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Heating patterns of white bread loaf in combined radio frequency and hot air treatment

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ABSTRACT

This research investigated heating uniformities of prepackaged bread loaf using combined radio frequency (RF) and hot air treatments to reduce mold growth. Experiments were conducted in a 6 kW, 27.12 MHz pilot-scale RF system. Effects of the gap between two RF plate electrodes, horizontal and vertical locations of bread loaf, as well as running speed of conveyor belt were studied. When the bread loaf was located in the center plane between the two electrodes 202 mm apart, and on a conveyor belt moving at a speed of 1 cm/s to reach a minimum sample temperature of 58 °C, the temperature distribution within each slice was relatively uniform, with less than a 5 °C difference. The cold spot was located at the core of the bread loaves. Higher surface temperature should be useful to assist in inactivation of molds that are commonly vegetated on the surface of the whole loaf.

1. Introduction

Small-scale laboratory tests have demonstrated the potential for using radio frequency (RF) energy to extend shelf life of bakery products (Bartholomew et al., 1948; Cathcart et al., 1947; Liu et al., 2009; Piyasena et al., 2003; Tang et al., 2005; Zhao et al., 1999). But in general, corner and possible thermal runaway heating makes it difficult to scale up the laboratory results to industrial practices. There is a need to study heating patterns and improve the heating uniformity of products in relatively large RF systems appropriate for scaling up to industrial applications.

RF treatment of a bread loaf an open ambient environment results in core heating for the whole loaf and severe moisture condensation adjacent to the product surface (Bartholomew et al., 1948; Cathcart et al., 1947). Circulating hot air during RF heating should help to alleviate such a problem. Thus combined RF and hot air treatment was proposed in this research as a way to treat white bread loaves for control of mold and retention of bread quality (Liu et al., 2009, 2011).

Heating uniformity of food products in a RF field is influenced greatly by RF treatment parameters, such as location of food products in the RF field, placement of food products, and the gap between two plate electrodes. An earlier simulation study on RF heating of wheat flour suggested that reducing the electrode gap improves RF power uniformity (Tiwari et al., 2011a). But from our preliminary tests, we observed an optimum gap under which bread was heated more uniformly in the vertical direction, When the gap was larger than the optimum value, the bottom part of the bread was heated more, and conversely the top part heated more with smaller gaps.

Even when the gap was set to the optimum value, different vertical placement positions of the bread loaf between the two electrodes caused different heating patterns. A smaller distance between the bread sample and the bottom or the upper electrode resulted in edge heating at the bottom or on the top. Samples in contact with either of the electrodes had higher RF power densities near the contact surfaces due to increased electric field concentration at the contact locations (Tiwari et al., 2011a). Therefore, RF heating uniformity of bread loaf might be improved by determining an optimum electrode gap and an optimum vertical position for bread loaf in the RF field.

Heating uniformities were successfully improved for in-shell walnuts and almonds (Mitcham et al., 2004; Wang et al., 2005, 2006, 2007, 2008; Gao et al., 2010, 2011), dry grains and legumes (Wang et al., 2008, 2010; Jiao et al., 2011, 2012) and fresh fruits (Birla et al., 2004; Hansen et al., 2006) by adding hot air or hot water, and by moving or mixing samples during RF treatments. The effects of the electrode gap and the vertical location of materials were not considered in those previous studies.

Effects of RF treatments on mold control and extending bread shelf life were reported by Cathcart et al. (1947) and Bartholomew et al. (1948). But the RF heating pattern and uniformity, which are essential to retention of bread quality, were not studied in full-sized bread loaves in a RF field. The objectives of this research were to: (1) study the heating uniformity of bread loaf in combined RF

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and hot air treatment, and (2) establish the optimal treatment design for combined RF and hot air treatment. We selected a minimum product target temperature of 58 °C to achieve more than a 4-log reduction of *Penicillium citrinum* spores based on our early studies (Liu et al., 2011).

2. Materials and methods

2.1. Materials

Sliced white bread loaves (Oven Joy White Enriched Bread made by Lucerne Foods, Inc., Pleasanton, CA, USA) were purchased from a local grocery store in Pullman, WA, USA. The ingredients of the bread can be found elsewhere (Liu et al., 2011).

2.2. RF system

A 6 kW, 27.12 MHz free-running oscillator RF system (COMBI 6-S, Strayfield International, Wokingham, U.K.) was used in this research, with an area of 750 mm × 550 mm for the top plate electrode and a much larger bottom plate electrode (Fig. 1). The gap between the two electrodes was adjustable from 130 mm to 240 mm. A conveyor belt with changeable moving direction and speed was equipped to assure different moving styles and residence time of food products in the RF field between the two plate electrodes. An auxiliary hot air system was installed to increase air temperature in the RF cavity to maintain product surface temperature. In the air heating system, ambient air entered from the inlet to the 5.6 kW electric heater, where it was heated to a desired temperature and blown upwards into the RF cavity by a fan through an air distribution box and air holes on the bottom electrode.

The electrical heater was immediately turned off after the bread was heated to a target temperature by combined RF and hot air treatment. Ambient air at 22 °C was then blown into the RF cavity through the same way to bring the bread's central temperature down to room temperature.

2.3. Horizontal heating uniformity of RF field using polyurethane foam sheets

Polyurethane foam sheets were used effectively in evaluating heating uniformity of RF field due to their homogeneity (Wang et al., 2007, 2010) and were used instead of bread to evaluate the horizontal heating uniformity of the RF field, and to eliminate the influence of bread inhomogeneity. The maximum RF output power was recorded at an electrode gap of 130 mm, which resulted in the highest heating non-uniformity in polyurethane foam sheets. The hot air system and conveyor belt were turned off for this evaluation.

Seven polyurethane foam sheets (McMaster-Carr, Los Angeles, CA) were stacked on top of each other to create an overall dimension of 290 mm × 102 mm × 102 mm, the same size as the bread loaf, and placed at different positions on the bottom electrode. Previous experiments proved that running the conveyor belt guaranteed uniform heating in products along the moving direction of the conveyor belt (Wang et al., 2007, 2010). Thus, there was no need to consider the heating uniformity of the RF field in the moving direction. The center position was selected for evaluating the RF heating uniformity. In the direction perpendicular to the movement of the conveyor, three positions, namely I, II and III as shown in Fig. 2, were selected for the preliminary tests. Polyurethane foam sheets were heated at the three positions in the RF system and surface temperatures of each sheet were recorded using an infrared thermal camera (Thermal CAM™ SC-3000, FLIR Systems, Inc., North Billerica, Mass., USA) with an accuracy of ±2 °C. The details for the measuring procedure of the camera can be found in some of our previous publications (Wang et al., 2006, 2007). After RF heating, the sheets were removed immediately from the RF system. The top surface temperature of each sheet was measured sheet by sheet and a total of 45,056 data points for each image was obtained for further data analyses. Each test was performed in duplicate.

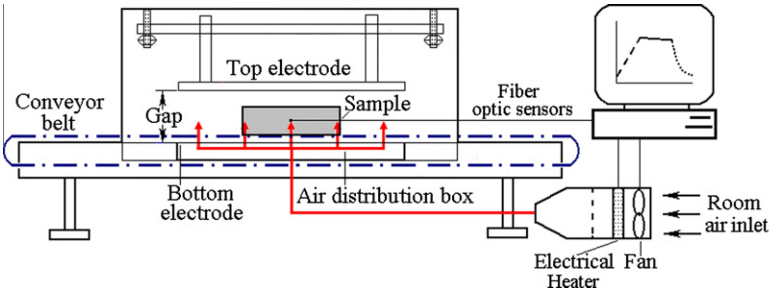


Fig. 1. Schematic diagram of combined RF and hot air treatment system (Wang et al., 2010).

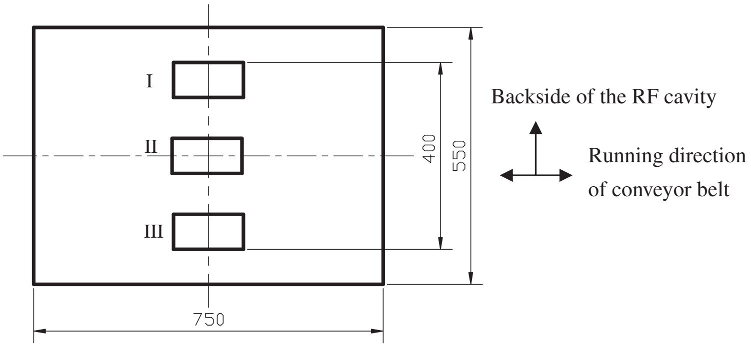


Fig. 2. Three locations (I, II, and III) of the polyurethane foam sheets on the bottom electrode. (Top view. All units are in mm.)

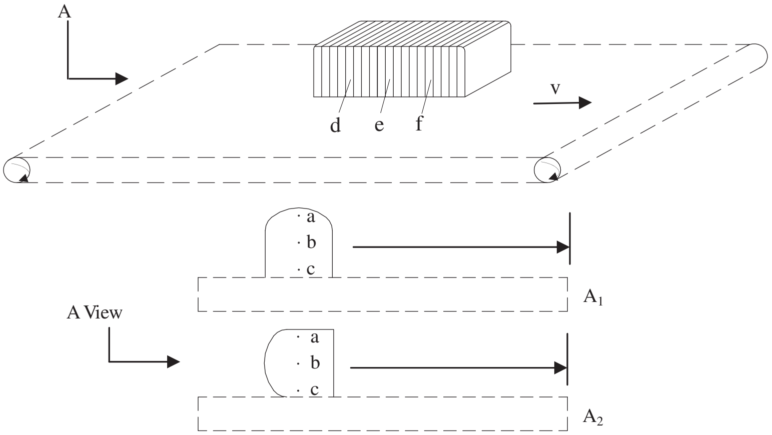


Fig. 3. Temperature sensor locations (a–f) with two placement positions of bread loaf on the bottom electrode within the RF field.

2.4. Combined RF and hot air treatment of bread loaf

A loaf of bread (290 mm × 102 mm × 102 mm) was placed at the center along the moving direction of the conveyor belt (Fig. 3) so that the same RF heating effect was obtained for each bread slice in the loaf. Thus, any interior bread slice could be used as a representative to evaluate RF heating patterns. In preliminary study, a loaf of bread was heated using combined RF and hot air system, the bread loaf was then removed from the RF system and placed below the infrared thermal camera, with the open end upwards. The loaf was unwrapped, the first slice was discarded, and the top surface temperature of each following slice was then measured one by one. The location of cold spot in each slice was then determined according to the surface temperature distribution. During combined RF and hot air treatment, temperatures at selected locations, including the cold spot (Fig. 1) were recorded using FISO fiber optic sensors (UMI, FISO Technologies Inc., Saint-Foy, Quebec, Canada). To study the vertical heating uniformity of bread slices, three fiber optic sensors were secured at three different positions vertically for one bread slice (namely a, b and c in Fig. 3) and the loaf was then wrapped in low density polyethylene film. Prior to the RF treatment, the hot air system was turned on until the RF cavity was heated to the target stable hot air temperature (58 °C), then a bread loaf with fiber-optic sensors was placed in the cavity and the RF system was started immediately. When the highest bread temperature reached the desired level, the RF system was turned off and the bread loaf was held in hot air with a speed of around 1 m/s till the cold spot reached the target temperature. Right after combined RF and hot air treatment, the bread loaf was removed from the RF system and surface temperature of each slice was measured immediately using thermal infrared camera. Each test was carried out in duplicate.

2.5. Determination of RF treatment parameters

Different placement positions of the bread loaf in the RF field resulted in different heating patterns due to the asymmetry of the bread shape. Two placements, on its base (A$_1$) or on one side (A$_2$) as in Fig. 3, were tested using different gaps with the hot air system on and conveyor belt off.

Heating uniformities of the bread loaf in each placement in the RF field with different electrode gaps were compared. Temperatures of the three selected locations for one bread slice (namely a, b and c in Fig. 3) were recorded for different electrode gaps using the fiber optic sensors during combined RF and hot air treatment. The optimum gap at either placement was determined in such a way that would produce about the same heating rate at each of the three positions, with a uniform vertical temperature distribution.

The effects of different vertical locations of the bread loaf in each placement in the RF field with the optimum electrode gap were also analyzed when the conveyor belt was kept stationary. Immediately after the RF treatment, the surface temperatures of each slice in one loaf were recorded using the infrared thermal camera. The optimum vertical location of the bread at either placement manner that produced a uniform surface temperature distribution was then determined.

2.6. Influence of conveyor speed on RF heating uniformity

Even if the gap and bread placement orientations and position were determined, different conveyor speeds might result in different heating patterns for breads in the RF cavity. In tests to study the effect of moving speed of convey belt, a fiber optic sensor was used to monitor the temperature of the middle of the center slice of the bread loaf. Prior to the RF heating, hot air was circulated until reaching a stable, target temperature of 58 °C in the RF cavity, the bread loaf with the fiber-optic sensor was placed at the center along the moving direction of the conveyor belt (Fig. 3), and the RF system was started immediately after power for the conveyor belt was turned on. When the bread's cold spot temperature reached the desired level, the RF system was turned off. Surface temperatures of the bread slices were immediately measured slice by slice using the infrared thermal camera. RF heating uniformities of the bread slices at different conveyor speeds (namely 0, 2, 4, and 8 cm/s) were then compared. Each test was carried out in duplicate.

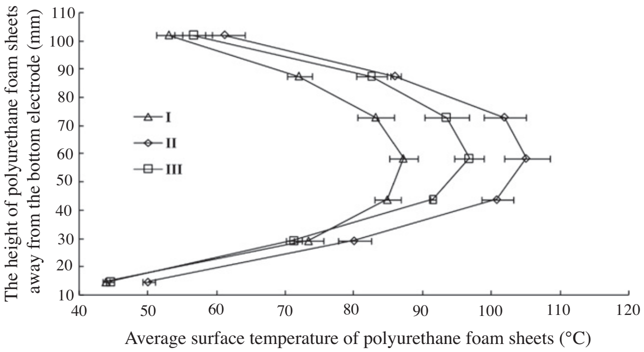


Fig. 4. Average and standard deviation of surface temperatures as a function of height of polyurethane foam sheets for three different locations (I, II, and III in Fig. 2) on the bottom electrode (two replicates).

2.7. Treatment validation

Temperature–time histories were studied for different locations in one slice and the center location of three different slices in one loaf to validate the determined treatment parameters. Three fiber optic sensors were inserted above, below and right at the center (a, c and b in Fig. 3) of the center slice of the bread loaf, another three fiber optic sensors were inserted at the center of three evenly spaced slices (No.5, No.10 and No.15 from the open end, excluding the end pieces, as d, e and f in Fig. 3) in the whole loaf. The bread loaf was then wrapped gently in a low-density polyethylene film to prevent moisture losses. Temperature–time histories of the selected locations were recorded during combined RF and hot air treatment using determined treatment parameters. All the experiments were carried out in duplicate.

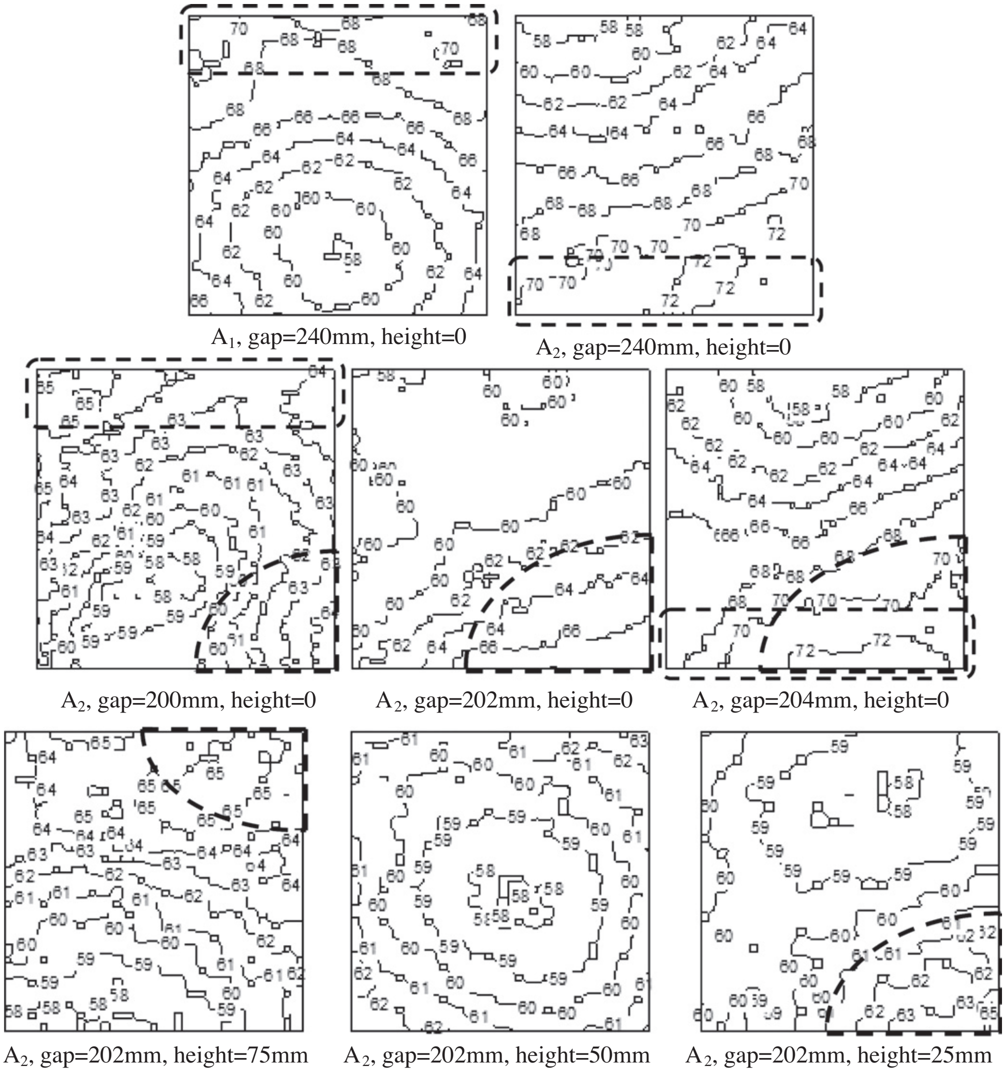
3. Results and discussion

3.1. Horizontal heating uniformity of RF field

Infrared camera recorded average surface temperatures of polyurethane foam sheets at different heights away from the bottom electrodes after RF treatments are shown in Fig. 4 for different locations, namely I, II and III as in Fig. 2, on the bottom electrode. The minimum temperature difference of 15.2 °C along the different height except for the both ends was observed when bread samples were placed in location I, while the maximum of 25.2 °C was observed in location II. Therefore, location I was selected for horizontal bread placement for later studies.

3.2. RF treatment parameters

When bread was heated at placement A_1 (in Fig. 3) using a maximum gap of 240 mm, the top was heated more than the bottom, showing a top heating pattern (Fig. 5). This means that the bread was heated with a smaller than optimal gap between two plate electrodes. In order to improve vertical heating uniformity of the bread loaf, the gap between two electrodes should be increased. But since the maximum gap allowed by the system design was used here, placement A_1 was not applicable to combined RF and hot air treatment of the bread loaf. When placed in placement A_2 (in Fig. 3), bread was heated more at the bottom, presenting a bottom heating pattern (Fig. 5). In this case, a more even temperature distribution can be achieved in the breads by reducing the elec-



A_1, gap=240mm, height=0

A_2, gap=240mm, height=0

A_2, gap=200mm, height=0

A_2, gap=202mm, height=0

A_2, gap=204mm, height=0

A_2, gap=202mm, height=75mm

A_2, gap=202mm, height=50mm

A_2, gap=202mm, height=25mm

Note: Dash line circled parts have higher temperatures compared with the rest in each graph.

Fig. 5. Surface temperature distributions (°C) of bread slices as influenced by two different placement styles (see Fig. 2), three different gaps and three different vertical distances from the bottom electrode after combined RF and hot air treatment (two replicates) (Liu et al., 2011).

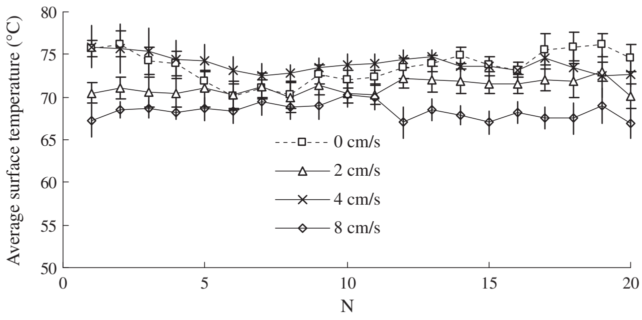


Fig. 6. Average and standard deviation of surface temperatures of bread slices in the whole loaf for different conveyor speeds (two replicates).

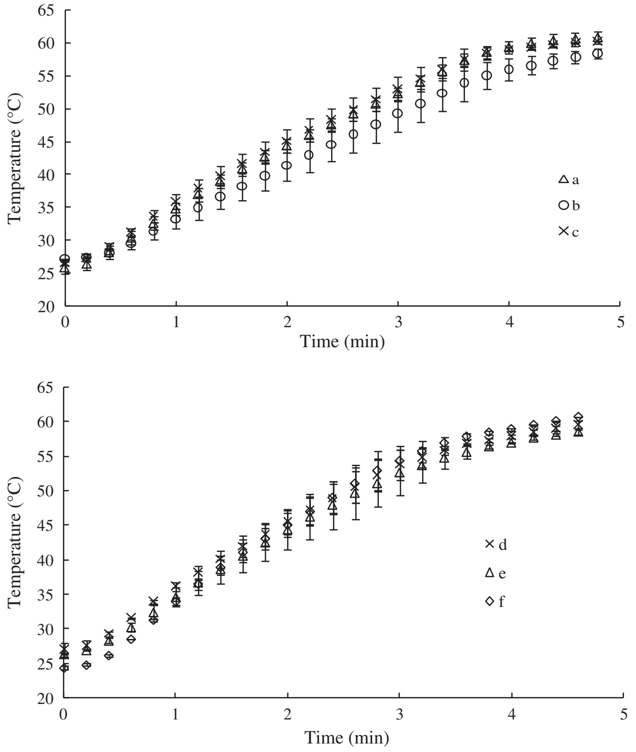


Fig. 7. Average and standard deviation for temperature–time histories of three locations for one slice and center position of three bread slices in one loaf during combined RF and hot air treatment (two replicates).

trode gap. Therefore, placement position A_2 was used for the bread loaf when placed in the RF field in further heat treatments.

For the same reason, when the gap of 202 mm was set between the two electrodes, identical heating rates and uniform surface temperatures (except for the right bottom corner) were recorded using fiber optic sensors and infrared thermal camera in breads placed position A_2 (Fig. 5). But the right bottom corner of the loaf was over-heated even when the top heating pattern was dominated (Fig. 5), coincident with findings in Tiwari et al. (2011a) that the sample in contact with either of the electrodes had higher RF power densities, and accordingly higher sample temperatures, near the contact surfaces due to an increased electric field concentration at the contact surfaces. The results demonstrated that the bread loaf should not be placed on the bottom electrode, but in-between two electrodes.

Bread was located at different heights away from the bottom electrode in position A_2 with a gap of 202 mm to determine an optimum height to eliminate edge heating. The best heating performance was achieved when a loaf of bread was located at the height of 50 mm (Fig. 5) which was midway between the two electrodes. In this case, the surface temperature difference for the bread slice was minimal, local overheating resulting from edge heating effects disappeared, as the electric field deflected by both (top and bottom) edges increased the net electric field concentration at the central parts of the sample (Tiwari et al., 2011b), accordingly, central temperatures of the bread samples should be the highest. The truth is that the periphery of the bread loaves were heated slightly more when compared with the core, that is, the cold spot was located in the core of the bread loaves after combined RF and hot air treatment. That's the results of auxiliary heating effect of hot air. The heating pattern was good for mold control of bread loaves, because molds appear mainly on the surface of the bread loaves (Rodríguez et al., 2002; Smith et al., 2004).

3.3. Influence of running speed of the conveyor belt

Average surface temperatures of each slice in one loaf were measured promptly after combined RF and hot air treatment for different conveyor speeds as shown in Fig. 6. The maximum temperature difference in bread slices was 6.2 ± 0.1 °C, 3.2 ± 0.1 °C, 3.5 ± 0.1 °C and 3.4 ± 0.0 °C for running speeds of 0, 2, 4 and 8 cm/s, respectively. This result suggested that moving the conveyor belt improved the heating uniformity of the bread loaf in the RF field. But the influence of the conveyor speed in the tested range on heating uniformity was not obvious.

3.4. Heating uniformity of the bread loaf using determined treatment parameters

When the bread loaf was placed position A_2 (Fig. 3) midway between the two electrodes which had a gap of 202 mm, on the conveyor belt sweeping at a speed of 1 cm/s, three temperatures (namely a, b and c in Fig. 3) in one slice were recorded using fiber optic sensors during combined RF and hot air treatment as shown in Fig. 7. Bread temperature increased almost linearly with time during combined RF and hot air treatment according to Fig. 7. After the RF system was turned off, the bread temperatures still increased to the lethal (for molds) temperature under the effect of hot air. The core had a slightly lower heating rate, that is, the cold spot (namely b) lay in the core of the bread slice with a maximum temperature difference of 5 °C. The center temperatures (namely d, e, and f in Fig. 3) were almost the same for different slices in one loaf as shown in Fig. 7 with a maximum temperature difference of 2 °C. This suggested each bread slice was exposed to the same field on the moving conveyor belt.

4. Conclusion

Vertical heating uniformity of products in the RF system can be improved by changing the gap between the two plate electrodes. Products should not be placed on the bottom electrode, but midway between the two electrodes to eliminate edge heating.

Bread temperature increased almost linearly with time during combined RF and hot air treatment. Cold spots lay in the core of the bread slice with a maximum temperature difference of 5 °C in one slice and temperature–time profiles were almost the same for center point of different slices with a maximum temperature difference of 2 °C.

Since RF heating uniformity was greatly influenced by product shape, distortion of the bread shape will cause an unexpected temperature distribution within the bread loaf.

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