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Application of radio frequency pasteurization to corn (*Zea mays* L.): Heating uniformity improvement and quality stability evaluation

Ajuan Zheng [a], Bo Zhang [a], Liyang Zhou [a], Shaojin Wang [a, b, *]

[a] *Northwest A&F University, College of Mechanical and Electronic Engineering, Yangling, Shaanxi 712100, China*
[b] *Department of Biological Systems Engineering, Washington State University, 213 L.J. Smith Hall, Pullman, WA 99164-6120, USA*

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ABSTRACT

Mildews caused grain losses and serious outbreaks have been becoming increasing concerns in domestic and international corn processing industry. This study intended to explore the possibility of using radio frequency (RF) heating as an effective treatment to eliminate the mold contamination and reduce the damage to corn quality. A pilot-scale, 27 MHz, 6 kW RF unit was used to study the heating uniformity in corn samples with five moisture contents (MC) and using three plastic material containers, and develop a treatment protocol for a corn sample with the MC of 15.0% w.b. and evaluate quality attributes and storage stability of treated samples. The results showed that only 7.5 min was needed to raise the central temperature of 3.0 kg corn samples from 25 °C to 70 °C using the RF energy, but 749 min for samples to reach 68.6 °C using hot air at 70 °C. The RF heating uniformity was improved by adding forced hot air, moving samples on the conveyor, and mixing during the treatment. An effective RF treatment protocol was finally developed to combine 0.8 kW RF power with a forced hot air at 70 °C, conveyor movement at 6.6 m/h, two mixings, and holding at 70 °C hot air for 14 min, followed by forced room air cooling through thin-layer (2 cm) samples. Corn quality was not affected by RF treatments since quality parameters of RF treated samples were better than or similar to those of untreated controls after the accelerated shelf life test. RF treatments may hold great potential as a pasteurization method to control molds in corns without causing a substantial loss of product quality.

1. Introduction

Corn or maize (*Zea mays* L.) is a plant of American origin and consumed worldwide for various purposes (Velu et al., 2006). Approximately 75% of corn productions are used for feeding animals and humans, and 25% are processed into various value-added products (FAOSTAT, 2013). Corn kernels are rich and inexpensive sources of starch (62%) and protein (7.8%) (Singh et al., 2003), and are abundant sources of mineral elements (Gu et al., 2015), such as G_u, F_e, M_n, K, and so on. Due to high nutrition values, international export quantity and value of corn had been increased from 2009 to 2011 in the international market (FAOSTAT, 2013). China is the second largest corn producing country with 218 million Mt corn yield, about 11.5% of the total world production (FAOSTAT, 2013). Therefore, the corn storage quality and production losses due to mold contamination are becoming major concerns of the cereal industry.

About 25% of grains worldwide are infected by mold and its mycotoxin each year, of which 2% loses its nutritional and economical values owing to serious infections (FAO, 2007). *Aspergillus parasiticus* is one of the most common molds infecting corn during storage (Reddy et al., 2009). Corn contaminations by *Aspergillus parasiticus*, and consequently presences of the aflatoxins are unavoidable during storage (Liu et al., 2006), which is a threat to health of human and animal (Massey et al., 1995; Bankole et al., 2010). However, it is difficult to remove aflatoxins from corns due to their stabilized molecular structures. Eliminating *Aspergillus parasiticus* before the aflatoxins are produced must be the actual goal rather than removing aflatoxins. It is, therefore, of a great interest to develop a postharvest processing method to reduce or completely eliminate fungus in corns before aflatoxins are produced during storage.

There are a large number of suggested potential methods for suppressing fungal growth and reducing mycotoxin formation. Except chemical treatments with ethylene (Gunterus et al., 2007),

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* Corresponding author. Northwest A&F University, College of Mechanical and Electronic Engineering, Yangling, Shaanxi 712100, China.
E-mail address: shaojinwang@nwsuaf.edu.cn (S. Wang).

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physical methods are commonly applied, such as plasma (Hertwig et al., 2015), irradiation (UV, gamma rays) (Kanapitsas et al., 2015), microwave (Mendez-Albores et al., 2014) and modified atmospheres (Skandamis and Nychas, 2001). Although these can reduce surface fungal contaminations in some extent, each of these physical methods has limitations in terms of low efficiency, high cost and negative effects on product quality. Thus, it is desirable to develop an effective, practical, and environmentally-friendly physical method for corn pasteurization.

Novel thermal treatments using radio frequency (RF) energy hold potential for pathogen control in agricultural commodities. RF energy can directly interact with agricultural commodities to rapidly raise the temperature of a whole treated sample volume in industrial systems (Tang et al., 2000). A major advantage of RF energy is deeper penetration depth and better heating uniformity in bulk materials (Wang et al., 2003) compared with microwave heating. Thermal effects of RF treatments are found to be effective for controlling *Salmonella* in in-shell almonds (Gao et al., 2011) and inactivating molds, *Salmonella* and *Escherichia coli* on bread, black and red pepper spices, respectively, with acceptable product quality (Liu et al., 2011; Kim et al., 2012). But there have been no reported studies on RF control of *Aspergillus parasiticus* in corns.

Heating uniformity is an important consideration in developing and scaling-up RF treatment protocols. Factors resulting in non-uniform RF heating include non-uniform electromagnetic field distribution and different dielectric properties between samples and surrounding medium mainly caused by the MC of various products (Wang et al., 2007a). Many practical methods are used to improve the uniformity of RF heating in agricultural products, such as adding forced hot air for sample surface heating, sample movement, rotation or mixing of samples during RF heating and immersing products into water for fresh fruits (Birla et al., 2004; Tiwari et al., 2008; Sosa-Morales et al., 2009; Zhou et al., 2015; Zhou and Wang, 2016; Ling et al., 2016). Research is needed to improve the RF heating uniformity in developing corn postharvest treatment protocols for pasteurization while maintaining the product quality.

Objectives of this study were (1) to analyze heating rates in corn under two heating conditions (hot air and RF heating), and develop an effective cooling method after RF heating, (2) to compare the temperature distribution and the heating uniformity index in corn after RF heating with additional forced hot air surface heating, sample movement, and mixing, (3) to determine the heating uniformity of corn samples with five different MC and three plastic-type containers, and (4) to evaluate the effect of RF pasteurization on the quality attributes (MC, water activity, ash, color, starch, protein, fat, fatty acid) of corns during an accelerated storage.

2. Materials and methods

2.1. Material and sample preparation

Newly harvested yellow corn (*Zea mays* L.) used in this research was purchased from a local farmer's market in Yangling, Shaanxi, China. The average initial MC of corn was 9.1 ± 0.2% wet basis (w.b.). To explore the RF heating uniformity in corns with different moisture levels, other samples with MC of 12.0%, 15.0%, 17.9%, and 20.9% w.b. were prepared for the experiment. The initial samples were conditioned by direct addition of predetermined amount of distilled water to obtain the targeted MC (Wang et al., 2015). The preconditioned samples were shaken by hands for 10 min. Then the samples were sealed in hermetic plastic bags and stored at 4 ± 1 °C for more than 7 days in a refrigerator (BD/BC-297KMQ, Midea Refrigeration Division, Hefei, China) for equilibrium. During the storage, the bags were shaken 6 times per day. Before each test, samples were placed in an incubator (BSC-150, Boxun Industry & Commerce Co., Ltd, Shanghai, China) to equilibrate for 12 h at 25 ± 0.5 °C.

2.2. Hot air-assisted RF heating system

A 6 kW, 27.12 MHz pilot-scale free-running oscillator RF system (SO6B, Strayfield International, Wokingham, U.K.) with a hot air system (6 kW) was used for this study. A detailed description of the RF unit, the hot air and conveyor systems can be found in Wang et al. (2010) and Zhou et al. (2015). The top electrode (40 cm × 83 cm) was moved to obtain the required electrode gap, thus regulating the outputted RF power. To simulate continuous processes, the corn samples between electrodes were moved on the conveyor belt started from inlet side to outlet side of the RF system. The sample surface heating was provided using the hot air during RF heating and holding without the RF power. The hot air speed was setup to be 1.6 m/s inside the RF cavity and measured at 2 cm above the bottom electrode by an anemometer (DT-8880, China Everbest Machinery Industry Co., Ltd, Shenzhen, China).

2.3. Determining heating temperature and holding time

For developing effective pasteurization processes, the RF treatment protocol parameters should be designed based on the thermal death kinetics of target molds (Buzrul and Alpas, 2007). Jin et al. (2011) studied the inactivation kinetic model of *Aspergillus parasiticus* in moldy corn by microwave processing, and reported that 6-log reductions of *Aspergillus parasiticus* spores in mL suspensions were obtained at 50, 55, 60, 65, 70 and 75 °C for 19.6, 15.6, 15.2, 13.6, 13.2 and 13.1 min, respectively. Fang et al. (2011) investigated the effect of microwave radiation on biochemical characteristics and mortality of *Aspergillus parasiticus* compared to effects of conventional heating treatment, and the research results showed that effects of microwave treatments on inactivating *Aspergillus parasiticus* were also determined around 70 °C. Taking into consideration of the required inactivation of *Aspergillus parasiticus*, non-uniformity of RF heating, the corn quality and treatment efficiency, the target sample temperature of 70 °C was selected to develop the RF treatment protocol.

2.4. Material selection of surrounding containers

To study the effect of different surrounding containers on the RF heating uniformity of corns, three kinds of materials (polyetherimide, polystyrene, and polypropylene) were selected based on the reported improvement of RF heating uniformity (Jiao et al., 2014; Huang et al., 2016). The containers had the same inner dimensions (300 mm × 220 mm × 60 mm) (Fig. 1) with the 5 mm thickness, which consisted of perforated screens on the side and bottom walls to allow hot and room air to pass through the samples for surface heating and cooling. Effects of the three-material containers with different dielectric properties on RF heating uniformity were compared.

2.5. Determining electrode gap and conveyor belt speed

A corn sample of 3.0 kg with MC of 15.0% w.b. was used for full loads in a polypropylene container (300 mm × 220 mm × 60 mm) (Fig. 1). This MC level was selected since its water activity was closed to that in the growth boundary of *Aspergillus parasiticus* at room temperature. To determine an appropriate electrode gap for RF treatments, the polypropylene container was placed on the stationary conveyor belt between the two electrodes to obtain a general relationship between electrode gap and electric current (*I*,

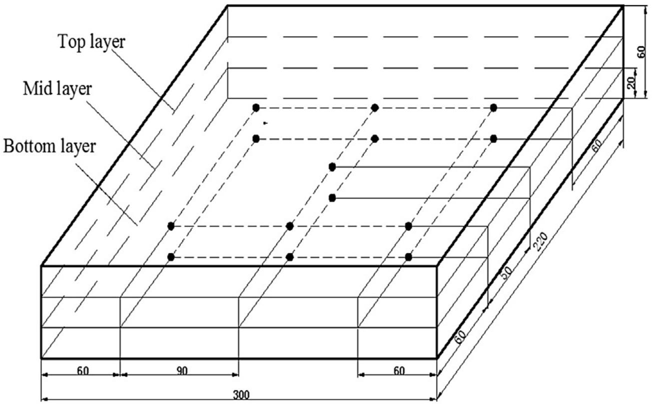

Fig. 1. Rectangular plastic container with 14 locations sample temperature measurements (all dimensions are in mm).

A). The range of the electrode gap was from 10.0 cm to 19.0 cm with a 1.0 cm interval. A detail description of measurement could be found in Zhou et al. (2015). All tests were repeated three times. Based on the measured electric current, three electrode gaps of 10.0 cm, 11.0 cm and 12.0 cm were selected for further temperature-time history experiments in RF treated corns based on no arcing and fast heating rates. To study the RF heating uniformity and treatment protocol, the best one was determined from the three selected electrode gaps. The time needed to heat the corns in the container center from 25 °C to 70 °C was recorded, and the sample temperature was measured at the geometric center of the container using a six-channel fiber-optic temperature sensor system (HQ-FTS-D120, Heqi Technologies Inc., Xian, China) with an accuracy of ±0.5 °C. The final electrode gap for the samples with MC of 15.0% w.b. was fixed based on the target heating rate (4–6 °C/min) with three replicates.

For the corn samples with different MC, the different electrode gaps were selected to achieve the similar effect of heating rates on the RF heating uniformity. To determine the time-gap relationship in RF treated corn samples with other four MC in the polypropylene container, three electrode gaps of 10.0, 10.5 and 11.0 cm were chosen for corn samples with MC of 9.1% and 12.0% w.b., respectively. Meanwhile, three electrode gaps of 11.0, 11.5 and 12.0 cm were selected for corn samples with MC of 17.9% and 20.9% w.b., respectively. The most suitable gap was obtained based on the closest heating rate of corn samples at 15.0% w.b.. Then the conveyor belt speed was calculated with dividing the electrode length by the resulted heating time.

2.6. *Comparisons of temperature profiles of corns between hot air and RF heating*

The most appropriate gap determined in section 2.5 was used for temperature profile comparisons, heating uniformity improvement and protocol development. The polypropylene container with 3.0 kg samples at 15.0% w.b. was placed on the bottom electrode for hot air and RF heating. The temperature at the geometric center of samples was recorded every 60 s by the fiber-optic temperature sensor system when subjected to forced hot air heating at 70 °C with speed of 1.6 m/s and RF treatments with the electrode gap of 11.0 cm. The measurement was stopped when the sample temperature reached 70 °C for RF heating or the temperature increase was less than 0.5 °C within 30 min for hot air heating. Ambient room temperature (25 °C) was used as the initial sample temperature, and each test was repeated three times.

2.7. *Determination of cooling methods*

Appropriate cooling method is of great importance to avoid quality degradation and improve processing efficiency for developing RF treatment protocols (Wang et al., 2010; Gao et al., 2011). The polypropylene container filled with 3.0 kg corn samples with MC of 15.0% w.b. heated to 70 °C by hot air was used to develop the suitable cooling method. Corn samples with 6, 3 and 2 cm depths held in the polypropylene container were subjected to natural ambient air and forced room air cooling. The forced room air was provided by an electric fan (FT20-10A, Guangdong Midea Environment Appliances Manufacture Co., Ltd., Zhongshan, China). The measured air speeds on the sample surface were about 0.2 and 3.5 m/s for the natural and forced air cooling, respectively. The temperature in the center position of samples was recorded every 60 s until the sample temperature dropped to 30 °C. The best cooling method was further used to determine the temperature-time histories of corns and develop RF treatment protocols.

2.8. *Heating uniformity tests*

2.8.1. *Comparison of RF heating uniformity under different operational conditions*

The heating uniformity is important for developing effective RF treatments and depends on practical treatment conditions, such as with or without forced hot air, with or without movement on the conveyor belt, and with or without mixing (Jiao et al., 2012; Zhou et al., 2015; Zhou and Wang, 2016). Tiwari et al. (2011) studied the effect of the sample position on the RF heating uniformity by the computer simulation, and the results show that RF energy distribution is improved and the required heating uniformity is achieved when samples are placed exactly in the middle of the two RF electrodes. The polypropylene container filled with 3.0 kg corn samples with MC of 15.0% w.b. was placed in the middle of two electrode gaps and heated in the RF system to compare the sample temperature distribution under seven conditions: (1) RF heating only, (2) RF heating with hot air assisted, (3) RF heating with conveyor belt movement, (4) RF heating with a single mixing, (5) RF heating with two mixings, (6) RF heating with forced hot air of 70 °C assisted, conveyor belt movement and a single mixing, and (7) RF heating with hot air, conveyor belt movement, two mixings and holding in 70 °C hot air for 14 min. The container movement started from the right edge (in-feed side) to the left edge (out-feed side) of the electrode. The forced hot air at 70 °C was provided through the air distribution box at the bottom electrode. One and two mixings were conducted outside the RF cavity at the interval of half and one third of RF treatment time by hand in a large container (355 mm × 275 mm × 105 mm), and then the samples were placed back again into the treatment container and finally the RF cavity for the remainder of the treatment time. The entire mixing process was finished within one minute. The sample at 15.0% w.b. with 3.0 kg in weight and 6 cm in depth in the polypropylene container were divided into three layers (Fig. 1) and separated by two thin gauzes (with mesh opening of 1 mm) to easily map the sample surface temperatures with a thermal imaging camera (DM63, Zhejiang Dali Technology Co., Ltd, Hangzhou, China) with an accuracy of ±2 °C. Before and immediately after RF treatments, the sample temperatures on the top, middle and bottom layers without mixing were measured by the thermal imaging camera. Each thermal image took less than 2 s. Details on the infrared imaging system to measure product surface temperature after RF treatment can be found in Wang et al. (2006a). The surface temperature data in the treatment area were obtained and used for estimating the average temperature and standard deviation (SD). With mixing, the sample temperatures of middle and bottom layers at 14 selected positions were obtained by two Type-T thermocouple thermometers (TMQSS-020-6, Omega Engineering Ltd., CT, USA). The 14 selected positions were equally distributed at two depths of 4 and 6 cm (Fig. 1). The average and SD values of the measured sample temperatures for each replicate were used for evaluating RF heating uniformity.

2.8.2. *Validating the final RF protocol for corns with different MC and containers*

Corn samples with the MC of 15.0% w.b. in the polyetherimide and polystyrene containers, respectively, were tested to examine the effect of treatment conditions with conveyor belt movement, hot air, two mixings and holding in 70 °C hot air for 14 min on the RF heating uniformity. Corn samples with the MC of 9.1%, 12.0%, 17.9%, and 20.9% w.b. in the polypropylene container, respectively, were also tested to determine the heating uniformity under the same treatment conditions. Temperature measurements were made according to the aforementioned methods. Each test was repeated three times. The average and SD values of the surface temperatures for each replicate were used for evaluating the RF heating uniformity.

2.8.3. *Evaluating RF heating uniformity*

Heating uniformity is a key factor in developing successful postharvest quarantine treatments using RF energy. Heating uniformity index (λ) has been successfully used for evaluating RF heating uniformity in different agricultural products, such as walnuts (Wang et al., 2007a), legumes (Wang et al., 2010; Jiao et al., 2012), and milled rice (Zhou et al., 2015). Heating uniformity index is defined as the ratio of the rise in standard deviation of sample temperatures to the rise in average sample temperatures during treatment and can be calculated by the following equation (Wang et al., 2008):

$$\lambda = \frac{\sqrt{\sigma^2 - \sigma_0^2}}{\mu - \mu_0} \tag{1}$$

Where μ_0 and μ are initial and final mean corn temperatures (°C), σ_0 and σ are initial and final standard deviations (°C) of corn temperatures over treatment time, respectively. The smaller values represent the better RF heating uniformity.

2.9. *Treatment protocol development*

The optimal RF treatment protocol could be developed with previously determined suitable electrode gap, heating uniformity tests and cooling methods. Based on the above tests, the electrode gap (11.0 cm) was used in the RF system together with conveyor belt movement at the speed of 6.6 m/h, and additional hot air heating at 70 °C, and a twice mixings to heat 3.0 kg of corn samples with the MC of 15.0% w.b. and 6 cm sample thickness in the polypropylene container. After the sample center temperature in the container reached 70 °C, RF was turned off, and the corn samples were held in hot air at 70 °C for 14 min, followed by forced room air cooling with thin-layer (2 cm in depth) for 33 min. The untreated samples were considered as controls. Each treatment was repeated three times. The treated and untreated samples were sealed in bags for storage tests and quality evaluations.

2.10. *Storage experiment and quality evaluations*

Before and after RF treatments, the quality of controls and RF treated corn samples with the MC of 15.0% w.b. in the polypropylene container was evaluated immediately and after accelerated shelf life storage. Corn usually has the relatively low temperature (10 °C) storage after harvest, and new corns would be available one year later (Wang and Zhang, 2011), so longer storage was not considered in this study. Corn samples (600 g) were packed individually in 10 bags and stored in the incubator set to 35 ± 0.5 °C with 68 ± 0.5% relative humidity (RH) for 17 d to simulate commercial storage at 10 °C for 1 year. The accelerated storage time at 35 °C was calculated based on a Q_{10} value of 3.41 for nutrition loss (Taoukis et al., 1997), which was validated by real-time storage experiments (Wang et al., 2006b). This accelerated tests was successfully used for simulating the real storage experiments in RF treated products (Wang et al., 2002; Gao et al., 2010; Jiao et al., 2012; Hou et al., 2014; Ling et al., 2016; Zhou et al., 2015; Zhou and Wang, 2016). After 0, 4, 8, 12 and 17 d of storage, the corn samples were withdrawn from each treatment for quality analysis. MC, water activity, ash, color, starch, protein, fat, and fatty acid were chosen to analyze the corn quality change.

A computer vision system (CVS) was used for measuring color values of control and RF treated samples at 15.0% w.b. in the polypropylene container. A detail description of the CVS unit can be found in Hou et al. (2014) and Zhou et al. (2015). Based on the measurement procedures suggested by Ling et al. (2015) and to reduce the data variability, the corns were ground in a universal high-speed blender (FLB-100, Feilibo Food machinery co., Ltd., Shanghai, China) and placed in a plastic Petri dish (8 cm diameter) for measurement. Color images of corn flour (20 g) surface per treatment were captured and stored in the computer, then analyzed by Adobe Photoshop CS3 (Adobe Systems Inc., USA). The color values: lightness (L), redness-greenness ($+$ or $-$ a) and yellowness-blueness ($+$ or $-$ b), which were obtained from Photoshop could be converted to CIE LAB (L^*, a^* and b^*) values (Briones and Aguilera, 2005). The L^* value changes from 0 to 100 represented dark to light. A higher positive a^* and b^* values indicated more redness and yellowness, respectively (Sandhu et al., 2007).

To evaluate the influence of RF heating on chemical components of corn samples with 15.0% w.b. in the polypropylene container, MC, water activity, starch content, protein content, fat content, ash content, and free fatty acid content were chosen for chemical analysis.

The MC of corns was determined according to the oven drying method described by AOAC (2000a). About 5 g corn samples with less than 5 mm thickness placed in aluminum dishes were dried in a vacuum oven (DZX-6020B, Nanrong Laboratory Equipment Co., Ltd., Shanghai, China) at 105 °C, and 103.1 kPa until a constant weight of samples was attained. The corn samples were placed in a desiccator with $CaSO_4$ for cooling. Until the temperatures of corn samples dropped to room temperature, their weight was recorded. The MC was estimated from initial and final weights of the corn samples. About 5 g of corn samples were placed into a sample cup and then in an Aqua Lab water activity meter (Model 4TE, Decagon Devices, Inc., Pullman, WA, USA) to measure water activity under ambient temperature (25 °C).

Starch is one of the most important compositions of corns and a valuable ingredient to the food industry, being widely used as a thickener, gelling agent, bulking agent and water retention agent (Ubwa et al., 2012). Corn starch was determined by using the enzymatic hydrolysis method following the AOAC Standard (AOAC, 2000b). The protein was detected using the Kjeldahl method following the AOAC method (AOAC, 2005). A nitrogen conversion factor of 6.25 was used to calculate the protein content of the corn (Malumba et al., 2009). Fat content in corn was measured by the Soxhlet extraction method following the AOAC method (AOAC, 2006). Total ash content was determined by weighing the residual ash obtained by combustion in a Muffle furnace at 550 °C for 4 h. The fatty acid content is frequently determined as a quality index during production storage, and was determined by the manual titration method following the National Standard of China (GB/T 20570-2015, 2015).

2.11. Statistical analysis

Mean values and standard deviations were calculated from the three replicates for each treatment. Differences were estimated by the analysis of variance (ANOVA) followed by Tukey's test and considered significantly at $P \leq 0.05$. All statistical analyses were performed using the statistical software SPSS 16.0 version (SPSS Inc., Chicago, IL, USA).

3. Results and discussion

3.1. Electric current as influenced by the electrode gap

Fig. 2 shows the relationship between the electric current and electrode gap when the polypropylene container filled with or without corn samples at 15.0% w.b. was placed on the RF bottom electrode without movement and forced hot air. Electric current decreased with increasing electrode gap (10.0–19.0 cm). The repeatable current resulted in small standard deviation. Specially, electric current decreased rapidly from 0.56 A to 0.40 A when the electrode gap increased from 10 cm to 13 cm, and then decreased slowly when the electrode gap changed from 13 cm to 19 cm. Three electrode gaps (10.0, 11.0, and 12.0 cm) were then chosen for the further tests.

3.2. Determination of electrode gap and conveyor belt speed

Fig. 3 shows the temperature at the geometric center of polypropylene container during the RF heating using three different electrode gaps. The corresponding time required to raise the sample temperature from 25 °C to 70 °C was about 4.52, 7.50 and 10.31 min for electrode gaps of 10.0, 11.0, and 12.0 cm, respectively. The temperature-time histories also demonstrated that heating rates decreased with increasing electrode gaps. The heating rates were 9.96, 6.00 and 4.36 °C/min for electrode gaps of 10.0, 11.0, and 12.0 cm, respectively.

Fig. 4 shows the time required to raise the temperature at the geometric center of polypropylene container from 25 °C to 70 °C for 3.0 kg corn samples with MC of 9.1%, 12.0%, 17.9%, and 20.9% w.b. using the selected three electrode gaps, respectively. The time needed for the temperature to increase from 25 °C to 70 °C was 5.80, 7.38 and 9.55 min for the samples with MC of 9.1% at electrode gaps of 10.0, 10.5 and 11.0 cm, respectively. These required time was reduced to 5.72, 7.17 and 8.57 min for samples with MC of 12.0% w.b., respectively. Correspondingly, these required time was 5.53, 6.33 and 7.72 min for the samples with MC of 17.9% w.b. at electrode gaps of 11.0, 11.5, and 12.0 cm, which were further reduced to 4.97, 5.30 and 7.35 min for samples with MC of 20.9%, respectively.

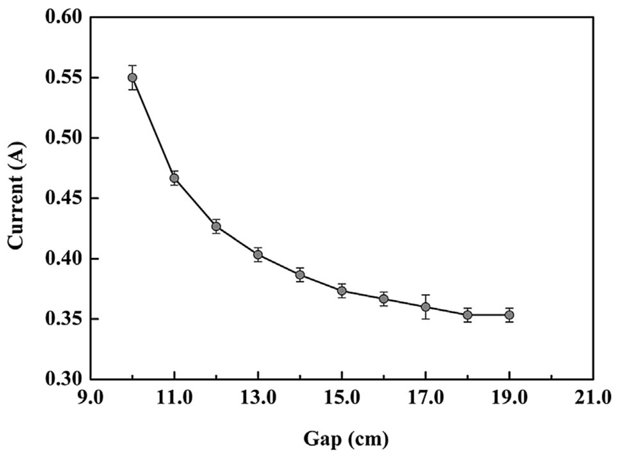

Fig. 2. The relationship between the electrical current and electrode gap with a polypropylene container filled with corn samples at the MC of 15.0% w.b.

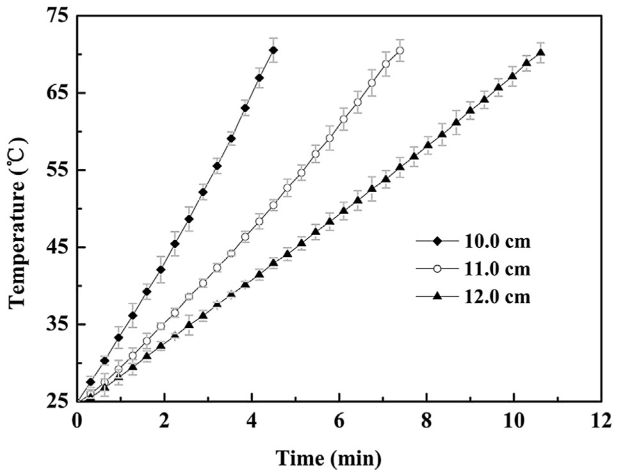

Fig. 3. Temperature-time histories of the RF heated corn samples with 15.0% w.b. in the center of polypropylene containers as function of the electrode gap.

The RF heating time decreased with increasing MC of corn samples under same electrode gap. Shorter heating time correspond to the higher throughputs, but the RF heating uniformity could be adversely affected by high heating rates. To obtain relatively high throughputs with acceptable heating uniformity in industrial applications, the electrode gap of 10.5 cm was determined to complete the RF heating test for corn samples with MC of 9.1% and 12.0%, respectively. An electrode gap of 11.0 cm was considered as suitable operational parameters for the corn samples with MC of 15.0% w.b. during RF heating, together with 12.0 cm for the corn samples with MC of 17.9% and 20.9% w.b. These optimal electrode gaps were used for further experiments.

Fig. 5 shows the comparison of the temperature-time histories of the RF heated corn samples in the center of polypropylene container at their optimal electrode gaps with five MCs. The heating rates of corn samples with MC of 9.1% and 12.0% w.b. for electrode gap of 10.5 cm were 6.09 and 6.27 °C/min, respectively. The heating rate of corn samples with MC of 15.0% w.b. was 6.00 °C/min for electrode gap of 11.0 cm. About 5.83 and 6.12 °C/min were considered as optimal heating rates for the corn samples with MC of 17.9% and 20.9% w.b., respectively. The heating rate range is generally required by RF heating uniformity and treatment throughput and is also used in many RF treatment protocols (Wang et al., 2007a; Jiao et al., 2012; Pan et al., 2012; Hou et al., 2014; Zhou et al., 2015).

The speed of conveyor belt was estimated under the three electrode gaps and five MC as shown in Table 1 together with total RF heating time (sample entirely moved through the top electrode length direction). The speed of conveyor belt was determined by the heating rates and the electrode length and around 6.5–6.9 m/h under different MC. The total RF heating time and the interval time of 2 mixings were around 9.83–10.43 min and 3.28–3.48 min, respectively. These values could be further used for pasteurizing corns in large-scale experiments.

3.3. Heating and cooling profiles

A comparison of the temperature-time histories of corn samples

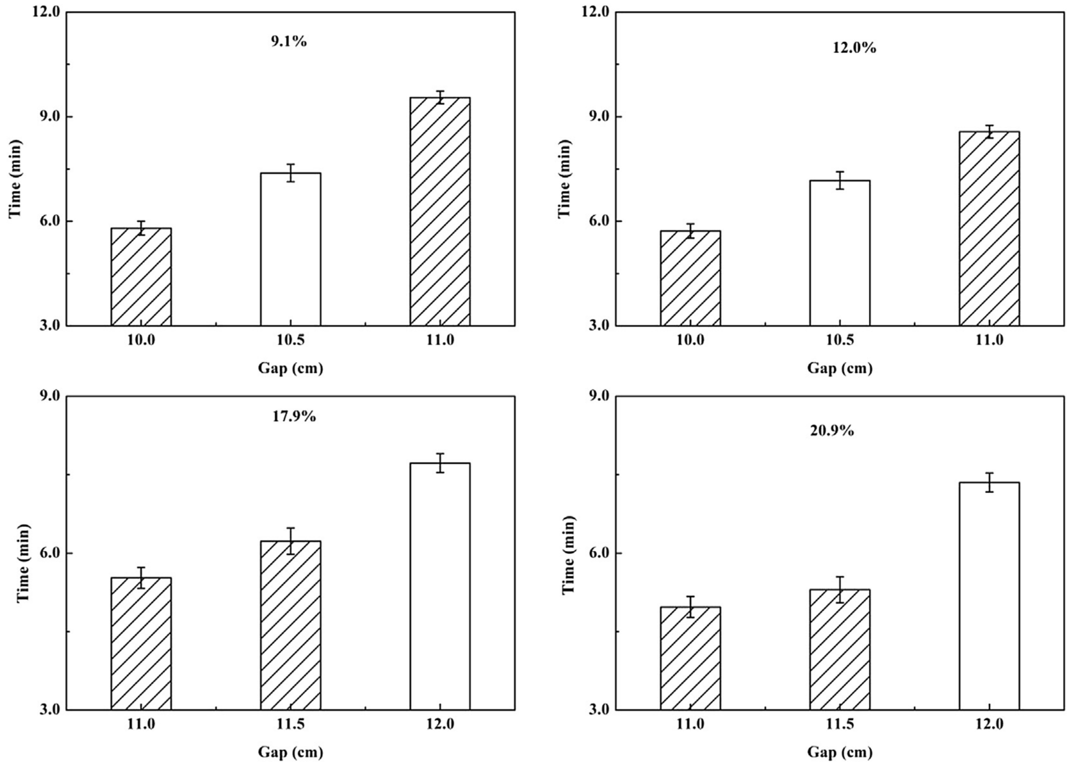

Fig. 4. Time-gap relationship of the RF heated corn in the center of polypropylene containers with the given four moisture contents to achieve the final temperature of 70 °C.

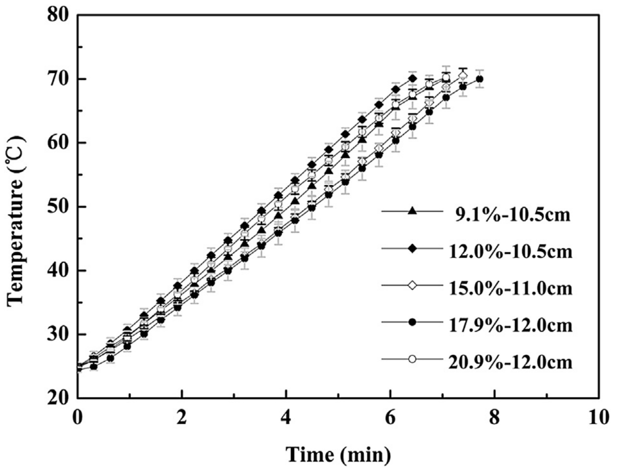

Fig. 5. Temperature-time histories of the RF heated corn samples with five moisture contents in the center of polypropylene containers under their optimal electrode gaps.

Table 1
Parameters of the optimal electrode gap, movement speed ($v_{movement}$), total RF heating time (t_{total}) and interval time ($t_{interval}$) of 2 mixings of corn samples during the RF treatment with the given five moisture contents.

	Moisture contents (MC, % w.b.)				
	9.1	12.0	15.0	17.9	20.9
Gap (cm)	10.5	10.5	11.0	12.0	12.0
$v_{conveyor}$ (m/h)	6.7	6.9	6.6	6.5	6.8
t_{total} (min)	10.1	9.8	10.3	10.4	10.0
$t_{interval}$ (min)	3.4	3.3	3.4	3.5	3.3

at 15.0% w.b. in the center of polypropylene container is shown in Fig. 6 using only hot air heating at 70 °C and only RF heating with the electrode gap of 11.0 cm. The heating time indicated a difference between RF heating and conventional hot air heating for 3.0 kg samples. Specifically, it took about 7.50 min for the center temperature of corn sample to reach 70 °C under the RF heating, but about 749 min to increase from 25 °C to 68 °C with forced hot air heating at 70 °C. The slow hot air heating could be caused by the poor heat conduction. The large heating time difference between RF and hot air heating in this study is similar to the results observed with legumes (Wang et al., 2010), almonds (Gao et al., 2010), coffee beans (Pan et al., 2012), chestnuts (Hou et al., 2014), milled rice (Zhou et al., 2015), and pistachios (Ling et al., 2016).

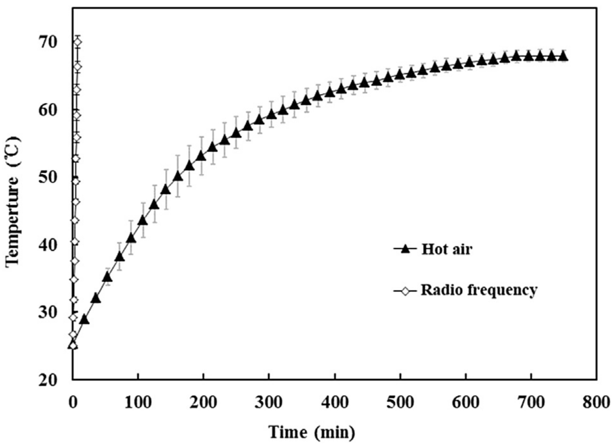

Fig. 6. Typical temperature-time histories of corn samples with 15.0% w.b. in the polypropylene container when subjected to hot air heating at 70 °C and RF heating (electrode gap = 11.0 cm).

Fig. 7 shows the temperature-time histories of corn samples with 15.0% w.b. in the polypropylene container center with three sample thicknesses of 6, 3, and 2 cm under natural or forced room air cooling. The cooling time decreased with increasing air speed and decreasing sample thickness. For example, when using natural room air cooling, about 196, 107, and 69 min were needed for 6, 3, and 2 cm thick samples, respectively, to cool down from 70 °C to 30 °C. However, the time was reduced to 68, 51 and 33 min, respectively, when subjected to a forced room air with speed of 3.5 m/s. This cooling time would further decrease by reducing the sample thickness in industrial applications. Compared to the cooling time of three sample thicknesses, the thin layer (2 cm depth) corn samples with the forced room air resulted in the shortest one, which was further used to develop the RF treatment protocol.

3.4. Heating uniformity evaluation

Table 2 provides a detailed comparison of the temperature distribution and uniformity index values in the top, middle, and bottom layers for corn samples at 15.0% w.b. in the polypropylene container after RF heating under different operational conditions. The initial sample temperature distribution was relatively uniform before RF treatment. After heating treatment, the average sample surface temperature in the middle layer was the highest, followed by the bottom and top layers. The relatively lower average temperatures of the samples in the top and bottom layers were probably caused by heat loss to ambient air. Conveyor belt movement, hot air assistance and mixing reduced the standard deviation of temperatures in each layer and improved heating uniformity over the RF only treatment. Forced hot air could help to raise the average temperature for all the locations with the decreased standard deviations of sample temperatures and the heating uniformity index values. Mixing was the best method to improve heating uniformity as compared to hot air and movement based on the reduced λ value. In the industrial-scale RF treatments, mixing could be achieved by mechanical tumbling between two RF units (Wang et al., 2007a,b). With holding, the average sample temperatures in the three layers were reduced by about 2 °C, but the heating uniformity was further improved due to reduced standard deviations. These were probably caused by the decrease of temperature difference between hot and cold spots by heat conduction. It was clear that the heating uniformity index was the smallest under the condition of RF heating, sample movement, 2 mixings and holding 14 min, and the average temperatures were close to the target 70 °C for meeting the pasteurization requirement. Therefore, including hot air, movement, mixing and holding in the design of an RF treatment protocol would be adequate to obtain the required heating uniformity. The heating uniformity indexes of corn samples at 15.0% w.b. in the polypropylene container are similar to those found for chestnuts (Hou et al., 2014), almonds (Gao et al., 2010), and milled rice (Zhou et al., 2015), but slightly larger than those observed for coffee beans (Pan et al., 2012), and lentils (Jiao et al., 2012), and smaller than those obtained for walnuts (Wang et al., 2007a), and pistachios (Ling et al., 2016).

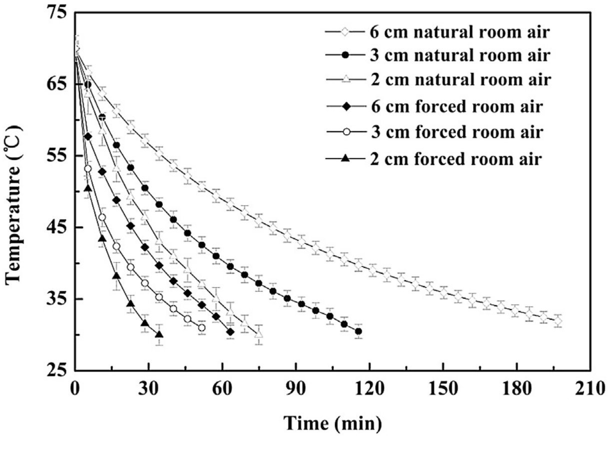

Fig. 7. Cooling curves of corn samples with 15.0% w.b. in the polypropylene container center as a function of sample thickness with natural and forced room air cooling.

Table 3 shows the comparison of temperature and heating uniformity index of the corn samples at 15.0% w.b. in the three different plastic containers after RF treatment. The temperatures of corn samples in the three layers were a little higher than 70 °C, and there was no significant difference ($P > 0.05$) among the three-type containers for the average temperatures and heating uniformity indexes of corn samples. The surface temperatures of corn samples in the polyetherimide container were the highest, but the standard deviation of the sample temperatures and heating uniformity index values were the lowest. Similar results are observed by Jiao et al. (2014) and Huang et al. (2015), indicating that a container having the similar dielectric constant and a negligible dielectric loss factor to those of samples can obtain the better RF heating uniformity. A further experiment is needed to evaluate the effect of the different material containers with various thicknesses on the RF heating uniformity.

Table 4 shows a comparison of surface temperatures and heating uniformity index of corn samples with five MC in the polypropylene container after RF treatment. The lower MC resulted in the better heating uniformity. For all corn samples, the average surface temperature and standard deviation, and the heating uniformity index of corns with the high MC were both higher than those in low MC. This result could be caused by the different dielectric properties of corn samples and electrode gaps. The previous research results indicated that the smaller dielectric properties lead to better RF power uniformities in the samples and dry products should provide a better uniform RF heating because of the smaller dielectric properties (Tiwari et al., 2011). Heating uniformity index of corn samples decreased as the electrode gap was reduced from 12.0 to 10.5 cm, which well agreed with the results in RF heated wheat flour (Tiwari et al., 2011).

3.5. Quality of RF heated corns

Table 5 shows the MC and water activity of corn samples at 15.0% w.b. in the polypropylene container before and after RF treatment during accelerated shelf life storage. A significant difference ($P < 0.05$) was observed between control and RF treated samples in the entire storage process. The RF treated corn samples lost about 1.6% w.b. of MC compared with control samples at the storage time of 0 d. The MC of corn decreased with the increasing storage time, and the MC of control samples significantly decreased ($P < 0.05$) at 4th d, but there were no significant differences ($P > 0.05$) in subsequent storage time. For RF treated samples, however, the MC significantly decreased after 8 d storage ($P < 0.05$). The changes of MC in control corn samples during storage were similar to those of corns during storage for 180 d at 10 °C reported by Zia-Ur-Rehman (2006).

Table 6 provides a detailed comparison of major quality parameters (protein, fat, starch, ash, and fatty acid) of corn samples with 15.0% w.b. in the polypropylene container before and after RF treatment during the 17 d accelerated shelf life storage. There was no significant difference ($P > 0.05$) between control and RF treated samples for five selected quality attributes except for fatty acid. The

Table 2
Comparison of the temperature and heating uniformity index (mean ± SD over 3 replicates) of the corn sample with 15.0% w.b. in the polypropylene container after RF treatments using different operational conditions.

Layer	RF	RF + hot air	RF + movement	RF + 1 mixing	RF + 2 mixings	RF + hot air + movement + mixing	RF + hot air + movement + 2 mixings + holding 14 min
Temperature (°C)							
Top	69.8 ± 8.4	70.1 ± 8.1	70.4 ± 7.0	70.9 ± 4.9	70.4 ± 3.7	72.1 ± 2.4	70.9 ± 2.0
Middle	73.6 ± 6.4	73.5 ± 6.1	73.1 ± 5.0	72.5 ± 3.0	71.6 ± 2.5	73.2 ± 2.1	71.2 ± 1.8
Bottom	70.3 ± 6.4	71.4 ± 6.0	70.8 ± 5.3	71.0 ± 3.1	70.7 ± 2.4	73.0 ± 2.0	70.2 ± 1.9
Heating uniformity index (λ)							
Top	0.172 ± 0.002	0.165 ± 0.003	0.143 ± 0.004	0.094 ± 0.003	0.066 ± 0.001	0.053 ± 0.002	0.050 ± 0.003
Middle	0.121 ± 0.004	0.115 ± 0.005	0.097 ± 0.003	0.057 ± 0.003	0.046 ± 0.003	0.042 ± 0.006	0.040 ± 0.004
Bottom	0.136 ± 0.008	0.122 ± 0.007	0.111 ± 0.002	0.063 ± 0.004	0.052 ± 0.007	0.048 ± 0.003	0.042 ± 0.002

Table 3
Comparison of temperature and heating uniformity index (mean ± SD over 3 replicates) in corn samples with 15.0% w.b. after hot air assisted RF treatments with conveyor movement, 2 mixings and holding for 14 min using three different plastic containers.

Layers	Container materials		
	Polypropylene	Polystyrene	Polyetherimide
Temperature (°C)			
Top	70.9 ± 2.0[a]	71.0 ± 2.0	71.4 ± 3.0
Middle	71.2 ± 1.8	73.0 ± 1.7	73.2 ± 1.7
Bottom	71.1 ± 1.9	71.2 ± 1.9	72.6 ± 1.8
Heating uniformity index (λ)			
Top	0.050 ± 0.003	0.045 ± 0.001	0.041 ± 0.002
Middle	0.040 ± 0.004	0.039 ± 0.002	0.035 ± 0.003
Bottom	0.042 ± 0.002	0.040 ± 0.002	0.037 ± 0.001

[a] No significant difference was observed both for container materials and layers ($P > 0.05$).

Table 4
Comparison of corn samples in the polypropylene container temperature and heating uniformity index (mean ± SD over 3 replicates) after hot air assisted RF treatments with conveyor movement, 2 mixings and holding for 14 min with five moisture contents (MC) under their optimal electrode gaps.

Layers	MC (% w.b.)				
	9.1	12.0	15.0	17.9	20.9
Temperature (°C)					
Top	70.0 ± 1.9	70.3 ± 2.0	70.9 ± 2.0	70.3 ± 3.0	70.8 ± 3.0
Middle	70.4 ± 1.5	70.7 ± 1.7	71.2 ± 1.8	71.1 ± 2.5	71.0 ± 2.9
Bottom	70.3 ± 1.4	70.5 ± 1.4	70.2 ± 1.9	70.9 ± 2.7	70.9 ± 2.7
Heating uniformity index (λ)					
Top	0.041 ± 0.003	0.048 ± 0.002	0.050 ± 0.003	0.056 ± 0.003	0.065 ± 0.001
Middle	0.034 ± 0.005	0.036 ± 0.008	0.040 ± 0.004	0.044 ± 0.007	0.055 ± 0.006
Bottom	0.039 ± 0.002	0.040 ± 0.006	0.042 ± 0.002	0.051 ± 0.010	0.061 ± 0.004

Table 5
Moisture contents (MC) (% w.b.) and water activities (A_w) (mean ± SD over 3 replicates) of corn samples with 15.0% w.b. in the polypropylene container before and after radio frequency (RF) treatment.

Treatment	Storage time (days)[b]				
	0	4	8	12	17
MC (% w.b.)					
Control	15.0 ± 0.2aA[a]	14.4 ± 0.1aB	14.2 ± 0.2aB	14.1 ± 0.1aB	14.0 ± 0.1aB
RF	13.4 ± 0.1bA	13.1 ± 0.1bA	12.9 ± 0.2bB	12.7 ± 0.1bB	12.7 ± 0.1bB
A_w					
Control	0.791 ± 0.006aA	0.780 ± 0.005aA	0.778 ± 0.009aB	0.767 ± 0.010aB	0.757 ± 0.008aB
RF	0.731 ± 0.007bA	0.715 ± 0.009bA	0.693 ± 0.013bB	0.685 ± 0.010bB	0.667 ± 0.009bB

[a] Different lower and upper case letters indicate that means are significantly different at $P = 0.05$ among treatments and storage time, respectively.
[b] 17 days at 35 °C, 68% RH to simulate 1-year storage at 10 °C.

protein and starch values fluctuated in a narrow range with increasing storage time both for control and RF treated corn samples. Fat and ash contents decreased but fatty acids increased with increasing storage time. Similar results were reported in RF treated milled rice by Zhou et al. (2015), and Zhou and Wang (2016). During storage time, the decreased protein content is caused by reducing content of free amino nitrogen (Onigbinde and Akinyele, 1988). The decreased fat ash and contents in grains are also obtained by Zhou and Wang (2016) and Reed et al. (2007).

Table 6 shows that fatty acid contents significantly increased with increasing storage time ($P < 0.05$). There was no significant difference ($P > 0.05$) observed in 0 and 4 d but significant difference ($P < 0.05$) in left three storage periods between the samples of control and RF treatment. The increasing content of the fatty acid increases the occurrence possibility of lipid oxidation reaction and resulted in the increased acidity of the stored corns (Onigbinde and Akinyele, 1988). During the same storage period, the fatty acid content in RF treated corns increased at a slower rate than that in controls, indicating that RF treatments would improve the corn storage stability.

The initial and final color values of corn samples at 15.0% w.b. in the polypropylene container before and after RF treatment are summarized in Table 7. L^* values decreased while a^* and b^* values increased after RF treatment, but there were no significant

Table 6
Storage quality characteristics (mean ± SD over 3 replicates) of corn samples with 15.0% w.b. in the polypropylene container before and after radio frequency (RF) treatment during the storage.

Quality	Treatment	Storage time (days) at 35 °C, 68% RH				
		0	4	8	12	17
Protein (%)	Control	5.8 ± 0.2aA[a]	5.8 ± 0.1aA	5.8 ± 0.05aA	5.7 ± 0.1aA	5.7 ± 0.1aA
	RF	5.8 ± 0.2aA	5.8 ± 0.1aA	5.8 ± 0.1aA	5.8 ± 0.0aA	5.7 ± 0.1aA
Fat (%)	Control	5.2 ± 0.0aA	5.2 ± 0.1aAB	5.1 ± 0.09aB	4.9 ± 0.1aBC	4.8 ± 0.0aC
	RF	5.3 ± 0.0aA	5.2 ± 0.1aAB	5.1 ± 0.08aAB	5.0 ± 0.1aBC	4.9 ± 0.0aC
Starch (%)	Control	71.3 ± 0.3aA	71.3 ± 0.2aA	71.0 ± 1.44aA	70.9 ± 0.9aA	69.9 ± 0.7aA
	RF	70.0 ± 0.3aA	71.0 ± 0.4aA	70.9 ± 0.57aA	70.7 ± 0.9aA	70.2 ± 1.0aA
Ash (%)	Control	1.2 ± 0.0aA	1.1 ± 0.0aA	1.1 ± 0.02aA	1.1 ± 0.0aA	1.1 ± 0.1aA
	RF	1.1 ± 0.0aA	1.1 ± 0.0aA	1.1 ± 0.01aA	1.1 ± 0.0aA	1.1 ± 0.0aA
Fatty acid (mg/100 g)	Control	26.5 ± 0.2aA	30.0 ± 0.1aB	34.9 ± 0.07aC	40.0 ± 0.1aD	48.8 ± 0.1aE
	RF	27.0 ± 0.2aA	30.1 ± 0.1aB	32.4 ± 0.11bC	36.6 ± 0.1bD	42.2 ± 0.1bE

[a] Different lower and upper case letters indicate that means are significantly different at $P = 0.05$ among treatments and storage time, respectively.

Table 7
Changes in color values of RF treated and untreated corn samples with 15.0% w.b. in the polypropylene container during storage.

Color parameters	Storage time (days)[b]					
	Treatment	0	4	8	12	17
L*[c]	Control	72.5 ± 4.5[a]	73.2 ± 4.5	73.7 ± 5.4	74.0 ± 5.1	74.2 ± 4.0
	RF	72.4 ± 4.4	72.6 ± 3.4	73.0 ± 5.8	73.7 ± 5.2	74.1 ± 4.0
a*[c]	Control	(−1.1 ± 1.5)	(−1.5 ± 2.7)	(−1.9 ± 2.1)	(−3.0 ± 1.6)	(−4.1 ± 2.0)
	RF	(−0.9 ± 1.4)	(−1.2 ± 2.4)	(−1.7 ± 2.1)	(−2.6 ± 1.6)	(−3.5 ± 1.6)
b*[c]	Control	36.2 ± 5.4	35.6 ± 5.7	35.2 ± 4.4	34.6 ± 4.2	34.4 ± 4.0
	RF	36.3 ± 5.5	36.1 ± 5.8	35.4 ± 4.5	35.0 ± 4.3	34.6 ± 4.0

[a] No significant difference was observed both for treatments and storage time ($P > 0.05$).
[b] 17 days at 35 °C, 68% RH to simulate 1-year storage at 10 °C.
[c] L* (lightness); a* (redness-greenness); b* (yellowness-blueness).

differences ($P > 0.05$) in L^*, a^* and b^* values of corn samples between the control and RF treatment. The result was consistent with that found by Odjo et al. (2012), showing that the temperatures slightly affect the color values of corn. The L^* value of RF treated samples slightly increased with increasing storage time, whereas a^* and b^* values decreased. This trend was likely to be caused by the decrease of protein content, and is explained in Jamin and Flores (1998) and Sandhu et al. (2007), who found that the a^* and b^* values were positively correlated with protein content while the L^* value were negatively correlated with protein content. The results showed that RF treatment protocol did not affect the color stability of corn after RF heating and for the accelerated storage time. The color changes of RF treatment corn samples with storage time are in agreement with those of the milled rice (Zhou et al., 2015).

4. Conclusions

RF treatments sharply reduced the heating time and raised the heating rate of corn samples at 15.0% w.b. in the polypropylene container compared to hot air heating, and the optimal heating rate of 6.0 °C/min with the corresponding suitable electrode gap of 11.0 cm was obtained to develop the RF treatment protocol. The RF heating uniformity was improved by adding forced hot air at 70 °C, movement at 6.6 m/h, two mixings, and holding 14 min at the hot air of 70 °C, which were used in the final RF treatment protocol. For the corn samples with five moisture levels, the smaller heating uniformity index appeared in the sample with low MC. The corn samples at 15.0% w.b. in the polyetherimide container had a better RF heating uniformity compared to samples in the polystyrene and polypropylene containers. Corn quality parameters were not affected by the RF treatments even after the accelerated storage. RF treatments, therefore, should provide a practical, effective and environmentally friendly method for pasteurizing corns while maintaining product quality. Future research is needed to confirm the treatment efficacy using inoculated corns and scaled-up for large-scale industrial applications.

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