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Improvement of radio frequency (RF) heating uniformity on low moisture foods with Polyetherimide (PEI) blocks

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ABSTRACT

Radio frequency (RF) heating is rapid, volumetric, and can penetrate most food packaging material. Thus, it is suited for in-packaged food pasteurization applications. However, the non-uniform heating problem needs to be resolved. In this study, a method of adding Polyetherimide (PEI) cylindrical blocks on top of and at the bottom of peanut butter samples in a cylindrical jar ($d = 10$ cm, $h = 5$ cm) was evaluated to improve RF heating uniformity. A computer simulation model built with COMSOL Multiphysics® was used for heating pattern prediction, and a new temperature uniformity index was proposed to suitably evaluate pasteurization process heating uniformity. Results showed that a pair of PEI blocks with a diameter of 8 cm among all five diameters (2, 4, 6, 8, and 10 cm) added to the cold spots of a given peanut butter sample could make the sample reach the best heating uniformity. Furthermore, the best height of PEI blocks with a diameter of 8 cm that allows the sample to be heated most uniformly was found to be 1.3 cm after sweeping from 0.1 to 2.3 cm with a step of 0.1 cm. Simulation results also showed that the combination of PEI surrounding and the addition of 8 cm diameter PEI blocks could further control the temperature distribution range in peanut butter within 7.1 °C when the peanut butter was heated from 23 to 70 °C. The newly developed temperature uniformity index provided a more reasonable evaluation on heating uniformity of pasteurization process than the traditional uniformity index.

1. Introduction

Most of the low moisture foods, e.g. beef jerky, milk powder, chocolate, peanut butter, and pet food, are considered as shelf stable ($a_w < 0.6$). However, many of those have been reported as being contaminated by *Salmonella* over the last decade (Matsui et al., 2004; Vought & Tatini, 1998). *Salmonella*, a foodborne pathogen, is one of the most common causes of food poisoning in the U.S. and Europe. According to the Centers for Disease Control and Prevention (CDC), *Salmonella* causes 1.2 million illness cases in the U.S. every year (CDC, 2012). The source of *Salmonella* is usually animal products, e.g. raw meat, egg, milk and animal excreta. Cross-contaminations due to unclean processing conditions or inappropriate storage may bring the pathogen from animal products to shelf stale foods and cause serious poisoning to people. To eliminate the pathogen, a post-packaging pasteurization process for shelf stable foods would be desirable.

Thermal inactivation is the most common pasteurization method for foods. When elevating the temperature of foods, the optimum living environment of the pathogen is disrupted, resulting in the inactivation of pathogens. Traditional thermal inactivation methods usually utilize hot air and hot water as a heat medium. However, low moisture food products are difficult to be heated due to the low thermal conduction rate. This results in a longer heating period, and consequently, a lower food quality (Birla et al., 2005; Gao, Tang, Wang, Powers, & Wang, 2010; Wang, Monzon, Johnson, Mitcham, & Tang, 2007b; Wang et al., 2001). Furthermore, the slow heating rate may increase the heat resistance of bacteria since the generation of heat shock protein made the bacteria adapt to the environment quickly (Chung, Wang, & Tang, 2007; Xavier & Ingham, 1997).

Radio frequency (RF) technology uses electromagnetic waves with a frequency range of 3 kHz to 300 MHz to heat target foods. It has been applied for drying, thawing and pest control in the food industry (Alberti et al., 2011; Alfaifi et al., 2014; Farag, Lyng, Morgan, & Cronin, 2011; Gao, Tang, Wang, Powers, & Wang, 2010; Jumah, 2005; Kocadagli, Palazoglu, & Gokmen, 2012; Lagunas-Solar et al., 2007; Wang, Tiwari, Jiao, Johnson, & Tang, 2010; Wang et al., 2014). Studies also showed that RF has the potential for packaged food pasteurization/sterilization (Houben, Schoenmakers, Van Putten, Van Roon, & Krol, 1991; Luechapattanaporn et al., 2004, 2005). RF over-heating at the edges and corners of food samples remains an important challenge. This non-uniform heating is mainly caused by the difference between the dielectric properties of food and its surrounding medium (Birla,

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Wang, Tang, & Hallman, 2004; Jiao, Tang, & Wang, 2014). Studies have been reported on improving the heating uniformity in a food matrix in RF treatments. For high water content food like fruits, researchers used water surrounding combined with a moving or rotating method (Birla, Wang, & Tang, 2008; Birla et al., 2004, 2005; Hansen et al., 2005; Ikediala, Hansen, Tang, Drake, & Wang, 2002; Wang, Birla, Tang, & Hansen, 2006); for intermediate/low moisture foods, scientists developed hot air assistance, intermittent stirring, movement, electrode modification, and plastic sheets surrounding methods to enhance the heating uniformity (Alfaifi, 2013; Gao, Tang, Villa-Rojas, Wang, & Wang, 2011; Jiao, Tang, & Wang, 2014; Liu, Wang, Mao, Tang, & Tiwari, 2012; Liu et al., 2011; Pan, Jiao, Gautz, Tu, & Wang, 2012; Wang, Monzon, Johnson, Mitcham, & Tang, 2007a; Wang, Yue, Tang, & Chen, 2005).

In this study, we propose a method to improve the heating uniformity by strategically increasing the amount of energy delivered to the cold spot of a sample. In a free-running oscillator RF system, the amount of energy delivered into the load is auto-adjusted by the matching circuit. When a homogeneous food sample with a non-uniform thickness is placed between the electrodes, the thicker portion of the sample would normally absorb a larger amount of energy and would be heated faster (Mehdizadeh, 2009). Therefore, for a product with a uniform thickness, increasing the thickness at the cold spot location will help localize the electric field and bring up the local temperature, which will result in a better heating uniformity. In order to prove this concept in low moisture food pasteurization, we chose to place cylindrical dielectric blocks at the cold spots of the peanut butter sample in a cylindrical container during RF treatment to improve the heating uniformity.

The objectives of this study were to: (1) establish a computer simulation model to predict the electric field intensity and temperature distribution with PEI blocks adjacent to the cold spots of peanut butter in a cylindrical container; (2) conduct experiments with peanut butter and various diameters of PEI blocks in a RF system to verify the simulation results; (3) use the validated computer model to explore the influence of the height of the PEI blocks; and (4) use the computer model to predict the effectiveness of a combination method of PEI sheets surrounding and PEI blocks addition, and compare the effectiveness.

2. Materials and methods

2.1. Sample preparation

Peanut butter (IGA brand) was purchased from a local grocery store (IGA, Pullman, WA). It is a homogeneous paste without peanut chunks and oil separation. Peanut butter (460 g) was fed into a cylindrical plastic container (polypropylene, $d = 10$ cm, $h = 5$ cm) for RF treatments. The physical, thermal and dielectric properties of the peanut butter were reported by Jiao, Tang, and Wang (2014).

2.2. Block material and size selection

PEI, also called Polyetherimide or ultem, was selected as the material for the dielectric blocks because of its high heat resistance and electric strength. The dielectric properties of PEI material limited its heat absorbance during RF treatment, which could make the heat focus more on foods (Jiao, Tang, & Wang, 2014). Since the peanut butter was in a cylindrical container, the PEI blocks were also cut into cylinders to match the shape of the cold areas in the food sample. The height of PEI blocks for experiments was selected to be 1.3 cm, which was determined from preliminary experiment results to better fit in the RF cavity and provide a reasonable heating rate to the food sample. Five diameters of PEI blocks were selected in the tests: 2 cm, 4 cm, 6 cm, 8 cm, and 10 cm.

A combination method for enhancing heating uniformity was to add a pair of PEI blocks with the best diameter among the five at the cold spots and a PEI sheet ($60 \times 20 \times 5$ cm^3) surrounding the peanut butter sample. The details of the PEI surrounding method could be found in Jiao, Tang, and Wang (2014).

2.3. Sequence of the studies

The studies were carried out in the following sequence: firstly a computer simulation model was built up to test the effectiveness of adding PEI blocks adjacent to a peanut butter sample on the RF heating uniformity improvement. Then a set of experiments were conducted to obtain the top surface temperature distribution of the peanut butter in a cylindrical container with a pair of different sized PEI blocks on and below the container to validate the simulation model. Once the model was validated, the temperature profiles at a cross-sectional surface of peanut butter were plotted, and the temperature uniformity index of each case was calculated. After finding the best diameter of the PEI blocks among five different options, computer simulations were run to compare the sample temperature uniformity index for different cases in which PEI materials were placed outside the container, on and beneath the containers, and combination of those three. The best height of PEI blocks with the selected diameter was also obtained with computer simulation.

2.4. Computer simulation

2.4.1. Physical model

The physical model was built for a 6 kW, 27.12 MHz RF heating system with a free-running oscillator and a pair of parallel-plate electrodes (COMBI 6-S, Strayfield International, Wokingham, U.K.). The waves with electromagnetic energy from the RF generator was transferred to the RF cavity and eventually converted to heat in the food load. To simplify the modeling procedure, only the RF cavity and food load were described as the physical model in this study. The dimensions of the RF system can be found in Jiao, Tang, and Wang (2014), and the scheme of the peanut butter sample size and position in the RF cavity was shown in Fig. 1.

2.4.2. Governing equations

The conversion from electromagnetic energy to thermal energy depends on the following equation (Metaxas, 1996):

$$P = 2\pi f \varepsilon_0 \varepsilon'' \left|\vec{E}\right|^2 \tag{1}$$

where P is the power conversion in foods per unit volume (W m^{-3}), f is the working frequency of the RF system (Hz), ε_0 is the permittivity of electromagnetic waves 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 (V m^{-1}).

Maxwell's equations are a set of partial differential equations describe the electromagnetic field. The RF field can be seen as a time harmonic field since the variation time of radio frequency is far smaller than the time needed for heat transfer. Therefore, the Maxwell's equations can be simplified to the Laplace's equation (Eq. (2)) based on a quasi-static assumption (Birla et al., 2008). By solving the Laplace's equation, the electric field intensity can be obtained and the temperature distribution in the food can be determined accordingly based on their thermal properties. It takes less time and effort solving the Laplace's equation than Maxwell's equations.

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

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 absorbed RF power raises the temperature of the food sample, so heat transfer takes place inside the food and between the food and the

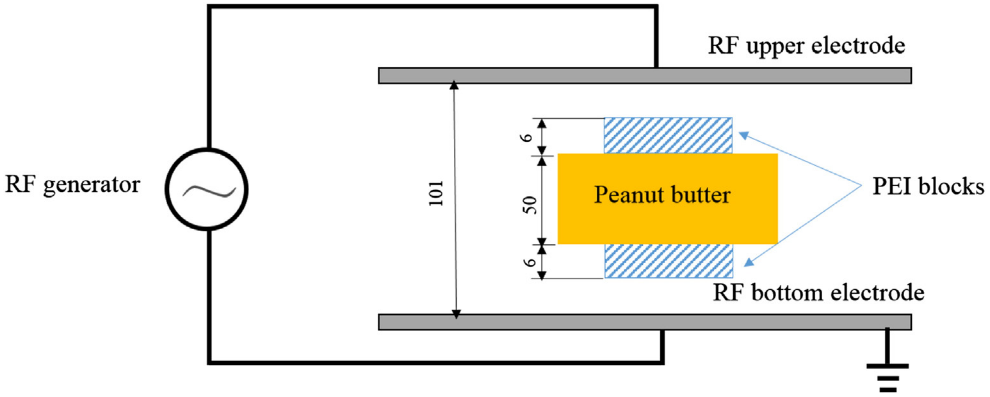

Fig. 1. Scheme of a peanut butter sample in a cylindrical container with two PEI blocks in a 6 kW 27.12 MHz RF cavity (unit: mm).

outside. The heat transfer process can be described in Fourier's equation (Incropera & David, 1996):

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

where T is the temperature of food in a unit volume (°C); $\partial T/\partial t$ 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 the specific heat of the food sample (J kg^{-1} K^{-1}).

The temperature distribution in the food can be obtained by simultaneously solving Eqs. (1)–(3).

2.4.3. Initial and boundary conditions

The initial temperature of all simulation cases was set as 23 °C. The boundary conditions at surfaces of PEI in contact with the peanut butter container were set as heat conduction, and all other surfaces exposed to air were set as natural convection with a heat transfer coefficient of 15 W m^{-2} °C^{-1} (Jiao, Tang, & Wang, 2014). Properties of the peanut butter, PEI blocks and air used in simulations were listed in Table 1.

The top electrode of the RF system was set as the electromagnetic source. The voltage on the electrode and electric field intensity were difficult to measure because any measurement of the high voltage and electric field intensity requires insertion of an external circuit which would, in turn, result in a disturbance to the existed field, leading to a false reading. Thus, researchers developed an estimation method to predict the top electrode voltage (Metaxas, 1996). The estimation equation (Eq. (4)) was developed based on an assumption that the electric field distribution is uniform in the food material when treated by RF. This method has been used by Choi and Konrad (1991), Birla et al. (2008), Alfaifi et al. (2014) and many others, and proven to be effective.

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

where d_{air} is the total air gap between the electrodes and food sample (m), d_{mat} is the thickness of the food material (m), dT/dt is the heating rate which describes the temperature change versus time (°C s^{-1}), and ε' and ε'' are the dielectric constant and loss factor of food materials, respectively. The voltage used in computer simulation was further finely tuned by trial and error until the heating rate in the food matched with the experimental results.

The bottom electrode and the metal shield of the RF system were set as electric insulation.

Table 1
Properties of peanut butter, Polyetherimide and air used in mathematical modeling (adapted from Jiao, Tang, & Wang, 2014).

	Peanut butter	Polyetherimide (PEI)[a]	Air[b]
Density (kg m^{-3})	1115[c]	1270	1.2
Heat capacity (J kg^{-1}·K^{-1})	2030[c]	2000	1000
Thermal conductivity (W m^{-1}·K^{-1})	0.209[c]	0.122	0.026
Dielectric constant	4.03	3.15	1
Dielectric loss factor	0.4	0.0025	0

[a] Kelly and Zweben (2000).
[b] COMSOL material library (2012).
[c] Jiao, Tang, Wang, and Koral (2014).

2.5. Simulation procedure

The commercial finite element method (FEM) software, COMSOL Multiphysics® (V4.2a COMSOL Multiphysics, Burlington, MA, USA), is commonly used to provide numerical solutions to the electromagnetic heating problem. The joule heating module, which conjugates the electric current and heat transfer models, was employed in this study to achieve a reliable and fast prediction of the heating pattern in foods.

After drawing the geometry based on the food sample and the RF system, all domains were meshed to obtain a numerical solution to the problem. The convergence criteria of meshing were to ensure that when the mesh elements are doubled, the maximum temperature difference before and after the mesh change was less than 0.1%. Based on preliminary simulation studies, default extremely fine tetrahedral meshes were generated in the food sample and on the top electrode, and normal size meshes were generated in all other domains. Numbers of elements in the whole geometry after meshing were shown in Table 2.

2.6. RF experiments

All RF experiments were conducted at a room temperature of 23 °C with a fixed electrode gap of 10.1 cm. Peanut butter in cylinder containers was prepared and capped with its original lid. PEI blocks were manufactured from PEI sheets with diameters of 2, 4, 6, 8 and 10 cm with the same thickness of 1.27 cm as stated in Section 2.2. A hole ($d = 2$ mm) was drilled at the center of all PEI blocks and the container lid along its axis to allow temperature sensors to go through.

Table 2
Numbers of different mesh elements generated in all domains in computer simulation.

	Diameter of PEI blocks					
	No PEI	2 cm	4 cm	6 cm	8 cm	10 cm
Tetrahedral	14,658	15,779	18,470	23,344	26,583	33,743
Triangular	2113	2298	2542	3125	3314	4312
Edge	300	320	336	356	356	413
Vertex	44	60	60	60	60	60

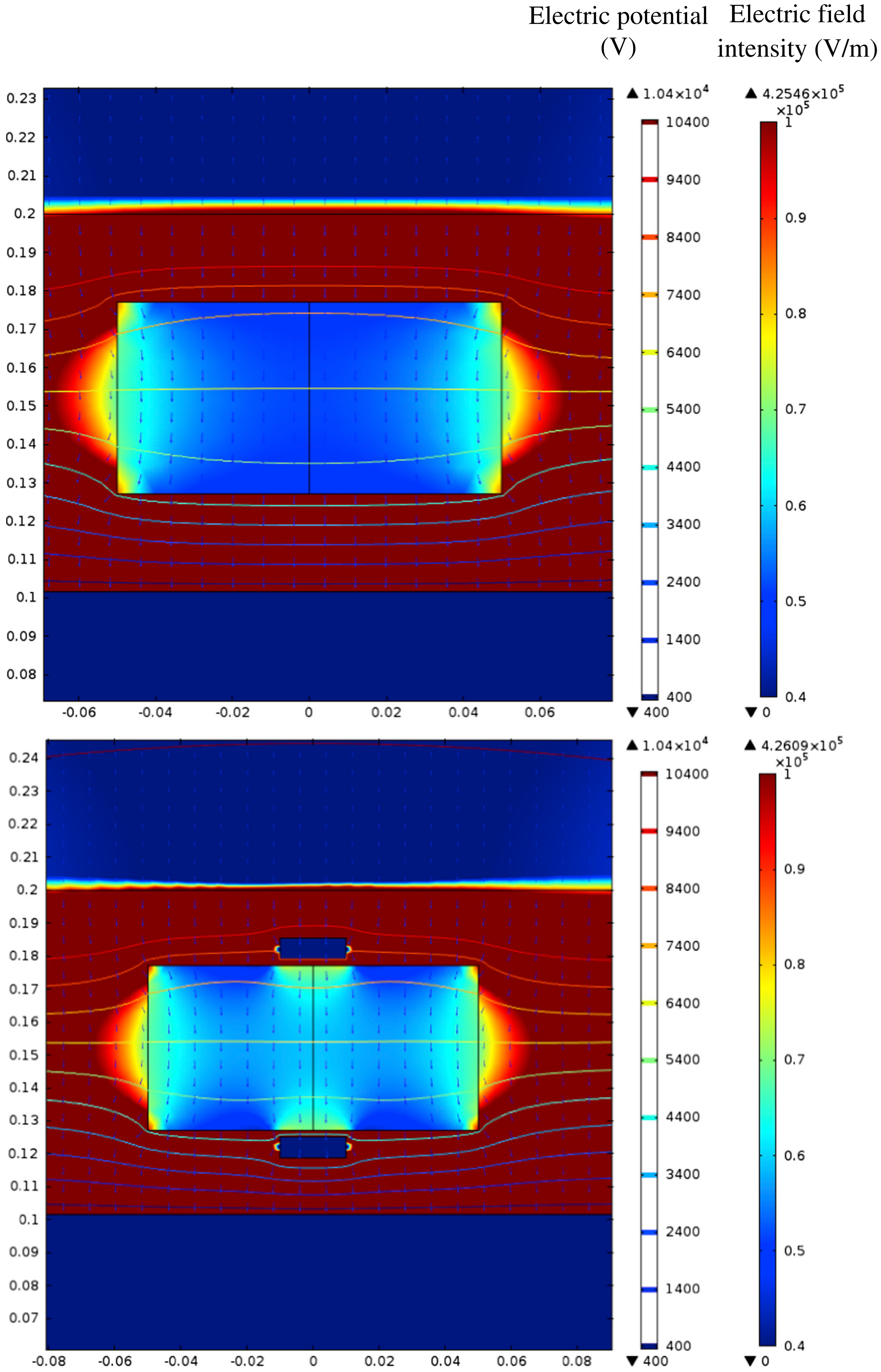

Fig. 2. Electric field direction (arrow), electric field intensity (color surface, unit: V m^{-1}), and electrode potential (streamline, unit: V) of peanut butter treated by RF without (top image) and with (bottom image) PEI blocks. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Influence of treatment parameters (heating time and voltages) on product average temperature and uniformity (difference between maximum and minimum temperatures, and heating uniformity indices) for peanut butter with various diameters of PEI blocks in a 6 kW 27.12 MHz RF system.

	No PEI	2 cm	4 cm	6 cm	8 cm	10 cm
Heating time (s)	600	600	540	506	480	450
Heating rate, dT/dt (°C s^{-1})	0.042	0.047	0.057	0.064	0.070	0.078
Estimated voltage (V)	4510	4755	5243	5552	5815	6150
Simulation voltage (V)	6100	5950	6000	5800	5700	5700
Average temperature (°C)	85.1	82.8	89.0	87.6	86.3	91.5
Maximum–minimum temperature (°C)	25.7	22.8	22.2	19.5	19.8	31.4
UI (Alfaifi's)	0.0839	0.0706	0.0649	0.0624	0.0694	0.0832
TUI (modified)	0.3649	0.3198	0.3011	0.2572	0.2243	0.4207

In experiments, the food sample was sandwiched by two PEI blocks and positioned coaxially in the center of the RF cavity. The food samples were elevated to the middle between the two electrodes to achieve a symmetric heating pattern and a better heating uniformity (Tiwari, Wang, Tang, & Birla, 2011). For all cases with different sizes of PEI blocks, cold spot locations were determined by finding the lowest temperature from thermal images of a top surface and a cross sectional surface taken by an infrared camera (ThermaCAM™ Researcher 2001, FLIR Systems, Portland, OR, USA). All RF experiments in this study were conducted based on the cold spot to reach the target pasteurization temperature (70 °C). A fiber optical sensor (UMI, FISO Technologies, Inc., Saint-Foy, Quebec, Canada) was inserted through the PEI blocks and the container lid to the center of the food to obtain the temperature–time history and calculate the heating rate. When the cold spot reached 70 °C, the sample was taken out immediately in order to take a thermal image.

2.7. Heating uniformity evaluation of different uniformity improvement methods

The effectiveness of several heating uniformity improvement methods was compared by obtaining a temperature uniformity index from computer simulation results. The methods were: PEI blocks addition method (this study), PEI surrounding method (Jiao, Tang, & Wang, 2014) and a combination of both.

The heating uniformity of heated samples was evaluated by two heating uniformity indices. The first heating uniformity index (UI) was developed by Alfaifi et al. (2014).

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

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

A new temperature uniformity index (TUI) (Eq. (6)) was developed based on Alfaifi's UI by replacing the ‘average temperature (T_{ave})’ with the ‘target temperature (T_t)’.

$$TUI = \frac{\int_{V_{vol}} |T - T_t| dV_{vol}}{(T_t - T_{initial}) V_{vol}} \tag{6}$$

where T_t is the target heating temperature (°C). A smaller index corresponds to better heating uniformity.

The new TUI might be more suitable for describing the heating uniformity of a pasteurization/sterilization process which requires the cold spot location to reach a certain target temperature. It would reflect the degree to which temperature in the volume deviated from the target temperature. Peanut butter samples treated with three methods in RF systems were simulated under the same electrode gap (10.1 cm) and were heated until the cold spot location to reach 70 °C for pair comparison. The combined method used the 8 cm diameter PEI block with PEI sheets surrounding. Both UI and TUI were calculated and compared.

2.8. PEI blocks height influence on heating uniformity

To further improve the heating uniformity, the optimum height of the PEI blocks was determined using computer simulation. With a fixed diameter ($d = 8$ cm), the height of the PEI blocks was swept from 0.1 to 2.3 cm with an interval of 0.1 cm. All the simulation cases were run under an electrode gap of 10.1 cm, electrode voltage 5700 V and heating time 480 s for comparison. Uniformity indexes were calculated and the heating patterns at cross-sectional surfaces of the peanut butter were compared.

3. Results and discussion

3.1. Predicted electric field distribution

Typical electric field directions, electric field intensities and electric potentials in the RF cavity and peanut butter with and without PEI blocks are shown in Fig. 2. When the peanut butter sample was treated without PEI blocks, the center of the top and bottom portraits of the sample had the lowest electric field intensity (5×10^5 V m^{-1}). However, when PEI blocks were attached to the center of the top and bottom of the sample, the electric field intensity increased (to 7×10^5 V m^{-1}). The electric field intensity seemed more uniform after adding PEI blocks, which indicates that increasing the local thickness of a sample could increase the local electric intensity, and could further elevating the local temperature.

3.2. Voltage estimation

The estimated and actual simulation voltages used in the computer simulation are listed in Table 3. Both the estimated and simulation voltage were in a range of 4500–6200 V. The difference was caused by the inaccuracy of the voltage estimation method based on an assumption that the temperature in the whole food volume was uniform (Birla, Wang, Tang, & Hallman, 2004). The reason for the unclear trend of simulation voltage with PEI block diameter change is due to the shift of the cold spot after adding PEI blocks in computer simulations, the simulation voltage was changed in order to make the lowest temperature reach 70 °C.

3.3. Computer model validation

The top surface temperature of peanut butter samples obtained from both the experiment and the simulation, and the cross-sectional surface temperature distribution from the computer simulation are shown in Fig. 3. The differences between maximum and minimum temperatures and the standard deviation of the sample's top surface temperature are summarized in Table 4. From the top surface temperature

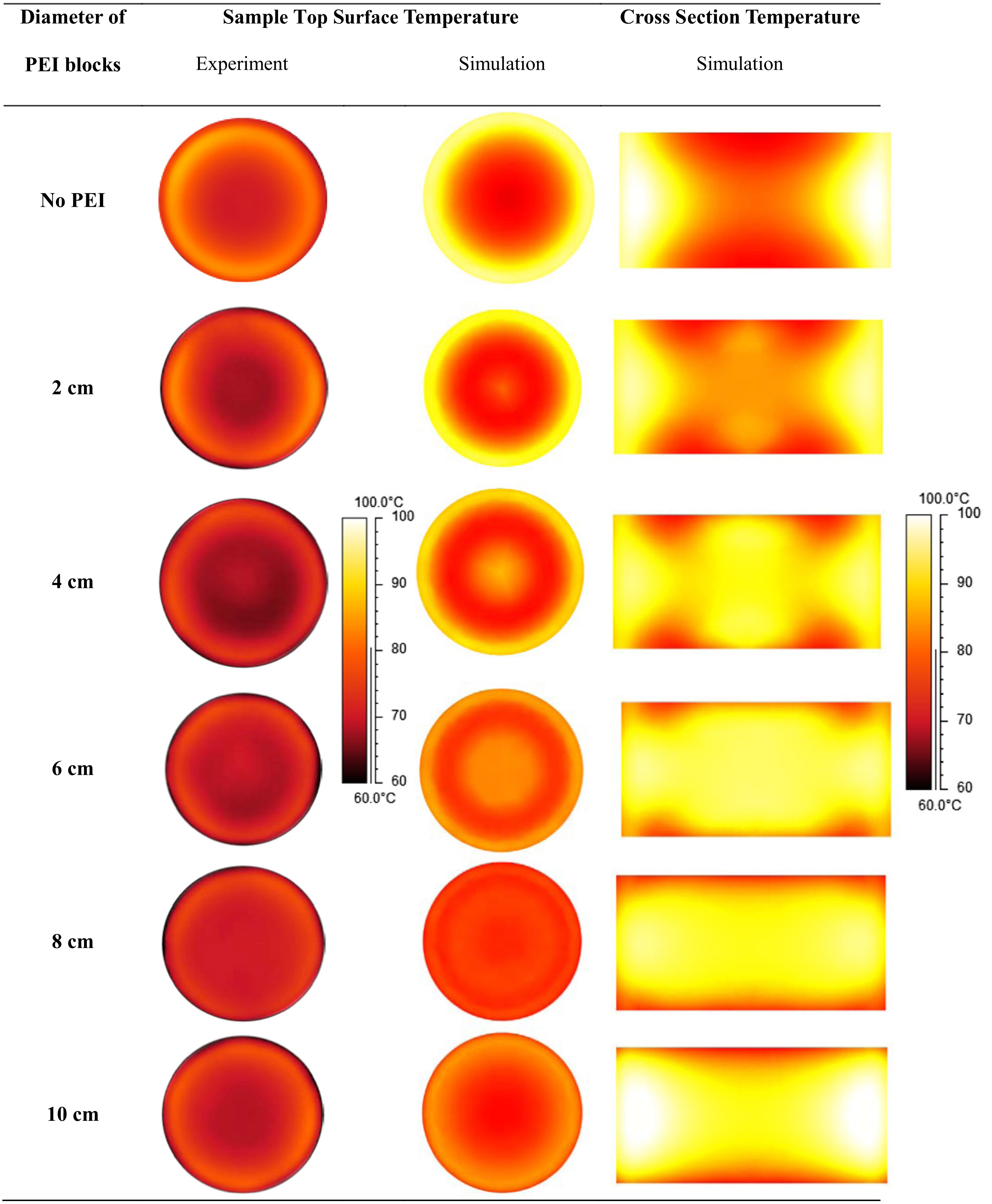

Fig. 3. Temperature distribution on the top surface of peanut butter from experiment and computer simulation with various sizes of PEI blocks in RF treatment (temperature scale on left: experiment; on right: simulation; T, °C).

comparison, computer simulation results had a similar heating pattern as the experiment results, showing that the smallest temperature deviation was achieved by adding a pair of 8 cm PEI blocks. From the experiment plots, when the center reached 70 °C, the hot spot reached around 87 °C without PEI blocks. After adding PEI blocks, the hot spot temperature on the surface was reduced gradually from 87 °C to 79 °C

Table 4
Distribution analysis for sample top surface temperature from experiment with different sizes of PEI blocks (T, °C).

	PEI block diameter					
	No PEI	2 cm	4 cm	6 cm	8 cm	10 cm
Minimum temperature	70	70	70	70	70	70
Maximum temperature	87	84	81	80	79	81
Maximum–minimum temperature	17	14	11	10	9	11
Average temperature	78	74	74	73	72	73
Standard deviation	5	5	3	2	2	3

as the diameter of PEI blocks increased from 2 to 8 cm. When the PEI block diameter was continually increased to 10 cm, the hot spot temperature increased to 81 °C.

From the cross-sectional surface plots (Fig. 3), the highest temperature of RF treated peanut butter without PEI blocks reached 95.7 °C. After adding PEI blocks, the highest temperature of the cross-sectional surface, which represented the temperature of the whole volume, reduced to 92.8, 92.2, 89.5, and 89.8 °C with PEI blocks of diameter 2, 4, 6, and 8 cm, respectively. The maximum temperature with 10 cm PEI blocks reached the highest value of 101.4 °C (Table 3). The 8 cm PEI block improved the heating uniformity most significantly, reducing the difference between maximum and minimum temperatures in the volume from 25.7 to 19.8 °C. Two temperature uniformity indexes of peanut butter with different sizes of PEI blocks after RF treatment were presented in Table 3. The uniformity index (UI) calculated from the validated computer model decreased from 0.0839 to 0.0624 when diameter of PEI blocks increased from 0 cm to 6 cm, and then started increasing gradually to 0.0832 when diameter of PEI blocks increased to 10 cm. But the new temperature uniformity index (TUI) showed that the smallest value was found when the diameter of PEI blocks was 8 cm. The results from 6 cm and 8 cm blocks were relatively close. This is due to the edge heating effect that usually happens within 1–2 cm near the edges in this study. The 8 cm diameter PEI blocks were selected for further testing as indicated by the TUI because it is more reasonable for describing the temperature distribution for bacteria inactivation purposes. When the diameter increased to 10 cm, the TUI was even higher than that of the peanut butter without PEI blocks.

3.4. PEI blocks height influence on heating uniformity

The uniformity indexes of peanut butter sandwiched by a pair of PEI blocks with various heights are shown in Fig. 4. The UI firstly decreased as the height of PEI blocks increased until the block height reached 1.3 cm, and started to increase afterward. The cross-sectional surface

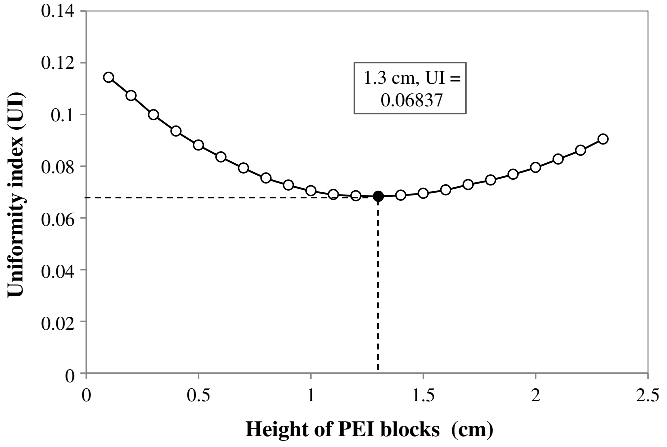

Fig. 4. Uniformity index (UI) of peanut butter with various heights and 8 cm diameter of PEI blocks in RF (Voltage V = 5700 V, time t = 480 s).

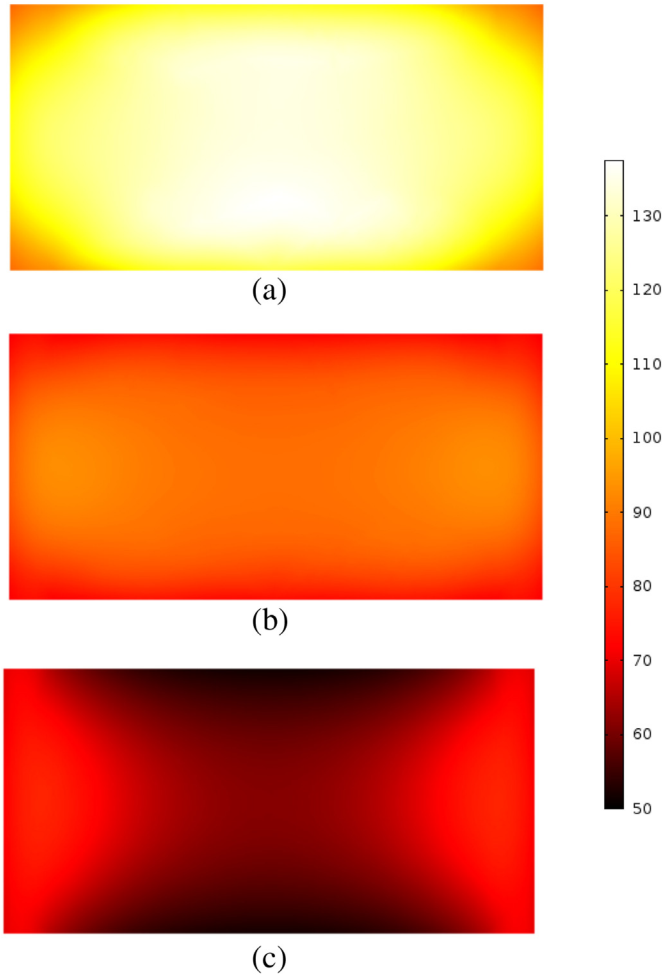

Fig. 5. Heating pattern of peanut butter with PEI blocks (a: height 0.1 cm, b: height 1.3 cm, c: height 2.3 cm) and diameter of 8 cm in RF treatments (T, °C).

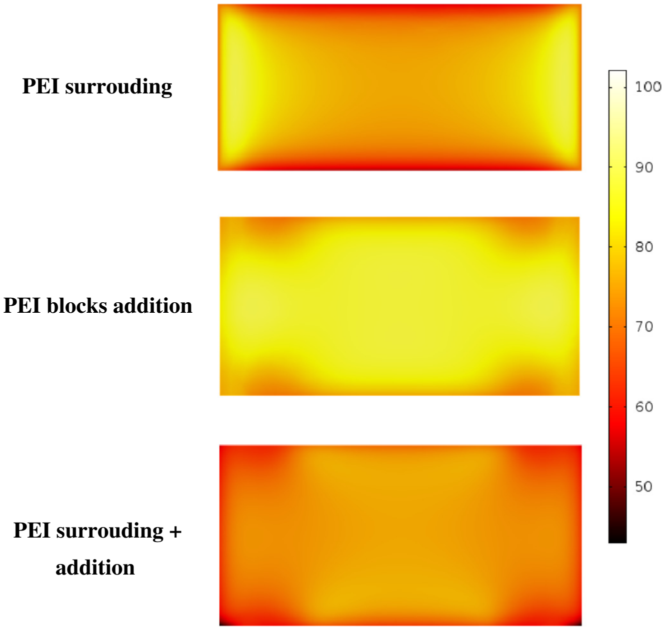

Fig. 6. Cross-sectional surface temperature (T, °C) distribution of peanut butter treated in RF system with three different methods (electrode gap is 10.1 cm).

Table 5
Simulated temperature uniformity in peanut butter treated with PEI surrounding, PEI blocks addition and combination.

	PEI surrounding	PEI blocks addition	PEI surrounding + addition
Voltage (V)	12,100	5700	12,100
Heating time (s)	165	480	140
Maximum–minimum temperature (°C)	19.5	19.8	7.1
UI (Alfaifi's)	0.0859	0.0694	0.0715
TUI (modified)	0.1634	0.2243	0.0715

temperature plot of peanut butter treated with 0.1, 1.3 and 2.3 cm height of PEI blocks in RF was presented in Fig. 5. Although the minimum temperature was not controlled in this computer simulation, it could still be found that the uniformity increased when the height of blocks increased from 0.1 to 1.3 cm, judging from the heating pattern. During the height increase from 0.1 to 1.3 cm (Fig. 5a to b), the hot spot stays at the same location, but the temperature distribution was more uniform from the radius direction of the cylinder. When the height increased to 2.3 cm, the heating pattern changed as the hot spot switched to locations between the sample center and the PEI blocks. This is probably because a longer PEI block can aggregate more electric energy and result in a higher temperature. Although the 2.3 cm PEI blocks did not provide the best heating uniformity among all heights, the resulted heating pattern made it more suitable for a combination with traditional hot air or hot water heating since the outside layer of the sample had a lower temperature.

3.5. Comparison of heating uniformity improvement methods

The cross-sectional surface temperature distribution of peanut butter that was treated by PEI surrounding method, PEI addition method and a combination method is shown in Fig. 6. The highest temperature in the peanut butter container reached 89.5, 89.4 and 77.1 °C in PEI surrounding, PEI addition and combination method, respectively. With the PEI surrounding method, the cold spot locations were still at the top and bottom surfaces, which suggested that the heating uniformity could be improved by combining the PEI blocks addition method. The computer simulation conditions and the calculated uniformity indexes for three heating uniformity improvement method are shown in Table 5. The PEI sheets surrounding method has the highest UI, 0.0859, then comes the combination method, 0.0715, and the PEI blocks addition method has the lowest UI, 0.0694. However, the TUI showed that the combined method has the lowest TUI, 0.0715, and the PEI surrounding method is in-between, and the PEI blocks addition method has the highest TUI, 0.2243. The reason for UI showing the PEI blocks addition method has the best heating uniformity is probably due to the average temperature of the food volume being higher than that of the other two methods. The TUI comparison results are in accordance with the cross-sectional plot since the combination method provides the lowest maximum temperature.

4. Conclusion

A method of adding cylindrical PEI blocks adjacent to the cold spots of peanut butter in a cylindrical jar was evaluated to improve its heating uniformity in RF treatment. Computer simulation results show that after adding PEI blocks, the electric field distribution was more uniform and the temperature distribution was more even, which indicates that the heating uniformity can be effectively improved by increasing the thickness of the blocks material in RF treatment. Among the five diameters of PEI blocks, 8 cm leads to the best heating uniformity. The best height of PEI block which could further improve the uniformity was 1.3 cm. A modified temperature uniformity index (TUI) was evaluated by comparing with traditional uniformity index and was found to be more effective. In a bacteria inactivation process or other heating process which requires a minimum heating temperature, the modified TUI would be more suitable in evaluating the heating uniformity. The combination of the PEI blocks addition method and the PEI surrounding method could reach a better heating uniformity than any single method applied. The computer simulation model can be used to explore the effectiveness of combining the PEI blocks addition with other methods for RF heating uniformity improvement.

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