective heat transfer coefficient (h) was assumed to be 15 W m^{-2} °C^{-1} for natural convection (Romano and Marra, 2008). In the case of peanut butter without PEI surrounding, a convective heat transfer boundary condition (h = 15 W m^{-2} °C^{-1}) was used at the outer surface of peanut butter container. The metal enclosure boundary of the RF machine was considered as thermal insulation, $\nabla T = 0$. The top electrode was set as the electromagnetic source since it introduced high frequency electromagnetic energy from the generator to the heating cavity. It was difficult to measure the actual voltage during processing without disturbing the electric field (Marshall and Metaxas, 1998), thus, the voltage of the top electrode was estimated by the following equation (Birla et al., 2008):

$$V = (d_{air}\sqrt{(\varepsilon')^2 + (\varepsilon'')^2} + d_{mat})\left(\sqrt{\frac{\rho c_p}{\pi f \varepsilon_0 \varepsilon'}\frac{dT}{dt}}\right) \quad (4)$$

where d_{air} is the air gap between the top electrode and food sample (m), d_{mat} is the thickness of the food material (m), and ε' and ε'' are the dielectric constant and loss factor of food materials, respectively.

Because of the different heating rates, the estimated voltages are 6350 and 11,000 V for simulation without and with PEI sheets, respectively. All the metal shielding parts except the top electrode were grounded, and considered as electrical insulation, $\nabla \cdot \overline{E} = 0$.

2.5.4. Simulation procedure

A commercial finite element method (FEM) based software COMSOL Multiphysics (V4.2a COMSOL Multiphysics, Burlington, MA, USA) was used to simulate the RF heating process. The joule heating module used in this study was a conjugation module of electromagnetic heating and heat transfer, which can solve the electromagnetic equations and heat transfer equations simultaneously. In the food sample and on the top electrode, extremely fine tetrahedral mesh was incorporated to guarantee the accuracy of temperature distribution prediction. Other parts of the system were meshed with normal size tetrahedral mesh. The mesh size was chosen based on the convergence study when the difference of the maximum temperature between successive calculations was less than 0.1%. The final meshes contained 115,231 domain elements, 20,104 boundary elements, 997 edge elements and 64 vertex elements. The time step used in this study was 0.1 s. The computer simulation was conducted on a Dell workstation with two Dual Core 2.80 GHz Xeon processors, 12 GB RAM on a Windows 7 64 bit operating system. Each simulation case took around 20 min to complete.

2.6. Model validation – RF experiments

The 6 kW free-running oscillator RF heating machine with a working frequency of 27.12 MHz was used in experiments to validate the computer simulation model. The cold spot location in the container was determined by both experimental and computer simulation methods. In a cylindrical container, the temperature distribution at every vertical cross-sectional surface across the central axis of the container should ideally be the same. Therefore, the temperature distribution of top surface and one such vertical cross-sectional surface could represent the whole geometry for determining cold spot locations (as illustrated in Fig. 2). In the experiment, thermal images of the top and a vertical cross-sectional surface of food were taken after RF treatments. The lowest temperature location of the two surfaces was identified as the cold spot of the food sample. In the computer simulation, the cold spot location was found from the volumetric temperature map with the software. In RF heating experiments, when the cold spot temperature of the food sample reached 70 °C, the sample container was removed from the heating cavity. Then the surface temperatures of the top surface or cross-sectional surface was immediately measured with an infrared camera with an accuracy of ±2 °C (ThermaCAM™ Researcher 2001, FLIR Systems, Portland, OR, USA). The camera was calibrated by comparing the output temperature with the actual temperature measured with a calibrated thermocouple. The emissivity of the food, plastic film and container were 0.99.

To obtain the temperature profile at a vertical cross-sectional surface, a cylindrical container was cut into half along the axis (Fig. 3), and each half was sealed with a 0.1 mm thick plastic film using super glue. The assumption behind using a thin plastic film was that the film and the peanut butter adjacent to it had equivalent temperatures. The two halves were reassembled

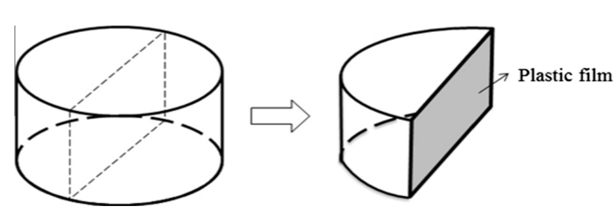

Fig. 3. Cutting a cylindrical container in half for temperature distribution measurement at the cross-sectional surface.

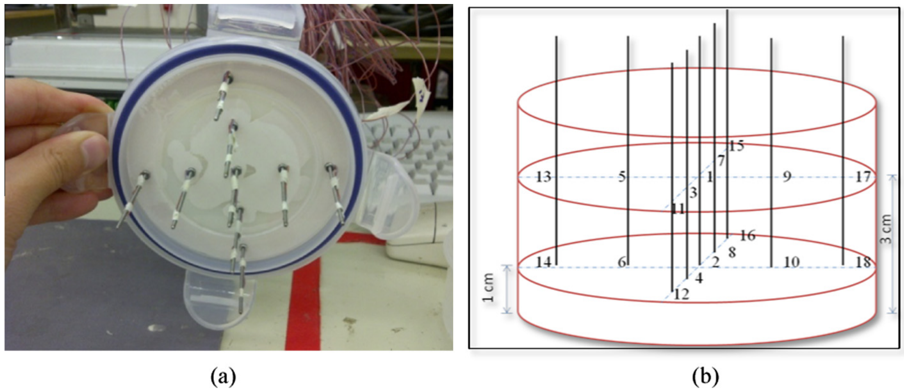

Fig. 4. Eighteen thermocouples (with labeled locations) connected to data logger for measuring temperature distribution inside the food container after RF treatment.

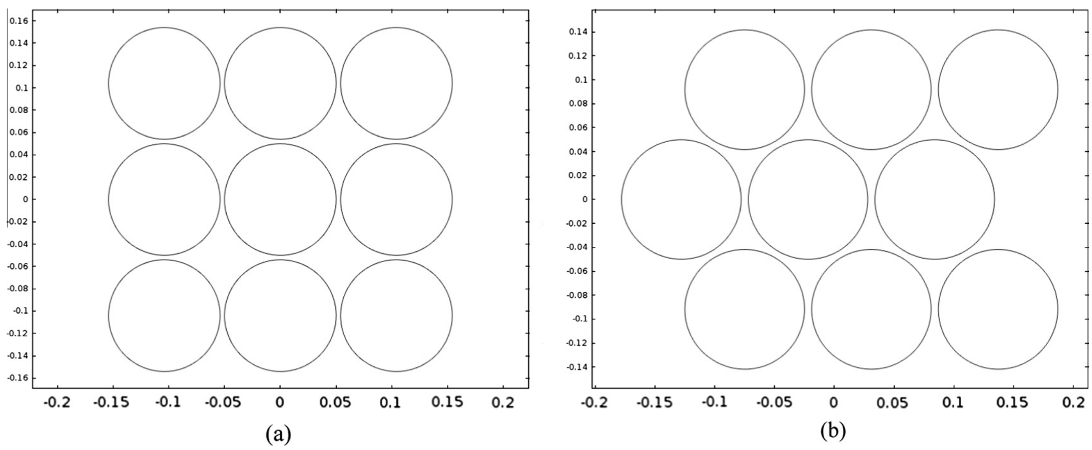

Fig. 5. Two spatial arrangements of 9 peanut butter jars for RF treatment (top view): Arrangement 1 (a) and Arrangement 2 (b).

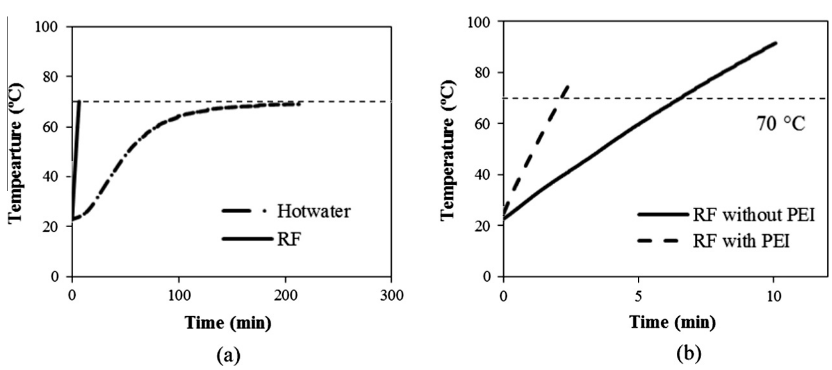

Fig. 6. A typical measured temperature–time curve of peanut butter in a cylindrical container (a) subjected to hot water heating and RF heating and (b) subjected to RF heating with and without PEI assistance with an electrode gap 9 cm (temperature at the center of peanut butter).

forming a cylinder, and then filled with peanut butter sample for RF treatment. A thermal image of the cross-sectional surface after treatment was also taken with the infrared camera. The target temperature was chosen based on normal food pasteurization temperatures.

A board fixed with 18 thermocouple sensors (Type-T, Omega Engineering Ltd, CT, accuracy ±0.5 °C) was used to obtain the temperature distribution in peanut butter samples after RF heating (Fig. 4a). The board was made from a plastic block (d = 10 cm, h = 2 cm) glued to the top of the container lid. Nine holes (d = 2 mm) were drilled through the lid and glued block. Nine threaded rods (d = 2 mm, h = 9 cm) were inserted through the block and extended beyond the base of the board by 5 cm to allow attachment of thermocouples. All the rods were fastened with nuts on both sides. Another 9 holes with diameters double those of the thermocouple wires' (d = 1 mm) were drilled next to the rods to allow sensor wires to pass through. Two thermocouple wires were fixed through each hole, and fastened with thread at two different vertical positions (h_1 = 3 cm, h_2 = 1 cm measured from the container bottom). All together, the board had 18 thermocouple wires labeled as shown in Fig. 4b. It was then used to determine sample temperature distribution of the two layers.

Immediately after infrared pictures of surfaces were taken, sensors were inserted into the peanut butter, and temperatures at all

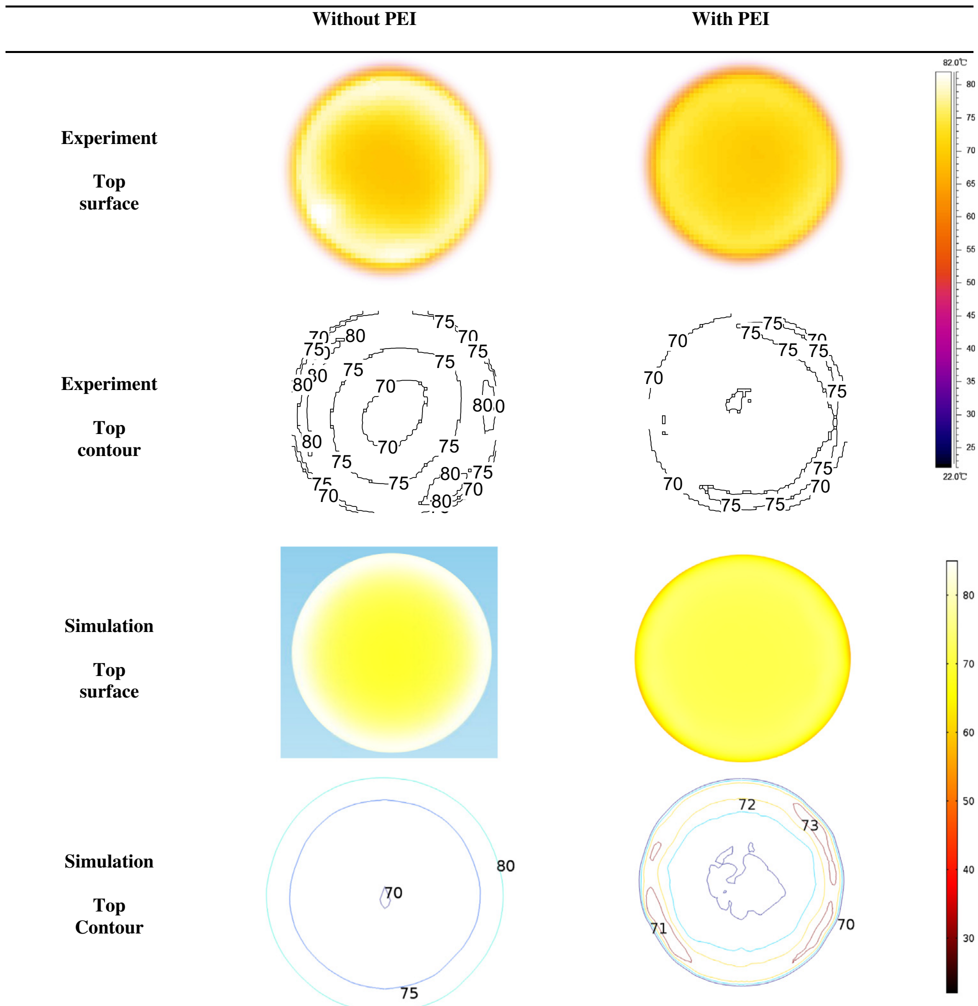

Fig. 7. Comparison of simulated and experimental results for top surface temperature distributions of peanut butter without and with PEI assistance after 10.0 and 2.8 min RF heating with an electrode gap of 9 cm.

18 spots were recorded. The entire temperature measurement procedure was completed within 15 s. These experiments were replicated three times.

2.7. Heating uniformity of wheat flour

The same RF treatment used for the peanut butter samples was applied to the wheat flour samples in a cylinder container with and without surrounding PEI. The target heating temperature was selected as 60 °C due to product quality limitations. A thermal image was taken of the top surface of the wheat flour. The effectiveness of the PEI surrounding method on improving the heating uniformity was evaluated by comparing the temperature distributions at the top surface of the wheat flour.

2.8. Heating uniformity of multiple containers under RF treatment

After the computer simulation model was validated, the model was used to study heating uniformity of multiple containers in a single RF cavity to simulate possible industrial RF heating processes. The model considered nine containers arranged in two different spatial patterns heated in RF systems with and without PEI assistance (Fig. 5). The heating uniformity of treated samples was evaluated by the uniformity index (UI) (Alfaifi et al., 2014) below. In RF treatments, a smaller index corresponds to better heating uniformity.

$$UI = \frac{\int_{V_{vol}} |T - T_{av}| dV_{vol}}{(T_{av} - T_{initial}) V_{vol}} \quad (5)$$

where T is the local temperature in the food (°C), $T_{initial}$ is the initial temperature of the food (°C), T_{av} is the average temperature of the food volume (°C), and V_{vol} is the volume of food (m^3).

In this study, we compared the UI of all 9 samples and also the centrally located sample in Fig. 5. The centrally located sample was selected to represent the samples in industrial large scale processing without the influence of edge over-heating.

2.9. Statistical analysis

The mean values of three replicates of temperature measured by thermocouples were analyzed by Microsoft Excel®. All the statistically significant comparisons were made at a significance level of $P = 0.05$.

3. Results and discussion

3.1. Dielectric and thermal properties of peanut butter

The properties of peanut butter, PEI and air at room temperature were used in the computer simulation (Table 2). Dielectric properties of peanut butter had a non-linear relationship with

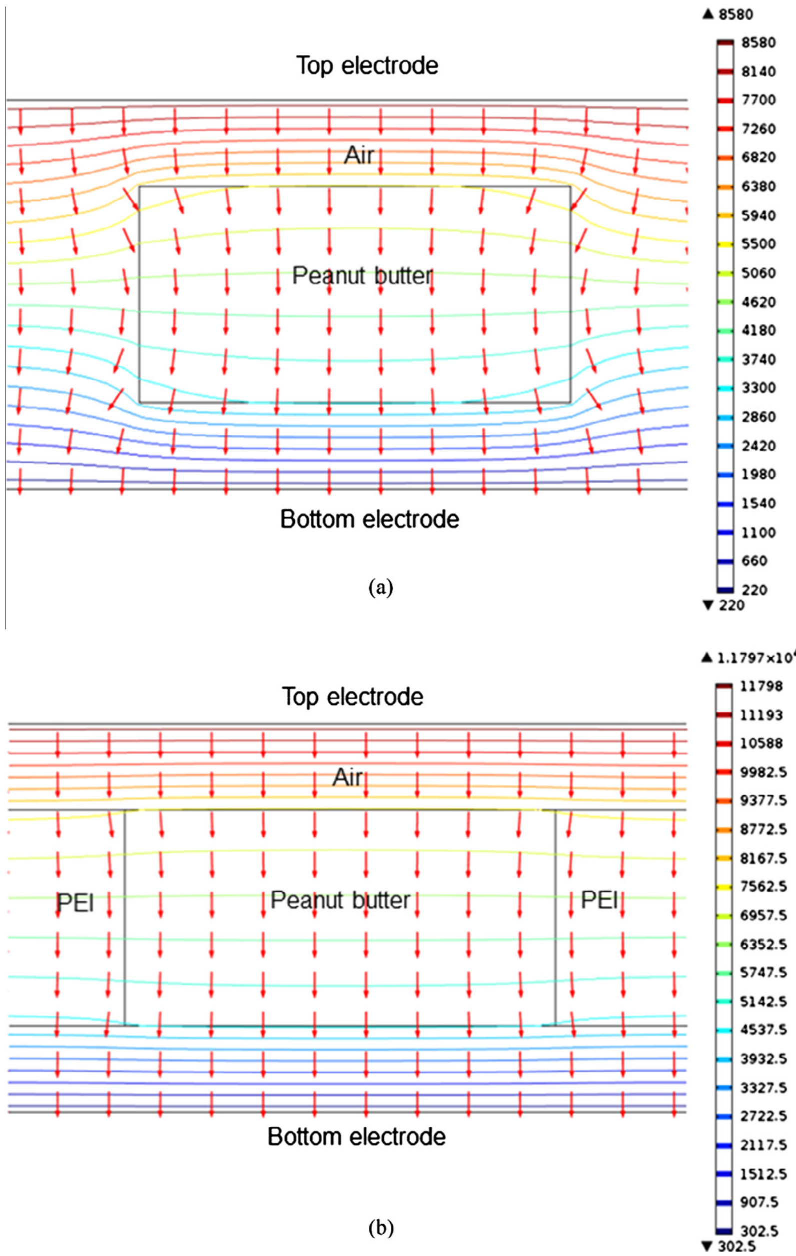

Fig. 8. Simulated electric field (arrow) and electric potential (contour) plot for peanut butter (a) without PEI and (b) with PEI assistance after 10.0 and 2.8 min RF treatment (electrode gap 9 cm).

temperature, so only average values at all temperatures were used in the simulation. The low dielectric constant and loss factor of peanut butter were due to the high fat content (around 50%) and low moisture content (1.3% w.b.) of the composition. The dielectric properties of peanut butter are close to those of vegetable oil (Kent, 1987).

3.2. Heating rate comparison among peanut butter in hot water, with and without PEI assistance in RF treatments

Fig. 6(a) shows the temperature histories of peanut butter samples during RF heating with an electrode gap of 9 cm and hot water heating from a starting temperature of 23 °C. In both cases, processing times were selected to ensure the cold spot in the food reached 70 °C for a fair comparison. The heating time of hot water treatment was around 220 min. This was reduced to 6.5 min with RF heating. With a more linear heating rate, RF heating was about 34 times faster than hot water heating. The rapid heating rate of RF suggests that RF technology could prevent unnecessary quality degradation of food samples by reducing excessive heating time.

Typical experimental temperature–time profiles at the center of peanut butter sample when subjected to RF heating with an electrode gap of 9 cm with and without PEI assistance are shown in Fig. 6(b). Heating rates were relatively constant under both conditions. After adding PEI sheets, the heating rate at the center of the peanut butter sample increased from 6.8 to 20.8 °C min^{-1} while the heating time required to reach 70 °C was reduced from 10.0 to 2.8 min. The corresponding anode current also increased from 0.52 to 1.20 A. This is because increased dielectric material volume provided a better impedance match between the load circuit and the tank circuit, which resulted in increased input power. The power conversion in the food sample was automatically adjusted by the free-running oscillator RF system based on the impedance match. During RF treatment, the temperature of the PEI plates

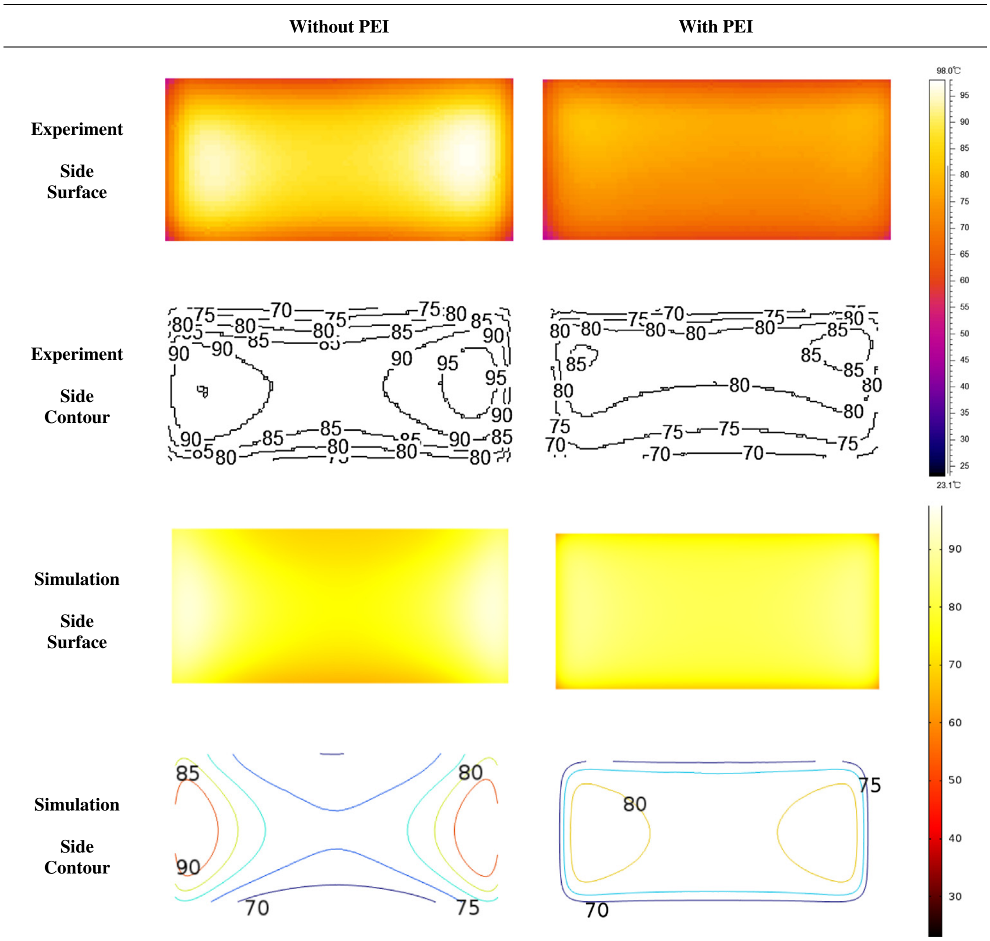

Fig. 9. Comparison of simulated and experimental results for cross-sectional surface temperature distributions of peanut butter without and with PEI assistance after 10.0 and 2.8 min RF heating with an electrode gap of 9 cm.

Table 3
Infrared picture analysis of top and side surfaces of a peanut butter jar with and without PEI assistance after RF treatment.

		Temperature (°C)				
		Min	Max	Max–min	Average	Stdev
Top surface	Without PEI	70	83	13	76	4
	With PEI	70	77	7	73	2
Central cross-sectional surface	Without PEI	70	98	28	87	6
	With PEI	70	88	18	79	4

increased from approximately 23 to 28 °C, which was only about 10% of the temperature increase in the food sample with the same treatment.

3.3. Determination of cold spot location in a sample container

The voltage used in computer simulation was 8800 and 12,100 V for peanut butter under RF treatment without and with PEI plates, respectively. The voltages were obtained by sweeping a voltage range around the estimation value in computer simulation to match heating profiles of experiments (Birla et al., 2008). The difference between the estimation and actual value used (around 2000–2500 V) was due to the limitation of using only the heating rate at the center of the sample to represent the sample geometry.

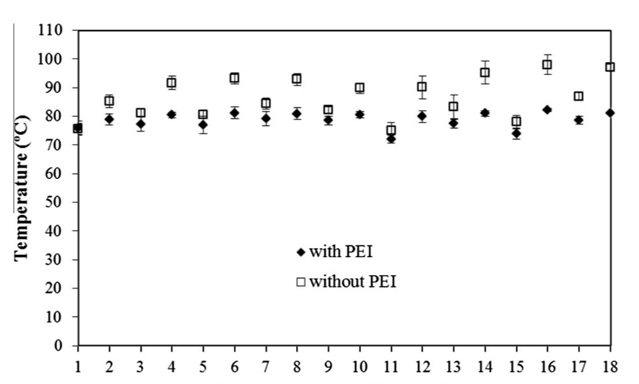

Fig. 10. Experimentally measured temperature at 18 locations in peanut butter container after 10.0 min RF treatment without PEI and 2.8 min with PEI.

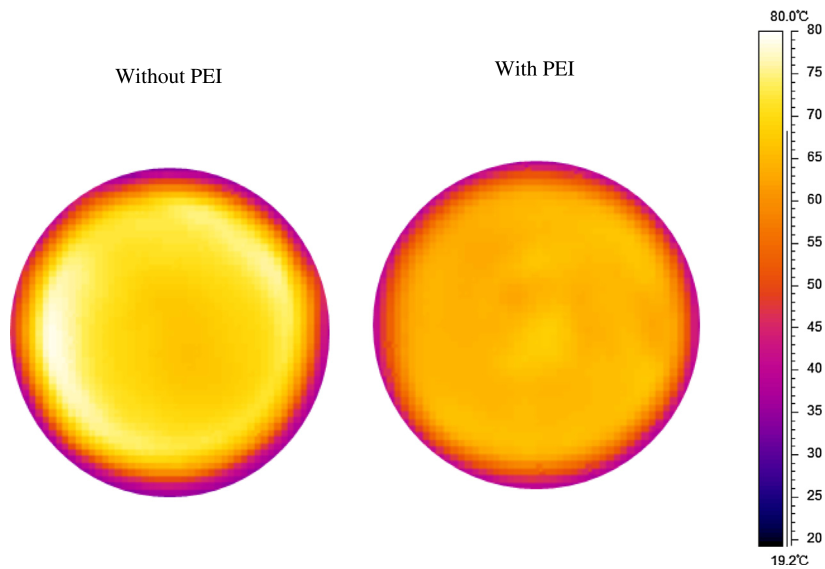

Fig. 11. Thermal images of surface temperature distribution of wheat flour after 8.0 and 4.3 min RF treatment without and with PEI sheets (electrode gap = 9 cm).

Based on both experimentation and computer simulation results, the cold spot location was found to be at the center of top and bottom surfaces for samples with or without PEI sheets (Figs. 7 and 9). The selection of the RF treatment period was based on confirmation that the cold spot location reached the target pasteurizing temperature, which was 70 °C in this study.

3.4. Model validation – comparison of experimental and simulated temperature profiles of the top layer and cross-section

Surface and contour plots of the top surface of peanut butter with and without PEI sheets assistance after RF treatment for 2.8 and 10.0 min are shown in Fig. 7. The low temperatures measured at the outer edge of the food in experiments were attributed to the heat loss that occurred during the time when the samples were being transferred from the RF equipment to the camera. Computer simulation result in Fig 8a illustrates how electric field pattern between two RF electrodes was distorted in the presence of the peanut butter jar which causes severe edge heating. The electric field distortion was reduced when placing a PEI material around the sample jar (Fig. 8b). Similar results were reported by Tiwari et al. (2011a) and Alfaifi et al. (2014) for wheat flour and dry fruits. Judging from the heating patterns presented in Fig. 7, the simulation and experimental results agreed well, which validated the simulation model. The experimental results showed that when the lowest temperature reached 70 °C, the highest temperature had reached 83 °C with no PEI sheets surrounding the sample. After adding PEI, the highest temperature was reduced to 77 °C. Computer simulation indicated that the temperature range was from 70 to 80 °C without PEI, and 70 to 73 °C when using PEI. The reduced temperature differential between the hot and cold spot validated the effectiveness of using PEI to surround the sample to improve RF heating uniformity.

Fig. 9 shows surface and contour plots of temperature distributions obtained from experiments and computer simulation for the central cross-sectional surface of a peanut butter container following RF treatment with and without PEI as the surrounding medium. The low temperatures at the edge of temperature profile from the experiments were, again, caused by a time delay for the temperature measurement after RF treatment was finished. The temperature pattern is symmetric both horizontally and in parallel since the sample is located at the center of the RF cavity. The experimental contour plot shows that the highest temperature on the cross-sectional surface was 95 °C without PEI, but was reduced to 85 °C with PEI. This comparison indicated that the hot spot temperature was sharply reduced using the PEI assisted method. Both computer simulation and experimentation showed similar results, which again validated the effectiveness of the mathematical model.

3.5. Overall heating uniformity improvement evaluation

The maximum, minimum, average temperature and standard deviation of the top surface and central cross-sectional of peanut butter are summarized in Table 3. For the top surface, the difference between maximum and minimum temperatures with PEI assistance was reduced from 13 to 7 °C. The standard deviation was reduced from 4 to 2 °C, which also implies a better heating uniformity. The heating uniformity improvement for the central cross-sectional area was also obvious. The difference between maximum and minimum temperature was reduced from 28 to 18 °C, and the standard deviation was reduced from 6 to 4 °C.

The internal temperature distribution in the peanut butter jar obtained from the thermocouples is shown in Fig. 10. The average temperature and standard deviation of all 18 locations without and with PEI assistance was 86.7 ± 1.0 and 78.6 ± 0.7 °C, respectively. Thus, the smaller scatter range showed that temperature uniformity improved volumetrically with PEI assistance.

3.6. Heating uniformity of wheat flour

The top surface temperature distribution of wheat flour after 8.0 min RF treatment (electrode gap of 9 cm) without PEI assistance and 4.3 min RF treatment with PEI assistance are shown in Fig. 11. The cold spot location was the same as that of peanut butter, which was at the center of the top surface. It is clear from Fig. 11 that the high temperature zone (white color) vanished after adding PEI sheets. Without PEI assistance, the edge temperature reached 80 °C when the center temperature reached 60 °C. When PEI sheets were added, the edge temperature decreased to 67 °C, which indicated that heating uniformity was improved. This demonstrates that the PEI assistance method could possibly be applied to other low moisture food products.

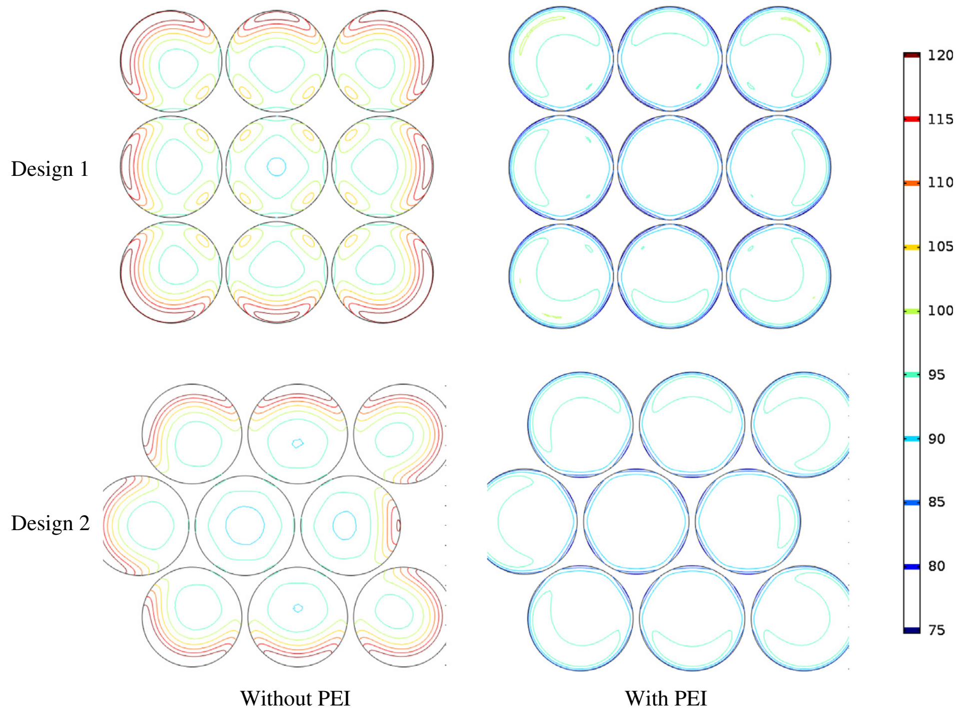

Fig. 12. Simulated temperature distribution (middle layer) of two spatial arrangements of 9 peanut butter samples with and without PEI assistance under 6 min RF treatment with an electrode gap of 9 cm.

3.7. Heating uniformity of multiple peanut butter samples

The simulated temperature profiles of the middle layer of 9 peanut butter samples in two different spatial arrangements are shown in Fig. 12. For both arrangements, heating uniformity was largely improved by adding PEI sheets around the samples, causing the maximum temperature to be reduced from 120 °C to 99 °C while minimum temperature stayed the same (70 °C). Overheating was observed at the outside layer of samples not surrounded with PEI, but found to be reduced when PEI sheets were added. Overheating problems remaining after applying PEI sheets can be explained by the difference in dielectric properties of PEI sheets and peanut butter samples.

The uniformity indexes (UI) were calculated volumetrically for all 9 samples and for the central sample with and without PEI (Table 4). For all 9 samples, the UI was clearly reduced after adding PEI sheets. Also, edge heating was effectively reduced by utilizing PEI assistance. There was little difference between the two designs in terms of average temperature and UI.

If we only consider the heating uniformity of the centrally located peanut butter container, which represents food samples in industrial processing, design 2 was better than design 1. The average temperature was lowered from 94.1 to 88.7 °C in design 1 and 93.0 to 89.4 °C in design 2. Also, the UI decreased from 0.0576 and 0.0499 to 0.0440 and 0.0336, respectively. This was because the spaces filled with PEI between containers were smaller, resulting in a better heating uniformity.

Table 4
Uniformity index (UI) comparisons between two spatial arrangements of 9 peanut butter samples and the centrally located sample under RF treatment with and without PEI assistance.

	Design 1		Design 2	
	Without PEI	With PEI	Without PEI	With PEI
9 samples				
Average temperature (°C)	98.6	89.8	99.6	90.6
Uniformity index (UI)	0.0887	0.0541	0.0948	0.0393
Centrally located sample				
Average temperature (°C)	94.1	88.7	93.0	89.4
Uniformity index (UI)	0.0576	0.0499	0.0440	0.0336

4. Conclusion

A computer model was developed to explore the effectiveness of PEI assistance method to improve the heating uniformity of peanut butter subjected to RF heating in a 6 kW, 27.12 MHz RF system. Results from computer simulation and experimental methods showed good agreement for the temperature distribution of both the top and cross-sectional surfaces of peanut butter samples. For peanut butter samples heated from room temperature to 70 °C, the maximum temperature difference in the peanut butter was reduced from 28 to 18 °C after adding PEI. The same treatment was applied to wheat flour with samples heated from room temperature to 60 °C, which resulted in a reduction in the maximum temperature difference at top surface from 20 to 7 °C after adding PEI. The validated computer simulation model was then used to test the PEI addition method in 9 peanut butter jars with two different spatial arrangements. All the results indicated that the use of the PEI addition method has the potential to improve the heating uniformity of low moisture foods heated in RF systems. The heating uniformity of multiple jars can also be improved by putting the jars as close together as possible. Furthermore, the model can be used to optimize the parameters in the heating uniformity improvement methods, for example, adjusting the dielectric properties of the surrounding material to explore the best material for a specific food sample.

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