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Evaluating radio frequency heating uniformity using polyurethane foams

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ABSTRACT

Heating uniformity is a vital obstacle needed to overcome before radio frequency (RF) treatments can be used commercially for agricultural products. There has been a lack of systematic means to evaluate RF heating uniformity for dry agricultural commodities. This study demonstrated the effectiveness of polyurethane foams for such evaluation. The influence of sample positions on RF heating uniformity was studied in a pilot-scale 27.12 MHz, 6 kW RF, with and without hot air circulation. The results showed that the stacked foam sheets at the corner or edge of the bottom electrodes heated more than in the center of RF cavity. Temperatures in the middle layers were higher than those in the bottom and top layers when heated only by RF energy. Circulating hot air during RF heating eliminated heat loss in the external layers of the stacked foams and improved heating uniformity. Similar RF treatment conditions were conducted with Macadamia nuts. Heating patterns and uniformity were compared between the foams and the nuts. The results suggested that selecting appropriate treatment conditions by starting tests with uniform foam loads should simplify procedures for developing effective heating and drying applications for complicated agriculture produces, such as Macadamia nuts.

1. Introduction

From 1950s, radio frequency (RF) energy has been used in pilot-scale studies for cooking meats (Pircon et al., 1953) or drying vegetables (Wang et al., 2011). Beans, alfalfa and corns are also dried in research by RF energy combined with hot air heating (Jumah, 2005; Murphy et al., 1992; Ptasznik et al., 1990). Starting late 1980s, RF heating has been used in the food industry for post baking of cookies and snack foods (Anon, 1987, 1989; Rice, 1993). For example, Orfeuil (1987) reported that a 30 m conventional oven in a commercial cracker production line was successfully replaced by a 5 m, 27.12 MHz RF heating system at 80 kW to remove 80 kg/h of water in final drying.

Heating uniformity is one of the most important considerations in the development of heating and drying processes when using RF energy (Wang et al., 2005, 2008b). Birla et al. (2008a) reported that sample temperatures are more uniform after RF heating when the sample was placed in the central plane between the two plate electrodes. Similar simulation and experimental results were reported by Liu et al. (2013) and Tiwari et al. (2011a). Experimental tests are the most direct method for analyzing RF energy distribution and heating patterns. A number of studies have been reported on heating uniformity in agricultural products using RF energy. Wang et al. (2005, 2007) studied the use of forced hot air surface heating, product movement and product mixing to improve heating uniformity in RF-treated walnuts in laboratory and industrial-scale RF systems. They used uniformity index values, defined as the ratio of the rise of standard deviation (SD) to average temperature rise during heating, to evaluate RF heating uniformity (Wang et al., 2005, 2007, 2008c).

RF heating patterns depend on many factors, including sample geometry, dimensions, and material properties and also on the RF field patterns in specific applicators (Birla et al., 2008b; Marra et al., 2007; Wang et al., 2006). To determine heating uniformity, model materials with consistent and stable properties were used in several studies to replace more complicated and often heterogeneous materials as the first step to gain insight into heating patterns in the RF applicators (Wang et al., 2008a). For example, Birla et al. (2008a) developed a model fruit using gellan gels to evaluate RF heating behavior in oranges, and Zhong et al. (2003) used CMC solutions to evaluate RF heating characteristics of pump-able foods. Polyurethane foam sheets were used in two studies to determine and analyze RF heating uniformity in dry

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products, such as breads and walnuts (Liu et al., 2013; Wang et al., 2010). But in the studies of Liu et al. (2013), small size of foam sheets were used that did not provide information on the overall field patterns within the RF cavities, while in the studies of Wang et al. (2010) the foams were only placed in the center of the bottom electrode. Polyurethane foam sheets can be repeatedly used because of the stability of its thermal and dielectric properties. But no systematic studies have been reported on direct comparisons of RF heating patterns for the foams and real food samples.

The overall goal of this research was to study the effectiveness of using polyurethane foam sheets as a systematic evaluation method for RF heating uniformity. Specifically we investigated the influence of different locations of foams in the RF cavity on the heating uniformity, compared the difference of heating patterns between RF alone and hot air assisted RF heating, and finally compared heating patterns obtained by the foams with those from a real dry product, Macadamia nuts.

2. Materials and methods

2.1. Hot air assisted RF heating system

A 6 kW, 27.12 MHz free-running oscillatory type pilot-scale RF system (COMBI6-S, Strayfield International, Wokingham, UK) with an additional hot air system (5.6 kW) was used to study heating uniformity of polyurethane foam sheets as the reliable first step in selecting appropriate RF heating conditions for Macadamia nuts (Fig. 1). The dielectric constant and loss factor at 27.12 MHz and 20 °C are 2.1 and 0.01, and 5.3 and 0.80 for polyurethane foam sheets and Macadamia nuts, respectively (Domeier and Hunter, 1999; Wang et al., 2013). Those properties together with the density and porosity for the two materials are listed in Table 1. For low moisture foods, dielectric constant is more critical than loss factor in influencing RF field patterns (Metaxas, 1996; Jiao et al., 2014). Thus we hypothesized that polyurethane foam sheets and Macadamia nuts in the RF applicators experienced similar RF field patterns. The configuration of the RF and hot air systems was described in detail in Wang et al. (2010). The gap between the two parallel-plate electrodes was adjusted between 11.0 and 20.4 cm for selection of approriate heating rates. Hot air produced by electric heating strips was blown into the RF cavity between the electrodes through the holes distributed on the bottom plate (Fig. 2). The hot air temperature and flow rate in the RF cavity were controlled by the input electric power and the fan speed. The conveyor belt was not used in this study.

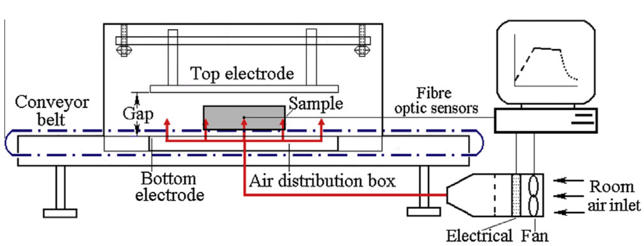

Fig. 1. Schematic view of the radio frequency (RF) unit showing the plate electrodes and the hot air system with the fiber optic sensor to monitor the central temperature in the sample container (Wang et al., 2010).

2.2. RF Heating uniformity in polyurethane foam sheets without hot air

Four heating uniformity tests were conducted in the RF system using polyurethane foam sheets without adding hot air, to evaluate the influence of sample positions and heights with respect to the two parallel electrodes. In the first set of tests, seven foam sheets, 25 cm $L \times 15$ cm $W \times 1.3$ cm H, were stacked on top of each other and placed at one of the five positions on the bottom electrode (Fig. 2b). The sheets were supported by two slim bars (15 cm $L \times 2$ cm $W \times 2$ cm H) made of polyurethane, which raised the bottom surface of the bottom sheet by 2 cm from the bottom electrode (Fig. 3a). The overall dimensions of the stacked sheets were 25 cm $L \times 15$ cm $W \times 9.1$ cm H, which was the same as the dimensions of the container for testing with Macadamia nuts. All samples were conditioned at the room temperature (23 °C) prior to RF heating.

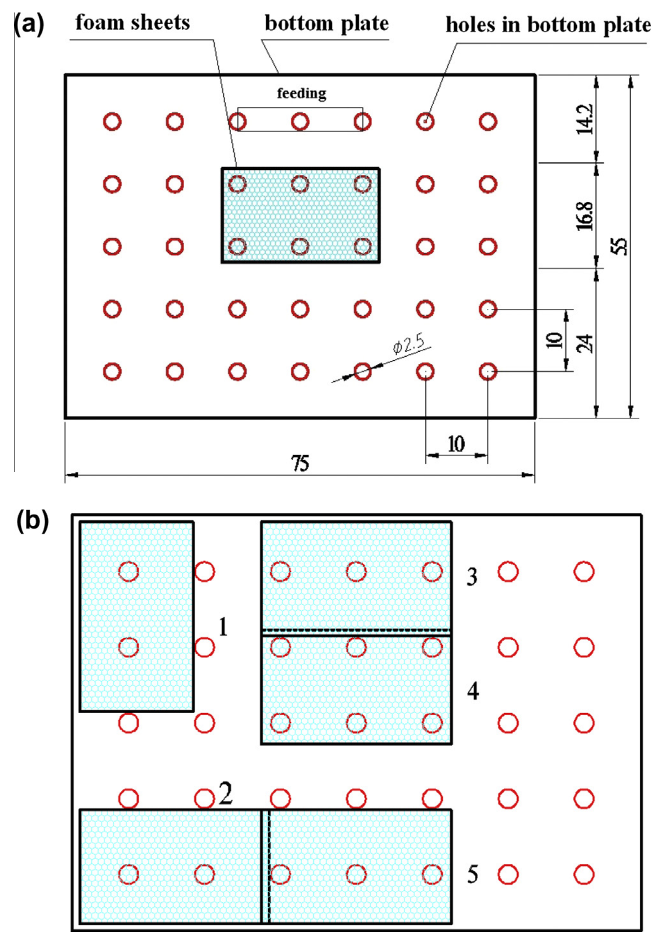

Fig. 2. Distribution of holes on the bottom plate for air outlets (a) and 5 different locations for heating uniformity tests with the foam sheets (b) (all dimensions are in cm).

Table 1
Physical and dielectric properties of polyurethane foam and Macadamia nut at 20 °C.

Material	Dielectric constant at 27.12 MHz	Dielectric loss factor at 27.12 MHz	Density (kg/m^3)	Porosity (%)
Polyurethane foam	2.1	0.01	32	95
Macadamia nut	5.3	0.80	1008	35
	Wang et al. (2013)		Domeier and Hunter (1999)	

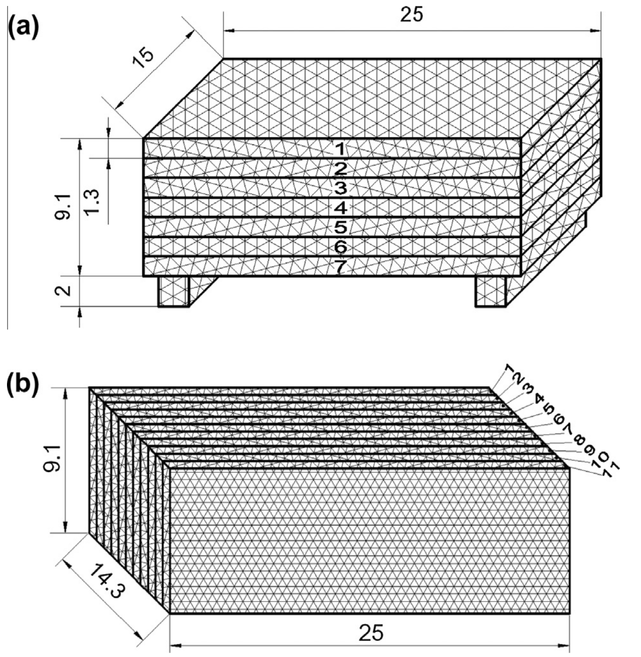

Fig. 3. Schematic view of horizontal (a) vertical (b) polyurethane foam sheets for RF heating uniformity tests (all dimensions are in cm).

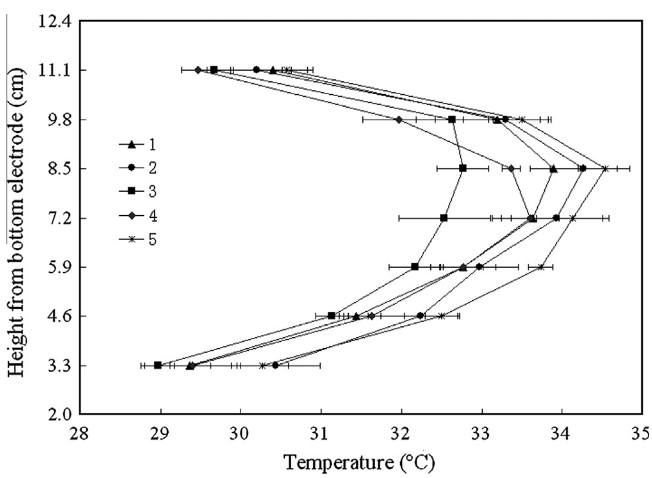

Fig. 4. Surface temperature (mean ± SD) profiles as a function of height of foam sheets at five positions after stationary RF treatments (Gap = 15.5 cm) for 5 min without hot air heating.

The electrode gap was set at 15.5 cm for all RF heating tests. This gap was determined from preliminary tests to obtain appropriate heating rates in sample foams and Macadamia nuts. The RF heating was stopped after 5 min treatments to achieve a relatively low sample temperature (e.g. 35–40 °C), which could be used to evaluate the relative effects of the RF field on the heating patterns with a reduced heat loss to the ambient air. After the RF power was turned off, the foam stack was immediately taken out for temperature mapping. Upper surface thermal images of each sheet were taken using an infrared thermal imaging camera (ThermaCAM SC-3000, FLIR Systems, Inc., North Billerica, MA, USA), beginning with the top sheet working towards the bottom one. The total imaging time for the seven sheets was about 30 s. From each of the thermal images, 25,410 individual surface temperature data points were collected using the software of the system (ThermalCAM Researcher 2001). The average surface temperatures and

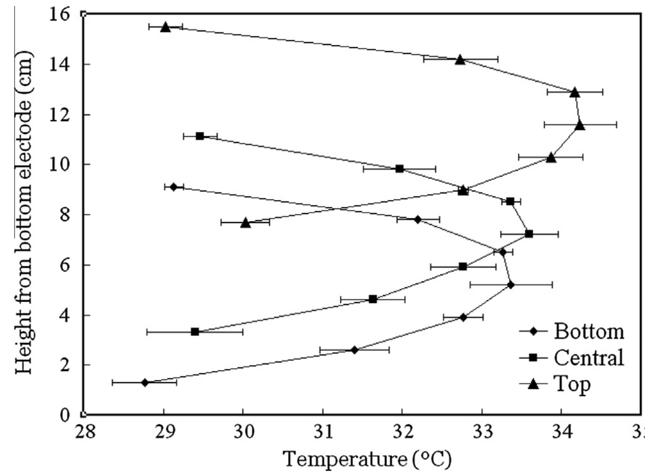

Fig. 5. Surface temperature profiles in sheets horizontally placed at position 4 after RF treatments (Gap = 15.5 cm) for 5 min without hot air heating. The forms were placed three different heights, close to the bottom electrode, in the central plane, and close to top electrode. The scattered points represent means of 3 replicates.

standard deviations were calculated for each foam sheet. Contour plots were used to analyze the surface temperature distribution using software Sigma Plot for Windows (Version 12.0, SPSS, Inc., Richmond, CA, USA) (Wang et al., 2005). The test was replicated thrice.

In the second set of tests, the foam sheets stacked on top of each other were placed at a chosen position (position 4 as shown in Fig. 2), which was located near the center of the bottom electrode. In this test, the foam sheet 7 was placed directly on the bottom electrode without the supported slim bars. All other procedures were followed as the first set of tests.

In the third set of tests, the foam sheets were placed again at the position 4 with the top surface of sheet one touched directly with the top electrode. All other procedures were followed as the first set of tests.

In the last set of tests, the foam stack had eleven same-size sheets, which were placed vertically (Fig. 3b) at the position 4 (Fig. 2b). The sheets were supported on two slim bars, which raised the stacks by 2 cm above the bottom electrode. All other procedures were followed as the first set of tests. 15,762 Individual surface temperature data points were collected using the thermal imaging software and also saved in EXCEL format.

2.3. Heating uniformity comparison

To evaluate the appropriateness of using foams as a reliable mean to determine RF heating uniformity for a real dry product, Macadamia nuts were filled in a specially design container that could be separated into four different tray sections. The tray sections with screen bottoms were made of Teflon, $27 \times 16 \times 2.4\ cm^3$ each. Four tray sections were stacked on top of each other with 500 g nuts in each section. The initial moisture content of nuts was 10.6% d.b. The stacked tray sections were also supported on two slim bars, to raise the sample bottom by 2 cm above the bottom electrode.

To compare the difference in heating uniformity between RF alone (RF) and hot air assisted RF heating (HARF), the 7 foam sheets or the Macadamia nuts container were placed at the position 4 horizontally as shown in Figs. 2 and 3. The sample bottom was supported on two slim bars with 2 cm of height on the bottom electrode. In HARF heating, hot air temperature in RF cavity was adjusted to 50 °C and measured using a fiber optic temperature measurement system online (UMI, FISO Technologies Inc.,

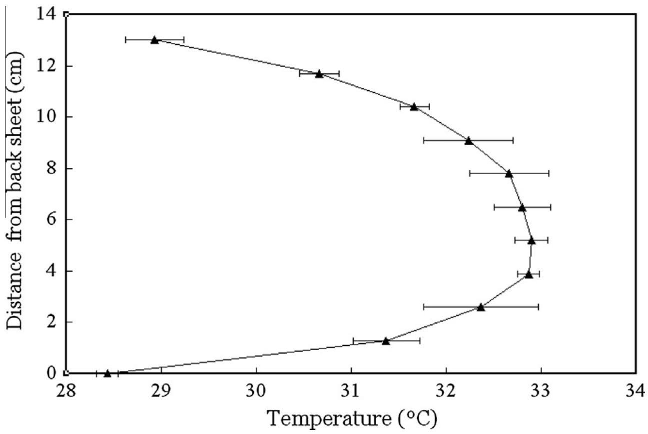

Fig. 6. Surface temperature profiles as a function of distance from the back sheet (sheet 1 as shown in Fig. 2b) vertically placed at position 4 after RF treatments (Gap = 15.5 cm) for 5 min without hot air heating. The scattered points represent means of 3 replicates.

Sainte-Foy, Quebec, Canada). The air velocity in the RF cavity was 1 ms^{-1} measured by a rotating vane anemometer (LCA 6000, AIRFLOW Instrumentation, Buckinghamshire, UK). Other procedures were the same as in the previous RF heating tests. The surface temperatures of each sheet and nut layer were recorded before and after heating by the infrared imaging system.

The uniformity index, λ, described in Gao et al. (2010) and Wang et al. (2007, 2010), was used as a parameter for assessing the heating uniformity under different heating conditions:

$$\lambda = \frac{\Delta\sigma}{\Delta\mu} \tag{1}$$

where $\Delta\sigma$ is the rise (°C) in standard deviation of sample temperature before and after heating and $\Delta\mu$ is the rise (°C) in average sample temperatures over the heating time. The smaller the λ value, the better heating uniformity in the sample.

3. Results and discussions

3.1. RF heating uniformity at different locations of polyurethane foam sheets

Fig. 4 shows the average surface temperature profiles as a function of height of foam sheets at the five positions after RF treatments without hot air circulation. Generally, average surface temperatures at positions 5, 2 and 1 were higher than those at positions 4 and 3. It could be attributed to the relatively high intense electric field at the far end of the electrode (positions 5, 2 and 1) as compared to positions 4 and 3, which were close to the feeding point of RF power as shown in Fig. 2a (Orfeuil, 1987). More RF energy was coupled into the samples at positions of edge or corner positions on the top electrode than those near the feeding position (in the middle of top electrode backside edge) of RF systems, resulting in higher temperatures (Tiwari et al., 2011b; Wang et al., 2011). Averaged surface temperatures of the middle three layers were higher than those of bottom and top two layers for each of the 5 positions. With low thermal conductivity of polyurethane foams, there was negligible heating conduction from central or its adjacent sheets to the top and bottom sheets, but there might have been some heat loss from the top or bottom layer to the ambient air caused by natural convection. If longer RF heating was conducted, the same heating profile shape as a function of sheet height could be achieved but more heat loss would be expected due to

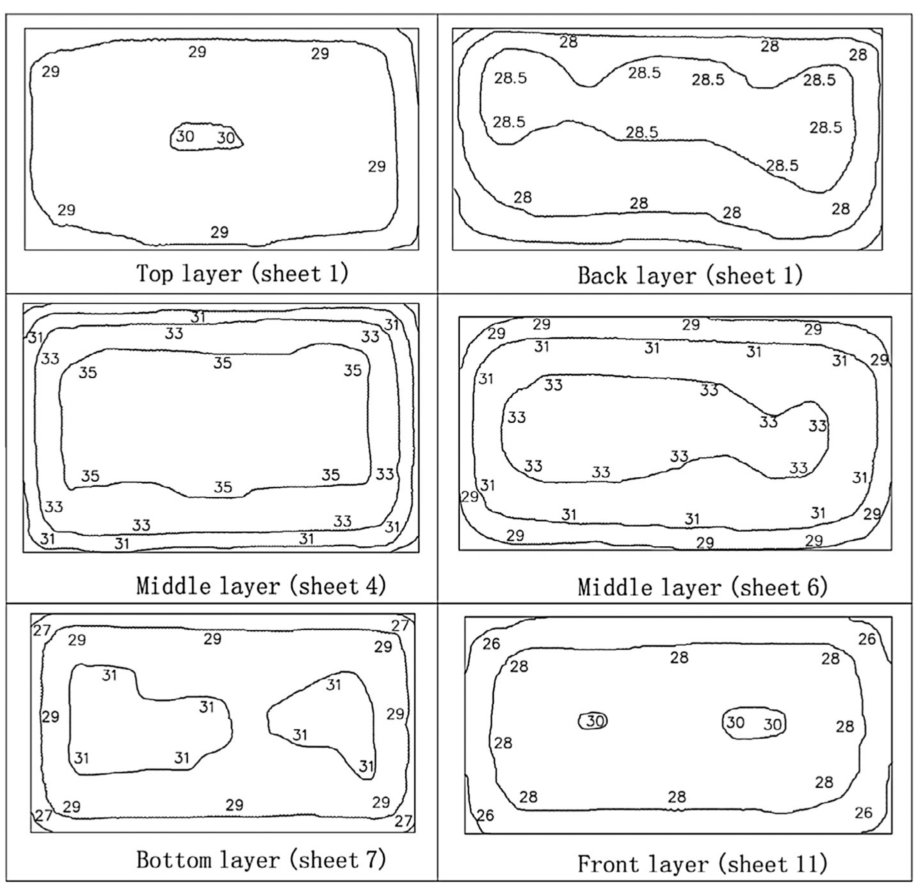

Fig. 7. Surface temperature (°C) distributions of foam sheets horizontally (a) or vertically (b) placed at position 4 after RF treatments without hot air heating.

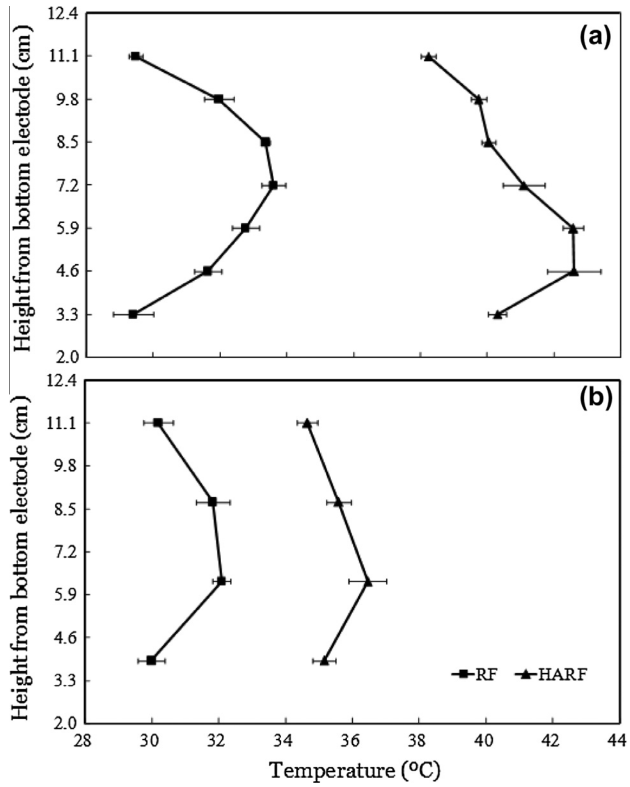

Fig. 8. Comparison of surface temperature profiles as a function of height for (a) horizontal foam sheets and (b) nuts in the four-layer tray placed at position 4 between RF heating alone (RF) and hot air (50 °C) assisted RF heating (HARF) for 5 min with electrode gap of 15.5 cm. The scattered points represent means of 3 replicates.

larger temperature difference between the top or bottom sheet and the ambient air. This typical and similar temperature profile in different layers was also observed in previous studies (Liu et al., 2013; Wang et al., 2007).

Fig. 5 shows the average and SD values of surface temperature profiles as a function of height of foam sheets horizontally located at position 4 after RF treatments for 5 min without hot air heating. The largest average temperature appeared in the top layer when the foam stack was at the top position. However, the lowest average temperature appeared in the bottom layer when the stack was at the bottom position. The above results may indicate that the electric intensity was higher near the top electrode and lower near the bottom electrode. Top and bottom layer average temperatures were almost the same when the foam stack was at central plane between the electrodes. The temperature distribution was approximately symmetric around the forth layer, suggesting that the electric intensity was almost symmetric about the central plane between the two electrodes. Similar phenomenon was also observed in RF treated wheat flour (Tiwari et al., 2011a) and bread (Liu et al., 2013) both by experiment and computer simulation.

Fig. 6 shows the average values of surface temperature profiles as a function of distance from the back surface of foam sheet 1 to sheet 11 vertically placed at position 4 (Fig. 3b) after RF treatments without hot air heating. Averaged temperatures in middle 6 layers were higher than others.

Fig. 7 shows the contour plot for surface temperature distributions in foam sheets horizontally or vertically placed at position 4. It was clear that for each layer either horizontally or vertically placed, temperatures near edges of the foams were lower than those of the center, which could be caused by heat losses to the ambient air. Although temperature distributions in the central layer were more uneven than those in the top or bottom and back or front layers, a relatively uniform area could be still obtained with a small temperature variation (e.g. less than 2 °C). It seemed that the increased heating rate might result in non-uniform RF heating. The center heating patterns existed in RF heated homogenous materials with cubical shape, which were found in other similar studies (Wang et al., 2007, 2010). However, it contradicted the results reported for RF heating of wheat flour (Tiwari et al., 2011a) and bread (Liu et al., 2013), where the cubical shape material had higher RF power densities at edges than center parts. The different heating pattern was likely caused by the different materials associated with different dielectric properties.

3.2. Heating uniformity comparison between RF and HARF treatments

Heating patterns in polyurethane foam sheets and Macadamia nuts treated by RF and HARF are shown in Fig. 8. After 5 min treatments, both foam and nut temperatures (average 40.7 and 35.3 °C) heated by HARF were clearly higher than those (31.7 and 30.5 °C) heated by RF alone. Additional hot air heating at 50 °C increased each layer temperature of the RF treated foams, especially for top and bottom layers due to high porosity of the foam sheets (Table 1). Hot air heating improved RF heating uniformity, since the uniformity index in HARF heated foams and nuts in each layer was lower than that in RF alone treated samples (Table 2). The hot air heating was thus helpful to improve the heating uniformity of RF treatments, which was in agreement with those reported by Liu et al. (2013), Gao et al. (2010), and Wang et al. (2007).

In comparison, the temperature profile, thus heating pattern, in foams (Fig. 8a) was in good agreement with that in nuts (Fig. 8b), both for RF alone and HARF treatments. Similar uniformity index value and trends with the measurement height were observed in RF treated foams and nuts (Table 2). But the average foam temperature was higher than the nut one after HARF heating for 5 min. The fast heating rate in foams was likely caused by the low density (32 kg m^{-3}) and high porosity (95%) of foams as compared to those (1008 kg m^{-3} and 35%) of nuts, although the dielectric loss factor (0.01) of foams was lower than that (0.8) of nuts.

Table 2
Comparisons of the heating uniformity index (λ) (mean ± SD over three replicates) at different height of polyurethane foam sheets and nuts at position 4 between RF heating alone (RF) and hot air assisted RF heating (HARF) for 5 min with electrode gap of 15.5 cm.

Height (cm)	Foam		Height (cm)	Nut	
	RF	HARF		RF	HARF
11.1	0.054 ± 0.000	0.037 ± 0.009	11.1	0.084 ± 0.014	0.060 ± 0.012
9.8	0.108 ± 0.000	0.048 ± 0.013			
8.5	0.146 ± 0.007	0.077 ± 0.007	8.7	0.161 ± 0.006	0.097 ± 0.020
7.2	0.178 ± 0.007	0.118 ± 0.016			
5.9	0.206 ± 0.008	0.117 ± 0.004	6.3	0.214 ± 0.007	0.134 ± 0.005
4.6	0.222 ± 0.000	0.134 ± 0.013			
3.3	0.220 ± 0.024	0.147 ± 0.015	3.9	0.245 ± 0.016	0.180 ± 0.014

4. Conclusions

Heating polyurethane foam sheets in RF cavity and capturing temperature profile using infra-red imaging revealed changes of RF field intensity with load location. At the central position in RF cavity, the middle layer was hotter than bottom and top layers, and the edges was heated less than central part either in horizontally or vertically placed foams, which were probably caused by heat loss to the ambient under RF alone treatments. Hot air circulation greatly improved the RF heating uniformity in each layer of the foams. Similar heating patterns and influence of hot air circulation were observed with Macadamia nuts, suggesting that polyurethane foam was appropriate to be used to evaluate RF heating uniformity in Macadamia nuts.

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