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Developing radio frequency technology for postharvest insect control in milled rice

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ABSTRACT

Since methyl bromide fumigation has an adverse effect on human health and environment, it is urgently needed for developing a non-chemical method to replace chemical fumigation for disinfesting milled rice. The purpose of this research was to study possible applications of radio frequency (RF) energy for disinfesting milled rice without affecting product quality. A pilot-scale, 27.12 MHz, 6 kW RF system was used to study RF heating uniformity and develop a treatment protocol for achieving 100% insect mortality and finally evaluating quality attributes in RF treated milled rice during storage. The results showed that the heating time needed only 4.3 min to heat the 3.9 kg milled rice from 25 °C to 50 °C using RF energy, but 480 min for milled rice to reach 48 °C using hot air at 50 °C. After comparing three selected electrode gaps, an appropriate gap of 11 cm was obtained to achieve the heating rate of 5.8 °C/min for further heating uniformity tests. An RF treatment protocol was finally developed to combine 1.0 kW RF power with a forced hot air heating at 50 °C, movement of the conveyor with the speed of 12.4 m/h, two mixings, and holding at 50 °C hot air for 5 min, followed by forced room air cooling through single-layer (2 cm thick) samples. There were no significant differences in quality parameters (moisture, protein, fat, starch, hardness, and color) between RF treatments and untreated controls during storage ($P > 0.05$). Therefore, RF treatments may provide a practical, effective and environmentally friendly method for disinfesting milled rice.

1. Introduction

Milled rice (*Oryza sativa* L.) is one of the major staples in the world with rich carbohydrates and high-quality proteins (Fan et al., 2012). China is one of the most milled rice producing countries with nearly 33% of world productions, which reached about 1,650,000 metric tons in 2013 (FAOSTAT, 2013). The occurrence of pests in milled rice is very common during storage, resulting in quality losses and reduced market values. The overall damage caused by insect infestation is about 27% of the annual total rice yield (Alfonso-Rubí et al., 2003). Up to now, most stored products over the world use methyl bromide and phosphine fumigation for postharvest phytosanitary treatments (Rajendran and Sriranjini, 2008). However, Montreal Protocol (UNEP, 1992) has proposed to phase out this conventional chemical disinfestation method by 2015 in developing countries, such as in China, due to its adverse effects on human health and environment (Wang and Tang, 2004). Therefore, it is urgent to develop an effective non-chemical alternative postharvest method for disinfesting milled rice.

Alternative physical methods have been proposed to replace chemical fumigations, including ionizing irradiation (Johnson et al., 1998; Follett, 2008; Carocho et al., 2014), controlled atmosphere (Zhou et al., 2000; Neven and Rehfield-Ray, 2006), cold storage (Aluja et al., 2010), low pressure (Jiao et al., 2013; Suhem et al., 2013), conventional heating (Hansen, 1992), microwave (Zhao et al., 2007; Vadivambal et al., 2007; Yadav et al., 2014; Jian et al., 2015), and radio frequency (RF) heating (Wang et al., 2008, 2010, 2013; Alfaifi et al., 2014). However, each of these methods has disadvantages based on the treatment effectiveness and cost. For example, ionizing irradiation requires high equipment investments to protect from harmful leakages. Additionally, irradiated products are not accepted by consumers in Europe and Japan. Cold storage, controlled atmosphere, and low pressure treatments take long time to achieve the required phytosanitary and quarantine levels, which may not be acceptable for many important international markets.

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Conventional thermal treatments, such as hot air (Li et al., 2011), water (Armstrong and Follett, 2007), and steam (Samtani et al., 2012) heating, have been widely used for insect control in agricultural products due to no chemical residues, no environmental pollution, small equipment investments, and simple operations. A common and major difficulty with conventional thermal treatments is the slow conductive heating, which may result in long treatment time in high medium temperatures and possible damage to product quality (Paull and Armstrong, 1994; Wang et al., 2001). In recent years, dielectric heating methods, such as microwave and RF energy, have been extensively studied for postharvest disinfesting agricultural products due to rapid and volumetric heating (Tang et al., 2000; Awuah et al., 2005; Wang et al., 2006a; Geveke and Brunkhorst, 2008; Gao et al., 2010; Jiao et al., 2012). With the limited penetration depth due to short wavelength, the uncertain cold spot and high equipment cost in microwave systems, there has been an increasing interest in developing RF heating technology for disinfestations.

Most RF treatments for disinfesting are first conducted on fresh fruits and then dry agricultural products. For example, hot water preheating combined with short RF treatments was used for control of codling moth in cherries (Hansen et al., 2005), and apples (Wang et al., 2006a), and Mexican fruit fly in persimmons (Tiwari et al., 2008). The lack of RF heating uniformity in fresh fruits often results in unacceptable product quality (Feng et al., 2004; Birla et al., 2005; Hansen et al., 2005; Wang et al., 2006a). However, RF disinfestation treatment protocols have been successfully developed for many dry agricultural products, such as beans (Wang et al., 2010; Jiao et al., 2012), walnuts (Mitcham et al., 2004; Wang et al., 2007b), coffee beans (Pan et al., 2012), almonds (Gao et al., 2010; Wang et al., 2013), and chestnuts (Hou et al., 2014). RF heating uniformity is improved with surface hot air heating, conveyor movement and sample mixing. For example, Liu et al. (2013) combined RF and hot air treatments improved the heating uniformity of prepackaged bread. Wang et al. (2010) studied postharvest disinfestation treatments for legumes and the heating uniformity was improved by adding forced hot air and sample movement on a conveyor belt at 0.56 m/min. Lagunas-Solar et al. (2007) showed that RF treatments controlled insects in rough rice without significant quality changes. The laboratory RF treatment protocols have been tried to scale up to continuous industrial applications (Wang et al., 2007a,b; Jiao et al., 2012). However, there is no detailed research on RF heating uniformity and treatment protocol development of milled rice up to now.

The objectives of this study were (1) to determine heating rates in milled rice when subjected to hot air and RF heating, (2) to select a suitable cooling method, (3) to study the RF heating uniformity in milled rice using forced hot air surface heating, conveyor belt movement, and samples mixing, and (4) to evaluate the main milled rice quality attributes, such as moisture, starch, protein, fat, hardness, and color, after RF treatments and for an accelerated storage at 35 °C for 60 days.

2. Materials and methods

2.1. Materials and hot air-assisted RF heating system

Milled rice (*Oryza sativa* L.) used in this research was two-months old, non-waxed, and purchased from a local grain and oil grocery store in Yangling, Shaanxi, China. The average original moisture content of milled rice was 12.7 ± 0.1% wet basis (w.b.). All the milled rice samples were stored with polyethylene bags in a refrigerator (BD/BC-297KMQ, Midea Refrigeration Division, Hefei, China) at 3 ± 1 °C before the experiment. Prior to RF treatments, all samples were taken out from the refrigerator and put into an incubator (BSC-150, Boxun Industry & Commerce Co., Ltd, Shanghai, China) for more than 12 h at 25 ± 0.5 °C for equilibrium.

To explore RF heating uniformity and the effects of RF treatment protocols on milled rice quality, a 6 kW, 27.12 MHz pilot-scale free-running oscillator RF system (SO6B, Strayfield International, Wokingham, U.K.) together with a hot air system (6 kW) was used for RF heating experiments (Fig. 1). A detailed description of the RF unit, the hot air and conveyor systems can be found in Wang et al. (2010). The hot air was used to provide surface heating and maintain the sample temperature during holding when the RF power was turned off. The hot air speed was 1.6 m/s inside the RF cavity, provided through an air distribution box under the bottom electrode, and measured at 2 cm above the bottom electrode by an anemometer (DT-8880, China Everbest Machinery Industry Co., Ltd, Shenzhen, China). By moving the top electrode (40 cm × 83 cm) changed the parallel plate gap, thus regulating the RF output power. Milled rice samples in a container between electrodes were moved on a conveyor belt during RF heating to simulate continuous processes.

2.2. Heating temperature selection

The milled rice was mainly infested by adult rice weevil (*Sitophilus oryzae*) during storage at room temperature, causing reduction in weight, quality, and commercial value. Developing RF treatment protocols should be based on the complete control of this insect. The thermal mortality curves of adult *Sitophilus oryzae* with the best-fit 0th-order model (Fig. 2) showed that the minimum holding time for 100% mortality was about 130, 50, 12, and 4 min at 44, 46, 48, and 50 °C, respectively (Yan et al., 2014). To achieve a high throughput, a sample target temperature of 50 °C with holding time of 5 min was selected to develop the RF treatment protocol.

2.3. Electrode gap selection and conveyor belt speed determining

A plastic container (300 mm × 220 mm × 60 mm) (Fig. 3) with 3.9 kg milled rice and perforated screens on the side and bottom walls was used to allow hot and room air to pass through the samples for surface heating and cooling. The sample container was first placed on the stationary conveyor belt between the two electrodes without hot air heating to obtain a general relationship between different electrode gaps and the electric current (I, A). The anode current displayed on the screen of the RF system was used to calculate the output power (P, kW) of the RF system with a relationship ($P = 5 \times I - 1.5$) provided by the manufacturer (Jiao et al., 2012; Hou et al., 2014). The range of the electrode gap was selected from 10 to 19 cm with a distance interval of 1.0 cm. After setting the electrode gap, RF power was turned on, and the electric current was immediately recorded. Tests were repeated three times. Based on the measured electric current, three suitable electrode gaps of 11, 12, and 13 cm were selected for evaluating subsequent heating tests.

To determine the best one from the three given electrode gaps for studying RF heating uniformity and the final treatment protocol development, the sample temperature was measured at the central position 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 time needed to heat the milled rice from ambient room air (25 °C) to the target temperature of 50 °C was determined and the temperature of samples was recorded every 1 s. The final gap was selected based on the target heating rate (4–6 °C/min) of samples with three replicates. The most suitable gap was then used in succeeding tests. Belt speed was calculated with dividing the electrode length by the resulted

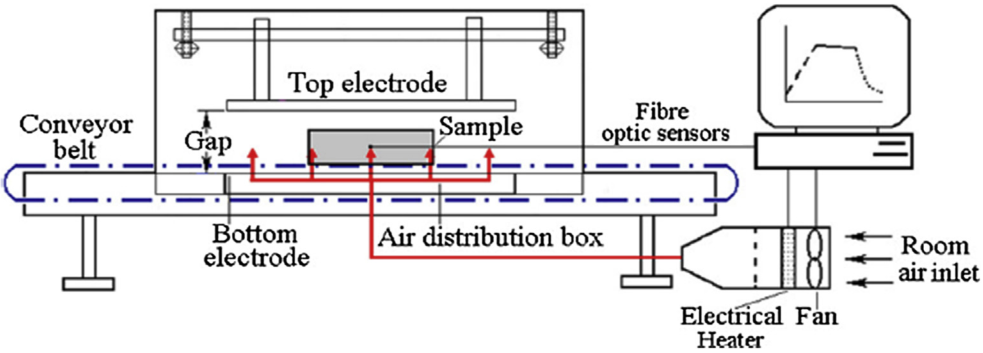

Fig. 1. Schematic view of the pilot-scale 6 kW, 27.12 MHz RF system showing the plate electrodes, conveyor belt, and the hot air system (Wang et al., 2010).

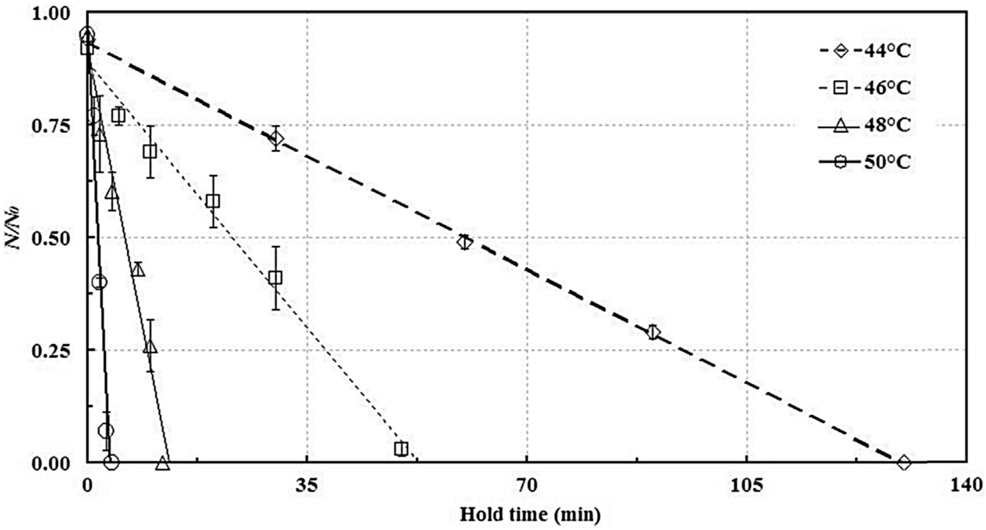

Fig. 2. Thermal mortality curves of adult rice weevil at different temperatures and exposures. *N* and N_0 are the surviving and initial numbers of rice weevils, respectively (Yan et al., 2014).

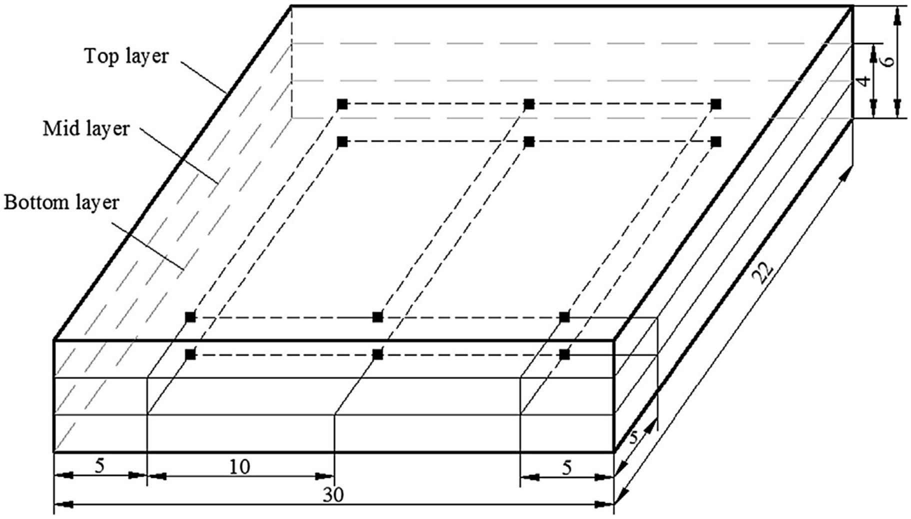

Fig. 3. Rectangular plastic container with12 locations for sample temperature measurements (all dimensions are in cm).

heating time.

2.4. Comparisons of temperature profiles of milled rice among RF and hot air heating

After the test described above, the most appropriate gap was used for temperature profile comparisons, heating uniformity improvement and protocol development. A plastic container with 3.9 kg milled rice was placed on the center of the bottom electrode for hot air and RF heating. Ambient room temperature (25 °C) was used as the initial sample temperature for each test. The fiber-optic temperature sensor system was used to record the temperature at the geometric center of the samples every 60 s. When the sample temperature increase was less than 0.5 °C within 30 min for hot air heating or the temperature reached 50 °C for RF heating the measurement was stopped. Each test was repeated 3 times.

2.5. Determining the cooling methods

Cooling is a crucial factor of effective RF treatment protocols since slow cooling may result in quality deterioration and reduce throughput of the industrial scale treatments. Milled rice samples preheated with 50 °C hot air were used to determine the cooling method and time. The samples were divided into 6, 4, and 2 cm depths, respectively, when subjected to natural ambient air and forced room air cooling. A fan (FT30-10A, Guangdong Midea Environment Appliances Manufacture Co., Ltd., Zhongshan, China) was used to provide forced room air. The air speeds at the sample surface were measured by the anemometer and obtained to be 0.2, and 3.5 m/s for the natural and forced air cooling, respectively. The temperatures at geometric center of the samples were recorded every 60 s by the fiber-optic temperature sensor system, until the sample temperature dropped to 30 °C. The best cooling method was obtained based on the shortest cooling time and then used to further RF treatment protocol development.

2.6. Heating uniformity tests

Non-uniformity heating is a major problem in developing a large-scale RF treatment for milled rice. Wang et al. (2005, 2008), proposed a heating uniformity index (λ) to evaluate temperature distributions in RF treated samples, which is defined as the ratio of rise in standard deviation of sample temperatures to the rise in mean temperatures over the treatment time. This uniformity index has been successfully used to evaluate the RF heating uniformity in walnuts (Wang et al., 2007a), legumes (Wang et al., 2010), lentils (Jiao et al., 2012), coffee beans (Pan et al., 2012), almonds (Gao et al., 2010), and chestnuts (Hou et al., 2014). In this study, the uniformity index was determined and compared under the following conditions: stationary or conveyor belt movement at 12.4 m/h; with or without hot air surface heating at 50 °C; with or without mixing of the sample between two RF exposures (Wang et al., 2007a; Jiao et al., 2012). It is essential to improve the RF heating uniformity before developing a successful RF treatment protocol for milled rice.

To examine the effect of forced hot air, sample movement, and mixing on RF heating uniformity, measurements were made under seven conditions: RF heating only; RF heating with conveyor belt speeds of 12.4 m/h; RF heating with hot air assisted; RF heating with one mixing; RF heating with two mixings; RF heating with conveyor belt movement, forced hot air at 50 °C and two mixings; RF heating with conveyor belt movement, hot air, two mixings and holding in 50 °C hot air for 5 min. In each condition, milled rice samples with 3.9 kg in weight and 6 cm in depth divided into three layers (Fig. 3) by two thin gauzes (with mesh opening of 1 mm) were placed on the conveyor belt to evaluate effects of RF treatments on heating uniformity and sample quality. Hot air was provided by the air distribution box, and through the holes of bottom electrode to help obtain the target temperature of 50 °C. Conveyor belt moved samples between electrodes started from in-feed side to out-feed side. One and two mixings were done outside the RF cavity at the interval of 2.7, and 1.8 min, respectively, during 5.4 min RF heating. Mixing was carried out with bare hand and spent about 22 s through putting the samples into a large container (35.5 cm × 27.5 cm × 10.5 cm), then placed it back again into the treatment container, and finally put it into the RF cavity for the remainder of the treatment time. The total time spent in mixing was less than 1 min. Before and immediately after the RF treatment was completed, first layer surface temperature was measured by a thermal imaging camera (DM63, Zhejiang Dali Technology Co., Ltd., Hangzhou, China) having an accuracy of ±2 °C. Second and third layers were mapped sequentially. Each thermal image took less than 1 s. Details on the infrared imaging system to measure product surface temperature after RF treatment can be found in Wang et al. (2006b). With mixing, the surface temperature of the first layer was measured with thermal imaging camera, and then two Type-T thermocouple thermometers (TMQSS-020-6, Omega Engineering Ltd., CT, USA) were used to obtain the temperatures of selected 12 positions in the middle and bottom layers. The 12 positions were equally distributed at two depths of 4, and 6 cm, which were specifically located in Fig. 3. The mean value and standard deviation of surface and interior sample temperatures were used to calculate the uniformity index. Each test was repeated twice.

2.7. Treatment protocol development

According to the description above, the whole treatment protocol consisted of RF heating, hot air holding, forced room air cooling, and storage. Specifically, 3.9 kg milled rice samples with thickness of 6 cm in the plastic container were RF heated under the selected electrode gap of 11 cm with the conveyor belt movement at the speed of 12.4 m/h. During RF heating, hot air at 50 °C was added for surface heating and together with a twice mixing. Then the RF system was turned off and the milled rice sample was held in hot air for 5 min, followed by forced room air cooling single-layer (2 cm in depth) samples for 18 min. The untreated samples were considered as controls. Treated samples were sealed in plastic bags for storage test. Each treatment was replicated three times.

2.8. Quality evaluation of milled rice before and after RF treatment with storage

Since the free fatty acid (FFA) content of rice is low (<0.06%) after microwave heating and storage at 50 °C for 5 days (Zhong et al., 2013) and that of RF treated walnuts with high oil contents is still below the limits (0.6%) required for good product quality by walnut industry even after stored at 35 °C for 20 days (Wang et al., 2002, 2007a,b), the proximate compositions of milled rice together with the color were analyzed for quality evaluations in this study. The quality of controls and RF treated milled rice was evaluated immediately after RF treatment and for a given storage period. Since common storage time of milled rice is 6 months at room temperature (Babu et al., 2009), the accelerated shelf life tests were conducted at 35 °C with 78 ± 0.5% relative humidity (RH) for 2 months. This was estimated based on a Q_{10} value of 3.4 for food nutrition loss (Taoukis et al., 1997). Similar methods have been effectively used for accelerated shelf life tests in RF treated products (Wang et al., 2002; Jiao et al., 2012; Hou et al., 2014), which were validated by real-time storage experiments (Wang et al., 2006b). During the storage experiment, controls and RF treated samples (1000 g) were packed individually in 5 bags and stored in the incubator. The samples were taken out every 15 days for quality evaluations. Each storage tests was replicated three times. Moisture content, color, protein, fat, starch, and hardness were selected as major parameters to evaluate the milled rice quality.

The moisture content of milled rice was determined according to the oven drying method described by AOAC (2000a). The milled rice 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 101.3 kPa, under the temperature of 105 °C until a constant weight of samples was attained. Then the samples were placed into a desiccator with $CaSO_4$ (Calcium sulphate) for cooling and the sample weight was recorded at room temperature.

Protein content in the milled rice was determined by using the Kjeldahl method following the AOAC method (AOAC, 2005). A nitrogen conversion factor of 5.95 was used to calculate the protein content of the milled rice (Chandi and Sogi, 2007; Ju et al., 2001; Tan et al., 2001). Fat content in milled rice is one of the most important nutritional quality properties and was measured by the Soxhlet extraction method following the AOAC method (AOAC, 2006). Starch was determined by using enzymatic hydrolysis method following the AOAC standard (AOAC, 2000b).

Hardness as a texture parameter was measured by a Texture Analyzer (TA-XT.PLUS/50, Stable Micro System Ltd., England) and using a maximum crushing force to make the sample broken. Detailed measurement processes are shown in Suhem et al. (2013). The force–time graphs were recorded by a computer and analyzed using the Exponent software (version 6.0.7.0, Stable Micro Systems Ltd., UK).

A computer vision system (CVS) was used to measure color values of RF treated and control samples, including a lighting system, a Cannon EOS 600 Digital camera with 1800 megapixel resolution and EF-S 18–55 mm f/3.5–5.6 Zoom Lens, and a computer with image-processing software. To capture color images, full load milled rice samples were placed in a plastic Petri dish with diameter of 9 cm and height of 1 cm at the bottom of a shooting tent. The obtained images were stored in the computer for further analysis. An Adobe Photoshop CS3 (Adobe Systems Inc., USA) system was used to obtain color values: lightness (L), redness-greenness (+or − a) and yellowness-blueness (+or − b), which were converted to CIE LAB (L^*, a^* and b^*) values using the following formulas (Briones and Aguilera, 2005; Hou et al., 2014):

$$L* = \frac{L}{2.5} \tag{1}$$

$$a* = \frac{240}{255}a - 120 \tag{2}$$

$$b* = \frac{240}{255}b - 120 \tag{3}$$

2.9. Statistical analysis

Mean values and standard deviations were calculated from three independent replicates for all treatments. The mean values were separated with Tukey's method at a significance level of 0.05 using a Microsoft Excel variance procedure (Microsoft Office Excel, 2010).

3. Results and discussion

3.1. Electric current under different electrode gap

In the conditions of no movement of conveyor belt, no hot air assisted heating, and container with or without milled rice, the relationship between electric current and electrode gap is shown in Fig. 4. With milled rice, electric current rapidly decreased from 0.62 A to 0.42 A when the electrode gap increased from 10 cm to 13 cm. However, when the electrode gap increased from 13 cm to 19 cm, the current decreased slowly. Without milled rice, as electrode gap increased, electric current fluctuated in a narrow range around 0.35 A. The same trends were also found by Jiao et al. (2012) and Hou et al. (2014). This result provided the basis for subsequent experiments to select the of optimal electrode gap.

3.2. Determination of electrode gap and conveyor belt speed

Fig. 5 shows the temperature-time histories in the geometric center of the container as a function of the electrode gaps. The milled rice sample temperatures increased almost linearly with the heating time under the three electrode gaps. The heating rates decreased with increasing electrode gaps, about 2.7, 4.3, and 7.0 min were needed to heat the 3.9 kg milled rice samples from 25 to 50 °C and the heating rates were 9.25, 5.80, and 3.56 °C/min for electrode gaps of 10, 11, and 12 cm, respectively. Fast heating rates lead to high productivity and throughput but might have an adverse effect on RF heating uniformity. To obtain relatively high throughput with acceptable heating uniformity, the electrode gap of 11 cm was selected for milled rice samples to achieve the heating rate of 5.8 °C/min and used for further heating uniformity tests. The obtained heating rate is closed to those in RF treated legumes (5.1 °C/min, Wang et al., 2010) and coffee beans (5.2 °C/min, Pan et al., 2012). Based on the RF heating time, the speed of the conveyor belt was therefore set to 12.4 m/h.

3.3. Heating and cooling profiles

Fig. 6 shows the typical temperature-time histories of milled rice when subjected to hot air heating at 50 °C and RF heating with electrode gap of 11 cm. An obvious heating time difference was observed between RF treatment and conventional hot air heating. For example, it took only 4.3 min for the center temperature of RF heated milled rice to reach 50 °C, as compared to 480 min for hot air heating to reach 48 °C. The slow hot air heating could be caused by the poor heat conduction within the relatively low-moisture milled rice samples with 6 cm thickness. The advantage of rapid RF heating is similar to the results observed with legumes (Wang et al., 2010), coffee beans (Pan et al., 2012), almonds (Gao et al., 2010), and chestnuts (Hou et al., 2014).

Fig. 7 shows the temperature-time histories of the milled rice samples with 3 thicknesses of 2, 4, and 6 cm under natural room air and forced room air cooling. Thin thickness and fast air speed resulted in short cooling time. For example, when using natural room air, about 168, 84, and 42 min were needed for the 6, 4, and 2 cm depths, respectively, to cool the samples from 50 °C to 30 °C. By contrast, when using forced room air, the corresponding cooling times were reduced to about 96, 42, and 18 min, respectively. This cooling time is slightly longer than that observed in coffee beans (Pan et al., 2012) and chestnuts (Hou et al., 2014). This is probably caused by poorer heat conduction due to smaller particles of milled rice samples. Therefore, the single layer (2 cm depth) milled rice samples with forced room air cooling were used in the final RF treatment protocol.

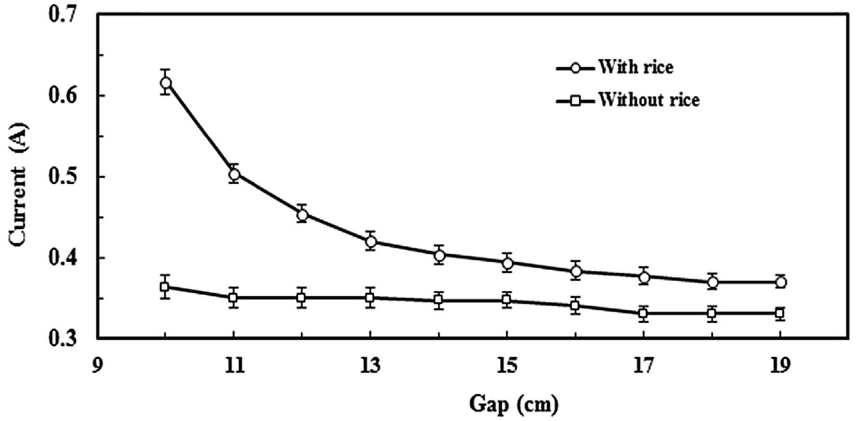

Fig. 4. Electric current of the radio frequency system as a function of electrode gap.

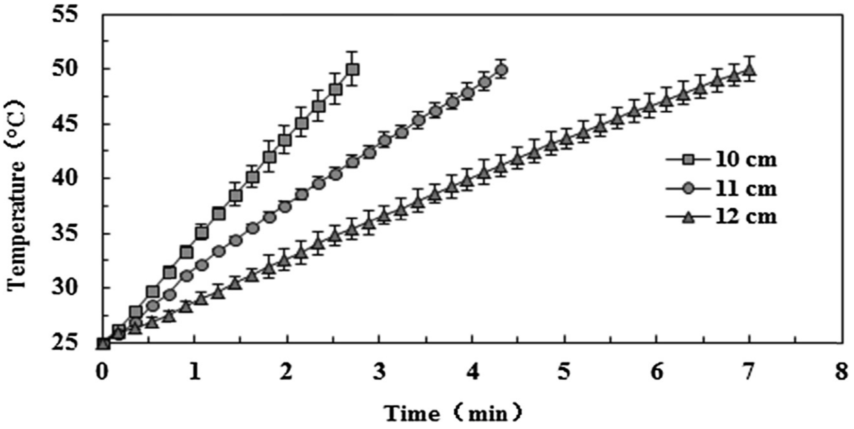

Fig. 5. Temperature-time histories of the RF heated milled rice in the center of the 6-cm thick container as a function of the electrode gap.

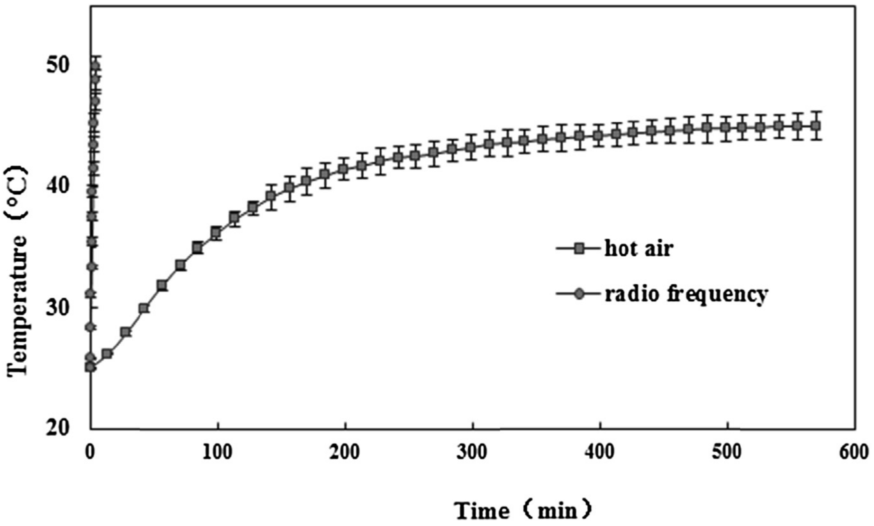

Fig. 6. Typical temperature-time histories of milled rice when subject to hot air heating at 50 °C and RF heating (gap = 11 cm).

3.4. Heating uniformity in RF treated milled rice

A detail comparison of the temperature distributions in the top, middle, and bottom layers after RF heating under different processing conditions was summarized in Table 1. The average surface temperature in bottom layer was the highest, followed by the middle and top layers. The standard deviation of the sample temperatures was reduced by adding hot air surface heating, sample movement, mixing and holding. Except for hot air, the sample movement, mixing and holding reduced the average temperature.

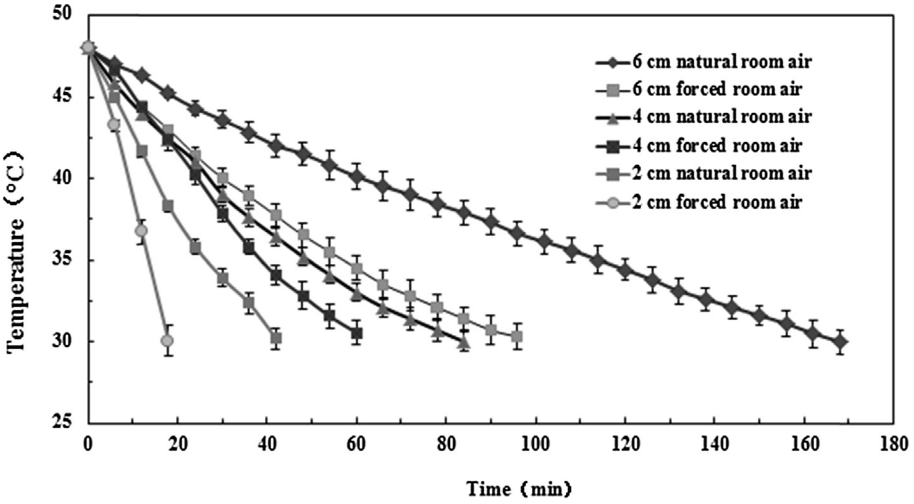

Fig. 7. Cooling curves of milled rice in the sample center as a function of sample thickness with natural and forced room air cooling.

Table 1
Comparisons of milled rice temperatures (mean ± SD over 3 replicates) after RF heating with different conditions.

Temperature (°C)							
Rice 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 5 min
Top	51.22 ± 4.07	52.37 ± 3.18	49.97 ± 3.17	50.96 ± 2.84	50.63 ± 2.43	52.27 ± 2.07	50.2 ± 1.76
Middle	52.46 ± 3.64	53.80 ± 3.10	51.27 ± 3.04	51.23 ± 2.58	51.07 ± 2.12	53.60 ± 1.86	50.80 ± 1.60
Bottom	53.53 ± 3.20	54.26 ± 2.44	52.07 ± 2.65	52.33 ± 2.45	52.17 ± 1.98	54.23 ± 1.67	51.40 ± 1.47

Especially for 5 min holding, the average temperature dropped about 1.7 °C in each layer. But all the average temperatures were higher than the target temperature 50 °C for complete thermal control of insects in milled rice (Yan et al., 2014). The similar RF heating patterns are also observed in wheat flour (Tiwari et al., 2011), coffee beans (Pan et al., 2012), raisins (Alfaifi et al., 2014), and chestnuts (Hou et al., 2014).

The uniformity index value allows uniformity to be objectively and quantitatively compared and is a key factor in developing successful postharvest quarantine treatments using RF energy (Pan et al., 2012). Fig. 8 showed that hot air surface heating, sample movement, mixing and holding all improved the RF heating uniformity in milled rice samples as shown by gradual reductions in λ values. The uniformity index in bottom layer was smaller than that in middle and top layers, which could be caused by the introduced hot air. In addition to hot air surface heating, mixing played a significant role in the reduced λ value due to the sharp reduction slope (Fig. 8). In the industrial-scale RF treatments, mixing could be achieved by mechanical tumbling between two RF units (Wang et al., 2007a,b). During holding, the uniformity was also improved

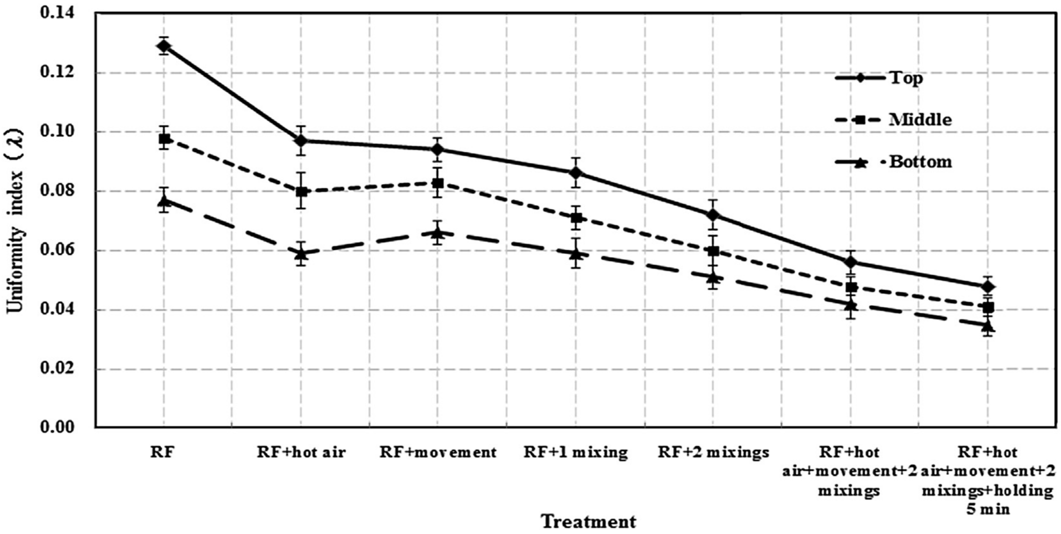

Fig. 8. Comparisons of heating uniformity index (mean ± SD over 3 replicates) of the milled rice after RF heating with different conditions.

Table 2
Moisture contents (mean ± SD over 3 replicates, % w.b.) of milled rice samples before and after RF treatments during storage at 35 °C.

Treatment	Storage time (days)				
	0	15	30	45	60
Control	12.71 ± 0.12aA[a]	12.40 ± 0.10aB	12.25 ± 0.07aB	12.20 ± 0.11aBC	12.10 ± 0.04aC
RF	12.50 ± 0.08aA	12.26 ± 0.08aB	12.17 ± 0.09aBC	12.08 ± 0.09aBC	11.99 ± 0.08aC

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

by reducing the temperature difference between the hot and cold spots. Therefore, the optimal heating uniformity was obtained by the combination of all these methods, which were used for the final treatment protocol. The uniformity index values in this study were similar to those found for chestnuts (Hou et al., 2014) and almonds (Gao et al., 2010), but slightly larger than those found for lentils (Jiao et al., 2012) and coffee beans (Pan et al., 2012), and smaller than those observed for walnuts (Wang et al., 2007a).

3.5. *Quality of RF treated milled rice*

Table 2 shows the moisture content of control and RF treated milled rice before and after RF treatments during accelerated shelf life storage. There were no significant differences between control and RF treated samples ($P > 0.05$). However, with the increasing storage time, the milled rice moisture content showed a decreasing trend. This phenomenon was also observed by Theanjumpol et al. (2007), indicating that after the RF heating treatment at different temperatures of 45, 60, 75, and 90 °C, there was no significant difference in milled rice moisture (P > 0.05). Furthermore, Sauer (1992) reported that the moisture content of milled rice is preferable to 12% w.b. during storage and can be reduced slightly because the movement of water from inside of the milled rice into the air by evaporation when the temperature increased. This may be the main reason resulted in the decreasing trend of milled rice sample moisture contents during 2 months storage.

Table 3 provides a detailed comparison of major quality parameters (protein, fat, starch, hardness, and color) between control and RF treated samples during the 2 months accelerated shelf-life storage. There was no significant difference between control and RF treated milled rice for the five selected quality attributes during 2 months storage ($P > 0.05$). With increasing storage time, the protein, fat, and starch values fluctuated in a narrow range both for control and RF treated milled rice. However, no significant changes ($P > 0.05$) in protein, fat, and starch were observed between control and RF treated samples both after RF treatment and during whole storage periods, indicated that those quality parameters were relatively stable. Similar results are also obtained by Vearasilp et al. (2011) and Theanjumpol et al. (2007), indicating that RF treatments did not influence the proximate compositions of the milled rice.

Table 3 shows that at the storage time of 0 day, the hardness of the untreated milled rice was 74.8 N whereas that of the RF treated one was reduced to 73.4 N. Under the same storage time, the RF treated milled rice had no significant difference ($P > 0.05$) from the controls. However, with the storage time increased to more than 15 days, a significant difference appeared in hardness ($P < 0.05$). The results showed that the storage time influenced the texture of milled rice samples, which was related to the interior structural changes of the milled rice (Theanjumpol et al., 2007). Generally, hardness was affected by storage time, temperature, and moisture content (Meullenet et al., 2000; Zhou et al., 2002). A further experiment is needed to evaluate the influential factors of milled rice hardness.

The color values of RF treated samples slightly increased with increasing storage time (Table 3) but there were no significant differences ($P > 0.05$) in L^*, a^* and b^* values of milled rice between the control and RF treatment. This trend is consistent with that found by Suhem et al. (2013). The similar studies are also reported by Dillahunty et al. (2000) and Theanjumpol et al. (2007), showing that the temperature and treatment duration affect the yellowness of milled rice. The increasing in the b^* values of milled rice samples during storage is consistent with that observed by Park et al. (2012) due to lipid oxidation. Similar results are also obtained by Kim et al. (2004), in which the phenomenon is resulted from the acceleration of Mailard reaction between the protein and sugar contents of milled rice. The results in this study confirmed that RF technology did not affect the color values of milled rice.

Table 3
Storage quality characteristics (mean ± SD over 3 replicates) of milled rice before and after treatments by radio frequency (RF) heating during storage at 35 °C.

Quality	Treatment	Storage times (days)[a]				
		0	15	30	45	60
Protein (%)	Control	6.38 ± 0.13aA[*]	6.38 ± 0.08aA	6.35 ± 0.08aA	6.42 ± 0.06aA	6.29 ± 0.05aA
	RF	6.51 ± 0.06aA	6.41 ± 0.04aA	6.43 ± 0.06aA	6.46 ± 0.03aA	6.37 ± 0.12aA
Fat (%)	Control	1.68 ± 0.05aA	1.70 ± 0.05aA	1.69 ± 0.02aA	1.68 ± 0.03aA	1.66 ± 0.07aA
	RF	1.71 ± 0.04aA	1.72 ± 0.03aA	1.73 ± 0.03aA	1.72 ± 0.06aA	1.73 ± 0.05aA
Starch (%)	Control	74.8 ± 0.45aA	74.8 ± 0.35aA	74.4 ± 0.31aA	74.8 ± 0.20aA	74.4 ± 0.23aA
	RF	74.4 ± 0.12aA	74.4 ± 0.21aA	73.7 ± 0.78aA	74.4 ± 0.30aA	74.3 ± 0.32aA
Hardness (%)	Control	90.68 ± 1.74aA	88.22 ± 1.85aAB	85.21 ± 1.61aB	86.18 ± 1.67aB	84.32 ± 1.78aB
	RF	88.16 ± 1.78aA	85.69 ± 1.89aAB	83.08 ± 1.96aB	84.33 ± 1.64aAB	82.17 ± 2.06aB
Color						
L^*	Control	70.55 ± 4.68aA	71.76 ± 5.14aA	72.54 ± 4.96aA	74.98 ± 4.78aA	76.21 ± 4.75aA
	RF	71.56 ± 5.03aA	72.13 ± 4.86aA	73.24 ± 5.34aA	75.55 ± 5.07aA	76.65 ± 5.21aA
a^*	Control	(-1.32 ± 1.05)aA	(-1.32 ± 1.19)aA	(-1.12 ± 1.22)aA	(-1.05 ± 1.08)aA	(-0.95 ± 1.03)aA
	RF	(-1.23 ± 1.22)aA	(-1.22 ± 1.01)aA	(-1.07 ± 1.17)aA	(-0.98 ± 1.26)aA	(-0.92 ± 1.13)aA
b^*	Control	13.01 ± 2.87aA	13.54 ± 2.86aA	14.13 ± 3.05aA	14.57 ± 2.96aA	15.01 ± 3.05aA
	RF	13.74 ± 2.92aA	14.12 ± 3.02aA	14.55 ± 2.67aA	14.98 ± 2.75aA	15.44 ± 2.99aA

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

[a] 60 d at 35 °C to simulate 6 months storage at 25 °C.

4. Conclusions

The optimal heating rate of 5.8 °C/min with corresponding suitable electrode gap 11 cm was used to develop the RF treatment protocol. Compared with traditional hot air heating, RF treatment has the advantages of rapid and volumetric heating through bulk milled rice materials. RF heating uniformity was improved by 50 °C hot air surface heating, sample movement, a twice mixing, and holding 5 min at the hot air of 50 °C. To obtain 100% insect mortality and maintain the quality of milled rice samples, an RF treatment protocol was developed with using RF energy to heat the milled rice samples from 25 °C to 50 °C together with conveyor belt movement at 12.4 m/h, two mixings during the whole heating time of 5.4 min and then holding 5 min only with forced hot air 50 °C, followed by forced room air cooling in a single layer for 18 min. RF treatments had no negative effects on all the measured quality parameters. Therefore, RF treatment provides a practical, effective and environmentally friendly method for disinfesting milled rice while maintaining product quality. The future study is desirable to conduct the efficacy confirmation tests and scale up the treatment protocol for continuous industry applications.

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