COFFEE BEAN HEATING UNIFORMITY AND QUALITY AS INFLUENCED BY RADIO FREQUENCY TREATMENTS FOR POSTHARVEST DISINFESTATIONS

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ABSTRACT. *Developing effective and economically viable treatments that replace chemical phytosanitary and quarantine practices is urgently needed for the coffee bean industry to maintain competitiveness in domestic and international markets. The objective of this study was to determine coffee bean heating uniformity and quality as influenced by radio frequency (RF) treatments for postharvest disinfestations. A pilot-scale, 27 MHz, 6 kW RF unit was used to study RF heating uniformity, develop a treatment protocol, and evaluate quality attributes in treated coffee beans. After comparing three selected electrode gaps, an appropriate gap of 14 cm was obtained to raise the central temperature of 2.75 kg samples to 48°C using RF energy by 4.6 min, compared to more than 237 min for samples to reach only 45°C when using forced hot air at 48°C. RF heating uniformity in bean samples was improved by adding forced hot air and back and forth movements on the conveyor at 0.89 m min^{-1}. The final temperatures reached 50.4°C in the interior of the sample and 50.6°C on the sample surface, resulting in small uniformity index values of 0.023 to 0.060 for the interior temperature and 0.073 for surface temperature distributions. RF treatments combined with forced hot air at 48°C to hold the target temperature for 10 min followed by forced room air cooling through a 3 cm product layer provided good bean quality. No significant differences in weight loss, moisture content, and color were observed between RF treatments and unheated controls.*

Keywords. *Coffee bean, Heating uniformity, Quality, Quarantine, RF.*

Coffee is one of the most-consumed beverages in the world (Briandet et al., 1996). Kona coffee bean (*Coffea arabica*) is cultivated on the slopes of Hualalai and Mauna Loa in the North and South Kona Districts of the County of Hawaii (i.e., the Big Island). It is one of the most costly coffees in the world (Pukui and Elbert, 2003). Hawaii is a major producer of coffee beans in the U.S., with annual production of 3,600 metric tons in 2010 with a value of $25.7 million (USDA-NASS, 2011). However, a harmful beetle, the coffee berry borer (*Hypothenemus hampei*), has been found in several coffee farms in Kona. This insect is considered to be the world's most destructive coffee pest, resulting in yield reduction, quality degradation, and entire bean destruction (Pereira, 2010; Ribeiro et al., 2011). Since the beetle's life cycle is completed for several generations inside the bean, it is difficult to control this pest with pesticides or detect it with outside inspections. Although the beetle has been shown not to thrive in dry green bean or parchment (Trujillo, 1991; Jaramillo, 2010), observations have been made of live beetles in dry coffee beans after weeks of storage. Therefore, the Hawaii Department of Agriculture has established a quarantine regulation of the movement of coffee in any form to prevent introduction and spread of the pest within the state of Hawaii.

Postharvest phytosanitary and quarantine treatments are generally required to completely control insect pests before the products are moved through marketing channels to areas where the pests do not occur (Armstrong, 1994; Heather et al., 2008). Fumigation with a chemical such as methyl bromide (MeBr) has been effectively used for postharvest insect control (Carpenter et al., 2000). Nevertheless, most phytosanitary uses of MeBr were phased out in 2005 by the U.S. Environmental Protection Agency (EPA) according to the Federal Clean Air Act (Browner, 1999) and the Montreal Protocol (UNEP, 2006). Hence, development of a practical alternative to MeBr is required for control of insect pests in coffee beans without adverse impacts on coffee bean quality and environment.

Thermal treatments by hot air, hot water, or steam are extensively used as MeBr alternatives to control insect pests in agricultural commodities because heat disinfestation treatments are relatively easy to apply, leave no chemical residues, and may offer some fungicidal activity (Tsang et al., 2003; Lurie et al., 2004; USDA-APHIS-PPQ,

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2009; Gao et al., 2011). Research conducted in Guatemala showed that heat is an effective treatment for control of insects in coffee beans during sun drying and mechanical drying (Hernandez-Paz and Sanchez de Leon, 1972). In an on-going study (L. Gautz, personal communication, 2011), temperatures over 48°C for longer than 12 min resulted in 100% mortality of 20 adult beetles placed inside green beans. Hot air is most commonly employed to increase the temperature of the commodity above the thermal limits of insect survival and control the target insects. However, a common and major difficulty in using hot air heating is the slow rate of heat transfer in large volumes of coffee beans, resulting in long treatment time (Wang et al., 2001). Unfortunately, hot air heating can also cause deleterious effects on product nutrient levels, flavor, and/or shelf life (Evans et al., 1983; Armstrong, 1994).

There has been an increasing interest in developing advanced thermal treatments for postharvest insect control in coffee beans (Nelson, 1996; Tang et al., 2000). Radio frequency (RF) treatment is a promising method that offers rapid and volumetric heating through bulk bean materials. Many studies have been made for applying RF energy to kill various pests in many postharvest crops (Frings, 1952; Nelson and Payne, 1982; Nelson, 1996). Recently, RF treatments have been developed to control codling moth (Wang et al., 2001) and navel orangeworm (Wang et al., 2002, 2007a, 2007b; Mitcham et al., 2004; Gao et al., 2010) in in-shell walnuts and almonds. Available research results on RF heating for low-moisture products (Wang et al., 2010; Jiao et al., 2011a, 2011b) have shown its potential as an environmentally friendly pest-control method in coffee beans.

Heating uniformity in RF-treated samples is important to achieve effective treatments that ensure insect control and provide acceptable product quality (Wang et al., 2008a, 2008b; Tiwari et al., 2011). Many practical methods are used to improve the uniformity of RF heating in agricultural products (Birla et al., 2004; Wang et al., 2006; Tiwari et al., 2008; Sosa-Morales et al., 2009; Gao et al., 2010). For example, forced hot air, product movement, and mixing have been successfully applied to improve heating uniformity in RF-treated dry products both in laboratory and industrial-scale systems (Wang et al., 2005, 2007a, 2008a, 2008b; Jiao et al., 2011a, 2011b; Gao et al., 2011). These practical methods could be further evaluated to improve the RF heating uniformity when treating coffee beans.

The objectives of this study were to investigate heating rates and uniformity in coffee beans when subjected to forced hot air and RF heating, to study the RF heating uniformity in coffee beans using additional hot air heating and sample moving, to develop an effective cooling method after heating, and to evaluate the quality of RF-treated coffee beans.

MATERIALS AND METHODS

RF AND HOT AIR HEATING SYSTEMS

RF heating of coffee beans was carried out using a pilot-scale, 27 MHz, 6 kW RF system (COMBI 6-S, Strayfield International, Wokingham, U.K.) with a hot air system (5.6 kW) and a conveyor belt. The hot air system provided surface heating and maintained the sample temperature during holding when the RF power was turned off. Coffee bean samples in the container were moved back and forth at 0.89 m min^{-1} between a single pair of plate electrodes by the conveyor belt during hot air or RF heating so as to simulate continuous processing (fig. 1). The size of the top perforated electrode plate was 75 cm × 55 cm.

Coffee bean samples were put in a plastic container (25.5 cm × 15 cm × 10 cm) (fig. 2) and then placed on the conveyor belt on the bottom plate electrode. The perforated walls of the container were made of nylon screen with five threads per cm (9318T27, McMaster-Carr, Los Angeles, Cal.) and a hole width of 1.4 mm, allowing hot air or room air to heat or cool the samples. Since studies with several runs of 20 adult coffee berry borers per sample indicated that about 10 min at 48°C would achieve 100% insect mortality (L. Gautz, personal communication, 2011), a sample target temperature of 48°C was selected to develop the treatment protocol. The hot air system can provide forced hot air at 48°C and an air speed of 3.1 m s^{-1} in the RF cavity through an air distribution box under the bottom electrode (fig. 1).

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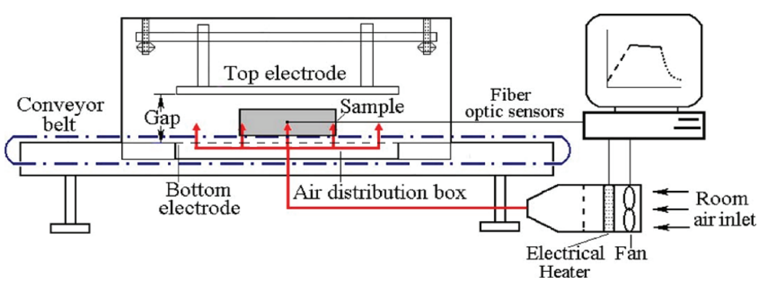

Figure 1. Schematic of experimental equipment showing the RF system, conveyor belt, and hot air system (Wang et al., 2010).

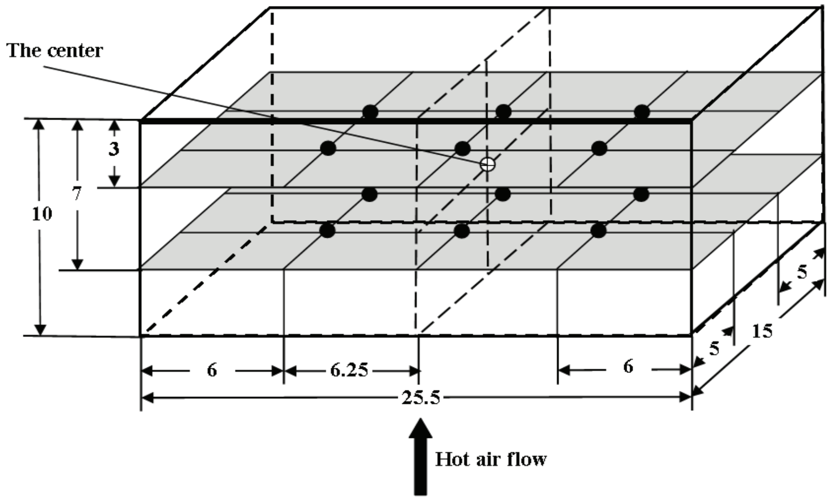

Figure 2. Plastic container and distribution of 12 locations (•) for sample temperature measurements (all dimensions are in cm).

ty through an air distribution box under the bottom electrode (fig. 1).

Materials and Electrode Gap Determination

Kona green coffee beans were obtained from a processing plant in Hawaii. The average original moisture content was about 12% wet basis (w.b.). The 100-seed weight of the tested coffee beans was 18.51 ±0.14 g. About 2.75 kg of coffee beans (10 cm depth in the container) were used as test samples. The sample container was placed on the stationary conveyor belt between the two electrodes to obtain a general relationship between different electrode gaps and the electric current. The range of the electrode gap was 11.0 to 16.0 cm with a 0.5 cm interval. After setting the electrode gap, RF power was turned on, and the electric current was immediately recorded. Based on the measured electric current, three electrode gaps (13, 14, and 15 cm) were selected as suitable for further temperature-time history experiments.

Under each of the three selected electrode gaps on a stationary conveyor belt, the time needed to heat the beans in the center of the container from ambient room air (25.0°C) to the target temperature of 48°C was determined. The center temperature of the samples was measured in real-time using FISO optic sensors (UMI, FISO Technologies, Inc., Saint-Foy, Quebec, Canada) with an accuracy of ±0.5°C during RF heating. The final gap was determined based on the target heating rate (4°C to 6°C min^{-1}) of samples with two replicates. The most suitable gap was then used in succeeding tests.

Determination of Cooling Methods

Rapid cooling is necessary after RF or hot air heating treatments to reduce high-temperature effects on coffee bean quality. Long cooling times for coffee beans may result in quality degradation and reduce throughput of industrial-scale treatments. Coffee bean samples with 10, 6, and 3 cm depths in the plastic treatment container were selected to develop suitable cooling methods. The cooling methods include natural room ambient air and forced room air. The forced-air cooling was obtained using a fan blowing on the sample surface to produce a cross airflow. The air speed at the sample surface was measured with a velometer (Alnor 6000 P Series, TSI, Inc., Shoreview, Minn.). The measured air speeds were about 0.2 and 3.7 m s^{-1} for natural and forced-air cooling, respectively. The center temperature of the sample was automatically measured and recorded with a measurement system (USB-1208LS, TracerDAQ Pro software, Measurement Computing Corp., Norton, Mass.) until the temperature dropped to 30°C. The best cooling method was selected according to the shortest cooling time and was then used to further develop the RF treatment protocol.

Heating Uniformity Tests

Heating uniformity is important for the development of effective RF treatments, since it may affect product quality and treatment efficacy, which are influenced by practical treatment conditions, such as with or without forced hot air or movement of the conveyor belt (Wang et al., 2005, 2010; Jiao et al., 2012). Good heating uniformity usually benefits product quality and ensures uniform insect mortality after RF treatments. Therefore, heating uniformity should first be determined. To examine the effect of forced hot air and product movement on RF heating uniformity, measurements were made under four conditions: RF heating only, RF heating with conveyor belt speeds of 0.89 m min^{-1}, RF heating with conveyor belt movement and forced hot air at 48°C, and RF heating with conveyor belt movement, hot air, and holding for 10 min. Full loads of coffee beans were heated in the RF cavity to compare the temperature distribution in the container. During each treatment, once the center of the container reached 48°C (as monitored by the FISO optic temperature measurement system), the container was immediately removed from the RF system. Thermal images were then taken of the upper surface of each sample with a digital infrared camera (SC-3000, FLIR Systems, Inc., North Billerica, Mass.) having an accuracy of ±2°C. The total measurement time was less than 10 s. As shown in figure 3, after RF treatment, 45,056 individual surface

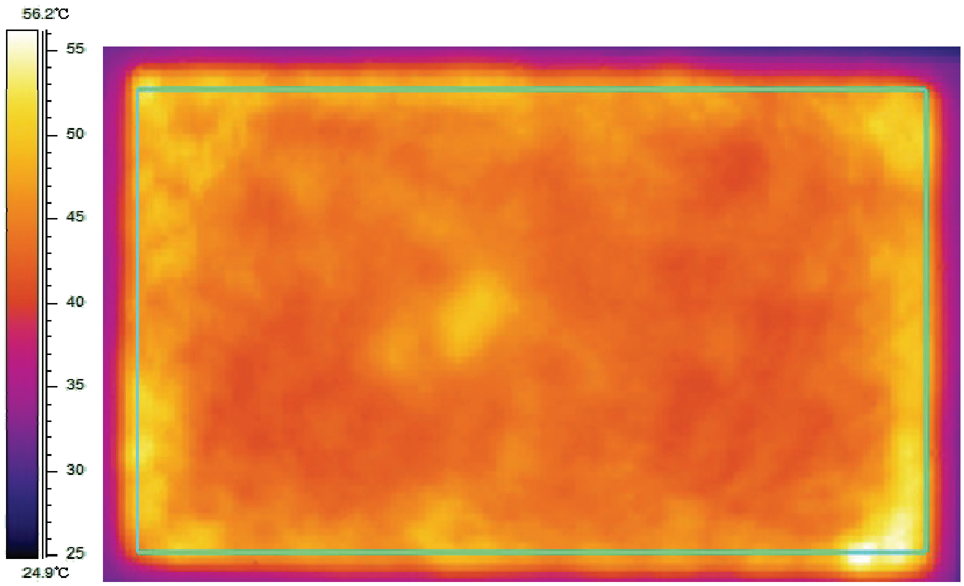

Figure 3. Surface temperature distribution (top view) of coffee beans obtained by infrared thermal imaging after RF treatment.

temperature data points were acquired and used to estimate the mean and standard deviation values of the temperature distribution.

After that, sample temperatures at 12 locations in the container (fig. 2) were measured using type-T thermocouples (91100-20, Cole-Parmer Instruments, Vernon Hills, Ill.) with an accuracy of ±0.5°C and 0.8 s response time. The 12 points were equally distributed over two sample levels with depths of 3 and 7 cm from the top. Every level had six points, with two points each at the right, middle, and left sides (fig. 2). Each test was repeated twice for each coffee bean sample. The mean and SD values of the surface and interior sample temperatures for each replicate were used for evaluating heating uniformity.

The heating uniformity index (λ), which has been successfully applied to quantitatively rank the RF heating uniformity of walnuts (Wang et al., 2005), legumes (Wang et al., 2010), and almonds (Gao et al., 2010), was also used in this study. It is defined as the ratio of the rise in standard deviation to the mean of product temperatures over the heating time, which can be calculated by the following equation (Wang et al., 2005, 2010):

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

where $\Delta\sigma$ and $\Delta\mu$ are the rise in the standard deviation and mean values, respectively, from the initial to final coffee bean temperatures (°C) over treatment time. The mean values for the temperature distributions under different treatments and at different depths were separated by the Tukey HSD test using PASW Statistics 18 (SPSS, Inc., Chicago, Ill.) at a significance level of 0.01.

Treatment Protocol Development

Lower temperatures with longer holding times or higher temperatures with shorter holding times both may be considered as potential RF treatments. However, a high-temperature, short-time treatment is usually recommended for the high throughputs needed for industrial applications. Experiments in a separate study showed that holding for 10 min at 48°C could result in 100% insect mortality of coffee berry borer at any life stage in coffee beans using hot air treatments (L. Gautz, personal communication, 2011). Based on these results, the previously determined electrode gap was used in the RF system together with conveyor belt movement at 0.89 m min^{-1} and additional hot air heating to heat 2.75 kg of coffee beans with 10 cm sample thickness and 0.654 g cm^{-3} density to 48°C. After the center temperature of the container reached 48°C, the RF power was turned off, and the coffee bean samples were held in hot air for 10 min. The depth of the RF-treated samples was reduced to the selected level, and the samples were subjected to the predetermined cooling method and time. Each treatment was replicated three times. Untreated samples were considered as controls.

Quality Assessment of Coffee Beans

The effect of hot air treatment on coffee bean quality was determined by heating the 2.75 kg samples in the same container as in the RF heating with forced hot air at 48°C, holding for 10 min when the center temperature of the container reached 48°C, and following the predetermined cooling method. The quality of coffee beans after the above RF treatment protocol was assessed immediately after treatment. Since roasting at 200°C for 8 min has little negative effects on the caffeine content of coffee beans (Farah et al., 2006), weight loss, moisture content, and color were the parameters selected to measure the treatment effect on product quality. Weight loss was estimated from the changes in sample weight before and after treatment. The moisture content was determined using ISO Standard 1447 (ISO, 1978). Approximately 5 g of whole green coffee beans were dried for 6 h ±15 min at 130.0°C ±2.0°C in a hot air oven (ADP-31, Yamato Scientific America, Inc., Santa Clara, Cal.). The sample was then removed from the oven and cooled to ambient temperatures in a closed desiccator with $CaSO_4$ before reweighing. The color of coffee beans was measured based on a computer vision system (CVS). A detailed description of the CVS can be found in Wang et al. (2010). For each treatment, color images of the surface of a 0.15 kg sample of coffee beans in an 11 cm (L) × 6 cm (W) × 1.5 cm (H) container were captured and stored in the computer. The color values of Hunter *L* (lightness, *L* = 0 and *L* = 100 indicate black and white, respectively), *a* (negative values indicate green, and positive values indicate magenta), and *b* (negative values indicate blue, and positive values indicate yellow) were obtained using Adobe Photoshop CS (Adobe Systems, Inc., San Jose, Cal.). Because of encoding between 0 and 255 in Photoshop, these values were converted algebraically to 0 to 100 for *L* values and to -127 to +128 for *a* and *b* values. Mean values and standard deviations for weight loss, moisture content, and color values were calculated from the three replicates. The mean values were separated by the Tukey HSD test using PASW Statistics 18 (SPSS, Inc., Chicago, Ill.) at a significance level of 0.01.

Results and Discussion

Determination of Electrode Gap and Heating Rate

The relationship between electrode gap and electric current is shown in figure 4 when one container full of coffee beans was subjected to stationary RF heating. For the eleven electrode gap settings tested (11.0 to 16.0 cm), the electric current decreased with increasing electrode gap. The electric current with gaps between 13 and 15 cm represented the best region to study the heating rate of RF treatments due to the relatively minor differences between the gaps.

The temperature-time histories of coffee bean samples in the center of the container during RF heating at the three selected electrode gaps of 13, 14, and 15 cm are shown in figure 5. The time required for the temperature to rise from 24.0°C to 48.0°C were 2.8, 4.6, and 8.1 min and the RF heating rates were 8.6°C, 5.2°C, and 3.0°C min^{-1} for electrode gaps of 13, 14, and 15 cm, respectively. Shorter RF heating time was obtained by using smaller electrode gaps, resulting in higher throughput but relatively poor heating uniformity due to high heating rates, as observed by Wang et al. (2008b). To obtain relatively high throughput with acceptable heating uniformity in industrial applications, an electrode gap of 14 cm (about 1 kW of RF power) and heating rate of 5.2°C min^{-1} were considered as operational parameters for further RF treatment protocol development.

Heating and Cooling Profiles

A comparison of the temperature-time histories of coffee beans in the center of a 10 cm thick sample using only hot air heating at 48°C and only RF heating is shown in figure 6. The center temperature of the coffee beans with forced hot air heating at 48°C required about 237 min to increase from 26°C to 45°C. This could have been caused by the poor heat conduction within the bulk low-moisture coffee bean samples, which is similar to the slow air heating observed with almonds, lentils, chickpea, and green peas (Gao et al., 2010; Wang et al., 2010). However, with RF treatment, only 4 min was required for the coffee bean center temperature to increase from 26°C to 48°C. Such a rapid heating rate with acceptable heating uniformity would give RF heating a distinct advantage as a practical disinfestation treatment for coffee beans as compared to conventional air heating.

Figure 7 shows the temperature-time histories in the sample center with three thicknesses of 10, 6, and 3 cm un-

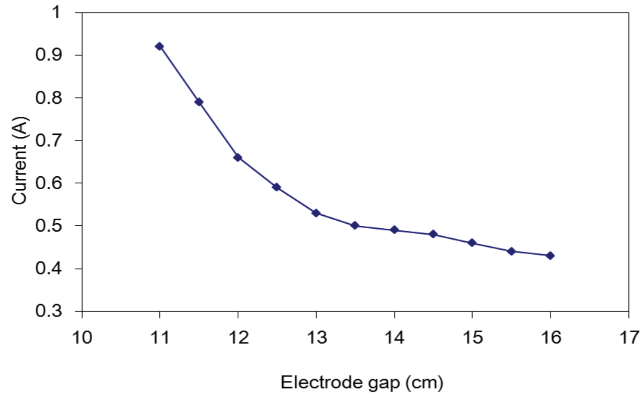

Figure 4. Relationship between electric current and electrode gap with a container filled with 2.75 kg coffee beans and stationary RF heating.

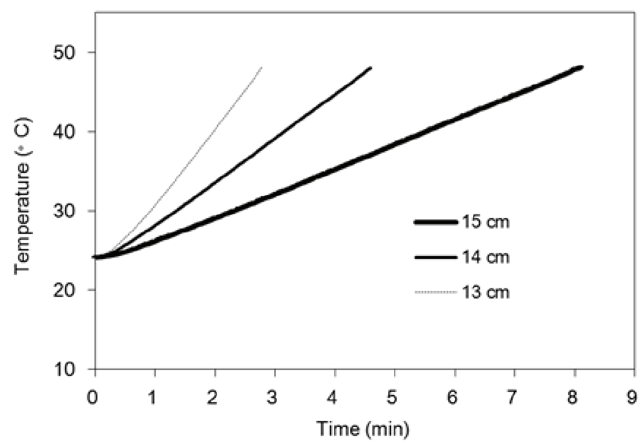

Figure 5. Temperature-time histories of RF-heated coffee beans in the center of a 10 cm thick sample with three selected electrode gaps.

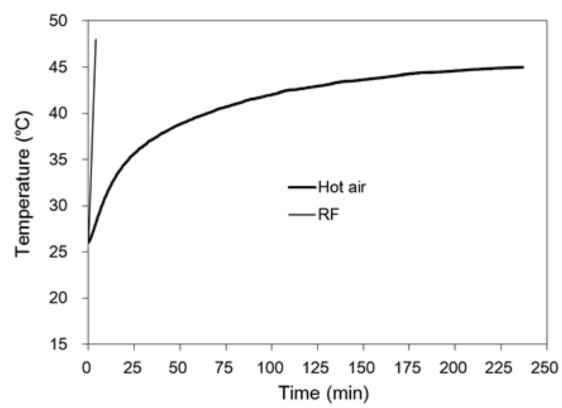

Figure 6. Typical temperature-time histories of coffee beans in the center of a 10 cm thick sample using hot air heating at 48°C compared with RF heating.

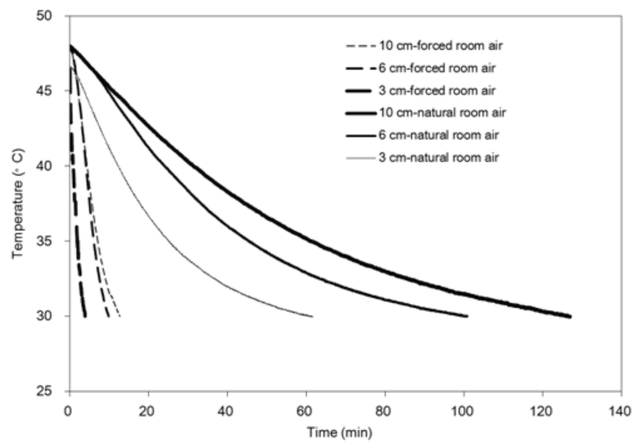

Figure 7. Cooling curves of coffee beans in the sample center as a function of sample thickness with natural and forced room air cooling.

der natural or forced room air cooling. Based on the cooling curves, the sample depth and cooling method greatly affected the cooling time. About 127, 100, and 61 min were needed for the 10, 6, and 3 cm depths, respectively, to cool the sample from 48°C to 30°C with natural room air at an air speed of 0.2 m s^{-1}. For a forced room air speed of 3.7 m s^{-1}, the corresponding cooling times were reduced to about 12, 10, and 4 min, respectively. The cooling time decreased with decreasing sample thickness and increasing air speed. Thus, forced room air cooling with a sample thickness of 3 cm was selected for the final RF treatment protocol.

Heating Uniformity in RF-Treated Coffee Beans

Table 1 provides a detailed comparison of the temperature distribution and uniformity index values for coffee beans at the sample surface and at depths of 3 and 7 cm from the surface after RF heating under different conditions. Heating uniformity is a key factor in developing successful postharvest quarantine treatments using RF energy. The uniformity index value allows uniformity to be objectively and quantitatively compared. Conveyor belt movement slightly improved heating uniformity over the RF-only treatment, especially for the surface and 3 cm deep measurements. Hot air heating increased the temperature at each depth, especially for the surface and around the container (fig. 3). Generally, movement and hot air improved RF heating uniformity due to the reduced standard deviation and heating uniformity index (table 1). The heating uniformity improvements are in good agreement with previous reports (Wang et al., 2005, 2007a, 2008a, 2010; Jiao et al., 2011a, 2011b). Mean temperatures after RF treatment with hot air and movement were higher than 49°C, resulting in conservative insect mortality in coffee beans, as required by the preliminary results. After holding for 10 min, the mean temperatures at different depths in the container were reduced slightly, but the heating uniformity was further improved due to reduced standard deviations. These were probably caused by the temperature drops at hot spots under the forced hot air heating that were greater than the temperature rises at cold spots during the holding time. Therefore, the optimal RF treatment protocol could be developed with hot air heating and movement.

Quality of RF-Treated Coffee Beans

Table 2 shows a quality comparison between the hot air and RF treatments. Weight loss was observed after both hot air and RF treatments, but it was greater with hot air treated coffee beans. Hot air heating resulted in conspicuous weight loss of about 2.17% ($p < 0.01$) and significantly lower moisture content compared to the RF treatments. RF treatment with movement, hot air, and holding for 10 min at 48°C resulted in 0.75% reduction in weight compared with the original coffee beans and did not significantly affect the moisture content ($p > 0.01$). The color results show that the *L*, *a*, and *b* values of coffee beans changed slightly after hot air and RF treatments. The *L* values increased after RF and hot air treatment as compared to the original coffee beans. There was no significant change in *a* values after hot air treatment and *b* values after RF treatment ($p > 0.01$). However, *b* values changed greatly with the hot air treatment compared to the original coffee beans. Based on these results, RF treatments could effectively disinfest postharvest coffee beans while maintaining good product quality.

Table 1. Comparisons of temperature and heating uniformity index of the coffee beans after RF heating with different treatments.[a]

	Location	RF Heating Only	RF with Movement	RF with Movement + Hot Air Heating	RF with Movement + Hot Air Heating + Holding (10 min)
Temperature (°C)	Surface	43.2 ±2.4 abA	44.6 ±2.0 bA	50.6 ±1.9 cABC	47.0 ±0.7 bdA
	3 cm depth	48.1 ±1.0 aB	49.2 ±1.3 abB	49.4 ±0.5 bB	47.6 ±0.5 cA
	7 cm depth	49.1 ±2.2 abcB	50.0 ±2.1 bB	51.5 ±1.4 bC	49.3 ±1.1 cB
Heating uniformity index (λ)	Surface	0.109 ±0.006 aA	0.105 ±0.006 aA	0.073 ±0.001 bA	0.030 ±0.003 cA
	3 cm depth	0.053 ±0.013 aB	0.044 ±0.011 aB	0.023 ±0.009 aB	0.024 ±0.007 aA
	7 cm depth	0.090 ±0.016 aB	0.092 ±0.008 aA	0.060 ±0.007 abA	0.038 ±0.008 bA

[a] Values are means ±SD of two replicates. Means followed by different lowercase and uppercase letters are significantly different among treatments and layers, respectively (Tukey HSD at p = 0.01).

Table 2. Quality comparison between hot air and RF heating with hot air, movement, and holding for 10 min followed by cooling.[a]

Treatment	Weight Loss (%)	Moisture (%, w.b.)	*L*	*a*	*b*
Control	-	11.89 ±0.10 a	127.74 ±3.38 a	122.66 ±1.10 a	161.74 ±2.30 a
Hot air	4.23 ±1.18 a	9.13 ±1.84 b	132.82 ±2.08 b	122.02 ±0.38 ab	165.10 ±0.35 b
RF	2.16 ±0.93 b	11.13 ±0.10 a	130.62 ±1.82 ab	121.51 ±0.09 b	160.76 ±0.32 a

[a] Values are means ±SD of two replicates. Means followed by different letters are significantly different among treatments (Tukey HSD at p = 0.01).

Conclusions

A heating rate of 4°C to 6°C min^{-1} was obtained in coffee beans by adjusting the electrode gap in RF treatments. Due to fast, volumetric heating, RF heating uniformity was marginally acceptable by using 48°C forced hot air together with conveyor movement. An RF treatment protocol was developed with RF heating to 48°C at an electrode gap of 14 cm, holding for 10 min at 48°C hot air and conveyor belt movement at 0.89 m min^{-1}, followed by forced room air cooling in a single 3 cm layer. After evaluating the coffee bean quality before and after RF treatment, little effect was observed on all the measured quality parameters. Hence, RF treatments should provide a practical, effective, and environmentally friendly method for disinfesting coffee beans after harvest without affecting product quality. The next steps will confirm the efficacy of large-scale RF treatments.

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