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Industrial-scale Radio Frequency Treatments for Insect Control in In-shell Walnuts

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Abstract. *Prior to the 2005 ban, in-shell walnuts were routinely fumigated with methyl bromide for insect control before export. Several pilot scale radio frequency (RF) studies have been reported as a new technology to completely control the most heat resistant insect, navel orangeworms, in in-shell walnuts without significant quality degradation. It is important to transfer pilot-scale or laboratory research results to large-scale industrial implementations. Heating uniformity is one of the most important considerations in scaling up of the established treatment protocol for walnuts. Temperature variations after RF heating may result from the different properties of walnuts and non-uniform electromagnetic field. It is desirable to determine the heating uniformity for a given RF unit and minimize the effect of walnut orientations and positions by stirring the walnuts during RF treatment. The required heating uniformity was achieved with one intermittent mixing at the electrode gap of 280 mm under the hot air temperature around 60°C for a continuous RF process. The average kernel and surface temperatures were around 55°C and 60°C after RF treatments, respectively. The efficacy treatments were conducted using a 25 kW, 27 MHz RF system at a conveyor belt speed of 57m/h. The results based on three replicates showed that 100% mortality of fifth-instar navel orangeworms was achieved with an acceptable walnut quality according to the industrial standard of peroxide, fatty acid and colour values. If this method could be economically integrated into the handling process, it would be an effective alternative to methyl bromide fumigation for disinfesting walnuts.*

Keywords. Heat, Navel orangeworm, Quality, Quarantine, Radio frequency, Walnut

Introduction

The use of methyl bromide (MeBr) has been declining since 1999 and its production for most applications was banned in January, 2005 by the U.S. Environmental Protection Agency in compliance with the Montreal Protocol (USEPA, 1998; Tang et al., 2000). Such restrictions on the use of MeBr fumigation have forced the multi-billion dollar U.S. nut industries to seek alternatives for control of postharvest insect pests. Because the future of alternative chemical fumigants is uncertain and public concern over residues in treated products is increasing, non-chemical control methods are of particular interest. Several laboratory-scale studies have described radio frequency (RF) as a new means to rapidly heat walnuts (*Juglans regia* L.) to control postharvest insects without significant quality degradation (Wang et al., 2001a; Wang et al., 2002c; Mitcham et al., 2004). However, it is important to transfer laboratory research results to industrial-scale applications.

RF energy has long been used to kill targeted insects by heating them beyond their thermal limits (Headlee and Burdette, 1929; Frings, 1952; Nelson, 1996). The RF frequencies 13.56, 27.12 and 40.68 MHz are allocated by the U.S. Federal Communications Commission (FCC) for industrial, scientific and medical applications, and are most often used for insect control. Most early work on RF insect control has focused on stored grain pests in small laboratory RF units (Nelson and Payne, 1982). Although many of these studies showed that RF could provide efficacious insect control, the method was not cost effective when compared to inexpensive chemical fumigations in use at that time (Nelson, 1996). Recently, Wang et al. (2001a; 2002c) have developed a successful laboratory-scale RF treatment to disinfest in-shell walnuts using a systematic approach based on the thermal death kinetics of the targeted insects (Johnson et al., 2004), dielectric properties of walnuts (Wang et al., 2003b), possible differential heating of insects in walnuts (Wang et al., 2003a) and the thermal responses of walnuts (Buranasompob et al., 2004). However, commercial processes based on RF energy have not yet been developed as a continuous treatment process to handle large quantities of walnuts during the relatively short harvest seasons.

Heating uniformity is one of the most important considerations in scaling-up the established treatment protocol for walnuts. Temperature variations after RF heating may result from variations in thermal properties and moisture contents of walnuts and a non-uniform electromagnetic field. The effect of walnut size, orientation, and location on RF heating uniformity may be reduced by mixing the nuts between treatments (Wang et al., 2005). The number of mixings needed can be determined by a simulation model for the required insect mortality level, and the lowest and final average temperatures (Wang et al., 2005). In the development of an optimal commercial treatment protocol, the heating uniformity for an industrial-scale RF unit must be determined to calculate the appropriate number of mixings between RF treatments needed to minimize the effect of walnut orientation and position.

Developing a successful thermal treatment relies on a thorough knowledge of the thermal death kinetics of the targeted insects. Several experimental methods are reported for characterizing the effect of thermal treatments on insect mortality (Yokoyama et al., 1991; Thomas and Shellie, 2000), of which direct hot water bath immersion is the most commonly used method (Hayes et al., 1984; Jang, 1986; Thomas and Mangan, 1997). The heating block system eliminates the effect of heat transfer on the intrinsic thermal death kinetics of insect pests and is able to generate highly repeatable results for any given set of conditions (Wang et al., 2002b), which are further confirmed by the infested samples (Wang et al., 2002c; Hansen et al., 2004). With this reliable test tool, the thermal death kinetics of the latest instars of codling moth, Indianmeal moth, navel orangeworm and red flour beetle were determined (Wang et al., 2002a;b; Johnson et al., 2003; 2004). The fifth-instar navel orangeworm is the most heat resistant life stage and species among these 4 insects at temperatures over 50°C. Consequently, efficacious treatments developed for fifth-instar navel orangeworm should control all other three pests in walnuts with considering the product temperature beyond 50°C.

The objectives of this research were: 1) to determine the heating uniformity in the industrial-scale RF system; 2) to conduct efficacy tests in in-shell walnuts for the commercial RF process; 3) to evaluate the walnut quality after RF treatment under different storage time.

Materials and Methods

Description of industrial-scale RF systems

The typical commercial process in walnut industry includes walnut harvesting from orchards, hulling, preliminary cleaning and infield drying, fumigation, sizing, washing/bleaching, static air drying, packaging and storing. The RF treatments can be implemented to replace the chemical fumigation after receiving and before washing/bleaching. A 25 kW, 27 MHz industrial-scale RF system (Model, S025/T, Strayfield International Limited, Wokingham, UK) (Fig. 1) was used for this study. The RF unit had two-pairs of identical electrodes (1.3 m L × 0.6 m W × 0.4 m H). Different heating rates were obtained by adjusting the gap between the electrodes from 260 mm to 400 mm. Adjustable conveyor belt speeds of from 4.8 to 57 m/h provided different product throughputs. The total treatment and heating times were calculated from the belt speed

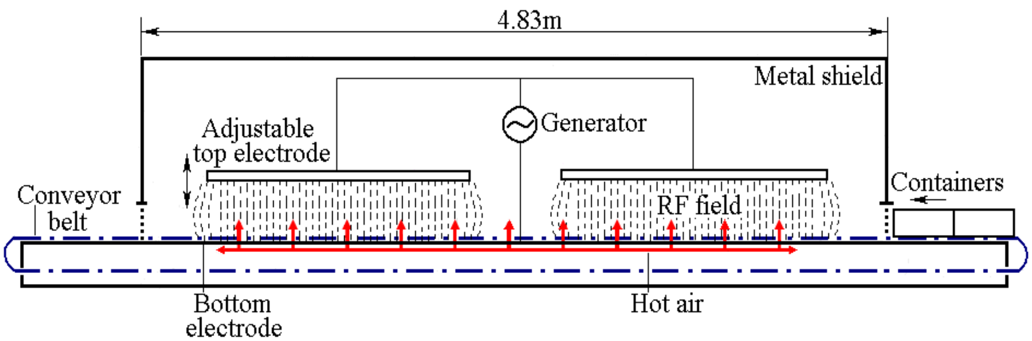

Fig. 1. Schematic view of the commercial 25 kW, 27.12 MHz radio frequency (RF) unit showing the two-pairs of identical plate electrodes and the conveyor system

and the lengths of the RF cavity and the two electrodes.

To heat the sample surface and remove additional moisture from treated product, the RF system was equipped with an auxiliary hot air heating system. Ambient air was forced through a 9 kW heater and, along with air used to cool the RF triode tube, was sent through a distribution pipe at the back side of the unit up through the conveyor belt (Fig. 1). Hot air was collected above the right electrode and exhausted through the top of the unit. The temperature of the hot air from the 9 kW heater was nearly constant, but hot air obtained from the cooling process gradually increased in temperature with the warm-up time and treatment periods.

RF heating uniformity tests

A critical step in developing effective commercial RF treatments is to determine the uniformity index (UI) of walnuts under different operation conditions. The UI is defined as the ratio of the increase in standard deviation to the increase of the mean product temperature during a RF heating process (Wang et al., 2005). The smaller the UI, the better the heating uniformity. The UI value is dependent upon the heated commodity and the design of the RF heating system. Tests were conducted before the walnut harvest season to determine the uniformity index for a single container (0.6 m × 0.4 m × 0.22 m) and a continuous process (seventeen containers) using stored walnuts from the previous season (11 kg per container). Walnut surface temperatures were measured with the thermal imaging camera (Thermal CAM^{TM} SC-3000, N. Billerica, MA, USA) before and after RF heating. The infrared camera was first calibrated with a thin Type-T thermocouple thermometer (Model 91100-20, Cole-Parmer Instrument Company, Vernon Hill, IL, USA) with an accuracy of ±0.2°C and 0.8 s response time, which estimated the emissivity of the walnut surface to be 0.92.

The uniformity index was determined for the following conditions: stationary (no belt movement); movement at the maximum conveyor belt speed of 57 m/h; with or without 60°C hot air heating; and mixing. Nuts were mixed with a single pass through a sample splitter (SP-1, Gilson Company, Inc., Lewis Centre, OH, USA). For all conditions, measurements were made during two replicated treatments. The uniformity index for stationary, moving nuts and hot air heating but without mixing was used to determine the final mixing number for further tests.

Insect mortality and quality evaluation

Before the tests, all the walnut samples were collected from trucks that brought walnuts from orchards. Plastic containers with perforated bottom and side walls were used to transport walnuts before and during RF treatments. Before the RF treatment, each container was evenly filled with 11 kg in-shell walnuts. The containers, with infested and un-infested walnuts, were then loaded on the conveyor belt of the RF system for treatment after the system went through an initial warming up time (2 hr). This preconditioning period was used to achieve a hot air temperature of at least 60°C inside the RF cavity. Operational parameters for RF treatments in the 25 kW RF system included: electrode gap, 280 mm; one-time mixing between two treatments; convey belt speed, 57 m/h; and hot air temperature, 60°C. The samples went through the system twice (to simulate treatments in two identical RF systems in series) with one time intermittent mixing. These test conditions were determined in the previous test for the system with a full load to bring sample temperature from 23-26°C to an average surface temperature of 60°C, and minimum kernel temperature of 52°C which are needed for 100% mortality of fifth-instar navel orangeworm (Wang et al., 2002b).

A total of 17 containers were used for a complete full load treatment process. Before containers entered the RF cavity (marked as the initial stage in Fig. 2a), the electrical current was around 0.41 A. With movement of the conveyor belt, the electrical current increased with increasing load until the current became stable. The end of the transient stage (Fig. 2b) corresponded to the moment when the first eight containers were under the two top electrodes. In order to avoid the boundary effect and simulate a steady state continuous RF treatment, we selected samples in containers #9 and #12 for efficacy and quality tests. Before the end of finish stage (Fig. 2c), the containers were filled in a continuous order to keep full load in the RF cavity. The RF was turned off when the container #12 came out of the electrode.

Before each run, about 2 kg of untreated walnuts were randomly collected for the initial quality evaluations. The surface temperatures for the two targeted containers, #9 and #12, were mapped by the thermal imaging camera. From each of these targeted containers, 10 in-shell walnuts were randomly selected to measure kernel temperature using the two thin Type-T thermocouple thermometers. Before the treatments, the 75 infested walnuts were randomly mixed with the un-infested walnuts in the container. The 17 containers were loaded on the conveyor belt moving at a speed of 57 m/h for the RF treatment. After the first time heating through the RF cavity, all the containers were transferred from the exit end to the starting end. To simulate the proposed mixing of nuts between two serial RF units, only the walnuts in containers #9 and #12 were mixed using the sample splitter and then placed back for the second time RF heating. The electrical current displayed on the control screen was recorded to

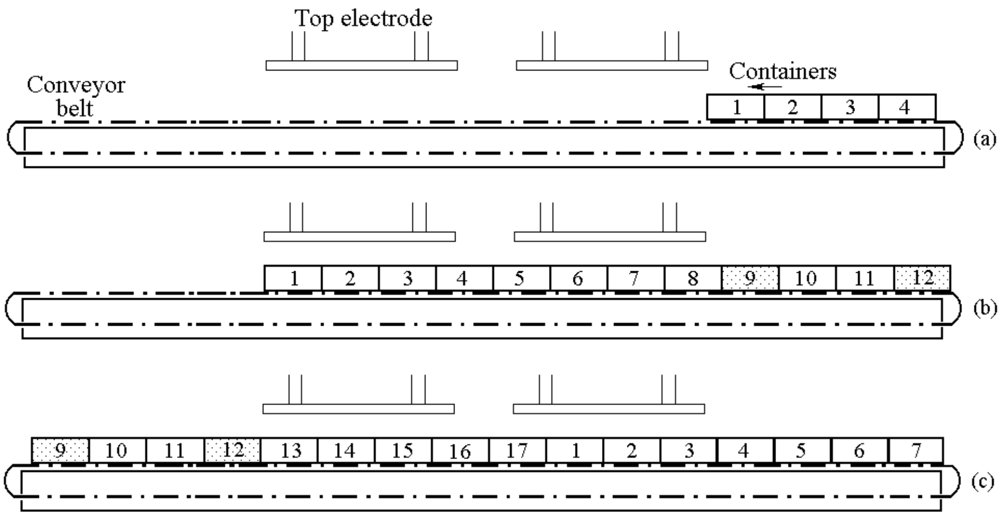

Fig. 2. Container arrangements during initial (a), transient (b) and finishing (c) stages of the commercial RF process in which containers 9 and 12 are targeted for efficacy and quality evaluations to avoid the boundary effect and simulate a steady state continuous RF treatment.

estimate the RF power. After RF heating, the surface temperatures for the two targeted containers #9 and #12 were immediately mapped by the thermal imaging camera. Then 10 in-shell walnuts were randomly selected from each of these containers to measure kernel temperature using the two thin thermocouple thermometers. This temperature measurement process took about 5 min, which was used as a holding time at the final temperatures. Finally, the infested walnuts were collected for efficacy studies and some un-infested walnuts were also collected from the same two containers for final moisture content measurements and quality analysis.

Fifth-instar navel orangeworms were reared at the USDA-ARS San Joaquin Valley Agricultural Sciences Center (SJVASC), Parlier, CA, packed in an insulated shipping carton, and brought to Diamond of California, Stockton, CA in the morning of the tested day. One insect larva was placed in each walnut through a 4 mm pre-drilled hole in the shell. Each hole was closed with a white polyethylene plug to prevent the insects from escaping the walnuts. Unwashed walnuts before fumigation and hot air-dried walnuts before packaging were used to develop two different treatment processes for industrial applications. Each replicate included 100 infested walnuts for unheated controls and 75 infested walnuts for each of the two targeted containers #9 and #12. Each replicate was conducted in a separate day with new insect colonies and consisted of two RF heating runs under the same test conditions. Before the treatments, the 75 infested walnuts in each targeted container were randomly mixed with the un-infested walnuts in the container using the sample splitter.

The efficacy tests with the unwashed walnuts were repeated three times. At the end of each treatment, the infested and control walnuts were taken back to USDA-ARS, Parlier, CA and held at 23°C, 60% RH with a 14:10 (L:D) h photo-period for one day before examination. The insect mortality could be a conservative estimation because some living larvae might not further develop to pupae. The shell of all infested walnuts was opened for examination. Insects were considered dead if no movement was observed. Mortality was calculated as the percentage of dead insects relative to the total treated insects for each treatment. Mean values and standard deviations were calculated from the replications for each run.

Walnuts before and after RF treatments were transferred directly to the Quality Assurance Laboratory at Diamond of California. Quality analyses were assed by evaluating the three most important quality indexes that are most likely to change at elevated temperatures, PV, FA and color. The effect of storage time on PV and FA changes were conducted using the accelerated shelf life tests. In those tests, in-shell walnuts were stored in an incubator at 35°C and 30% relative humidity (RH) for 10 and 20 d to simulate approximately 1 and 2 year storage periods at 4°C, respectively. The storage time at 35°C was calculated based on Q_{10} value of 3.4 for lipid oxidation (Taoukis et al., 1997) and which was further confirmed by real storage experiments (Wang et al., 2006). The PV and FA values were determined using methods Cd 8-53 and Ca 5a-40 of the American Oil Chemists Society (AOCS, 1998a&b). Detailed measurement procedures and calculation of PV and FA values were described in Wang et al. (2001a). The walnut kernel color was measured on Hunter scale by a colorimeter (Model CM-2002, Minolta Corp., Ramsey, NJ) calibrated to a standard white reflective plate. The change in kernel color was only analyzed for L –values that represent the light-dark spectrum with a range from 0 (black) to 100 (white). Though the color was not sensitive to the storage time, the measurements were conducted during the accelerated storage time at 35°C for 10 and 20 days.

Results and Discussion

Determination of the heating uniformity

Table 1 shows the uniformity index of stored walnuts after RF heating using different operational conditions. It is clear that movement on the conveyor belt and mixing improved RF heating uniformity as indicated by gradual reductions in λ values. Specifically, the heating uniformity was gradually improved from stationary condition to with movement, additional hot air heating and mixing. When 17 containers were treated in a continuous process, the heating uniformity index was similar to that in a single container under the same conditions.

Table 1. The heating uniformity index of stored in-shell walnuts after RF treatments under different operational conditions (data were from two replicates)

Treatments				Uniformity index, λ
Container No.	Moving	One-time mixing	Hot air	
1	No	No	No	0.103±0.017
1	Yes	No	No	0.087±0.005
1	Yes	No	Yes	0.083±0.012
1	Yes	Yes	Yes	0.061±0.012
17	Yes	Yes	Yes	0.062±0.012

Insect mortality

Table 2 shows the insect mortality and temperatures in in-shell walnuts after RF treatments along with insect mortality in controls that did not go through RF treatments. The low mortality of the control (≤1%) indicated that the effects of shipping and handling were negligible and the mortality data for samples after RF treatments required no correction. All the RF treatments resulted in 100% morality. The complete insect mortality resulted when the final average shell and kernel temperatures reached ≥55°C after the RF treatment. The shell temperatures were 2-8°C higher than the kernel temperatures, because the higher moisture contents in the shell. The efficacy results agreed with the thermal death time (TDT) curves of fifth-instar navel orangeworm obtained by the heating block system (Wang et al., 2002b). The

Table 2. Mortality (Mean ± SD, %) of fifth-instar navel orangeworm and final temperatures in control and treated walnuts using a commercial RF system

Treatments	Kernel temperatures (°C)		Surface temperatures (°C)		Mortality (%)	
	Control	RF treated	Control	RF treated	Control	RF treated
Rep 1	26.0±0.7	58.6±3.8	27.8±1.7	63.8±2.9	0	100
Rep 2	23.7±0.3	57.9±1.9	22.7±0.3	62.6±3.2	1.1	100
Rep 3	24.3±0.4	56.0±2.4	23.9*	59.2*	0	100

*Only mean surface temperatures were obtained.

TDT curve showed that holding 5 min at 52°C or 1 min at 54°C should result in 100% mortality (Fig. 3). The complete kill of the pests in this study was observed when the final product temperature was located at the right upper side of TDT curve, which was in good agreement with the small-scale infested studies on walnuts (Wang et al., 2001a; 2002c). That is, 100% mortality was achieved as long as the mean and standard deviations bars of the final walnut kernel temperatures did not cross the TDT curve. Generally, the higher temperature variations needed higher target mean temperature to achieve the complete kill. The final efficacy treatments developed for navel orangeworm using RF energy also would control codling moth, Indianmeal moth and red flour beetle in in-shell walnuts.

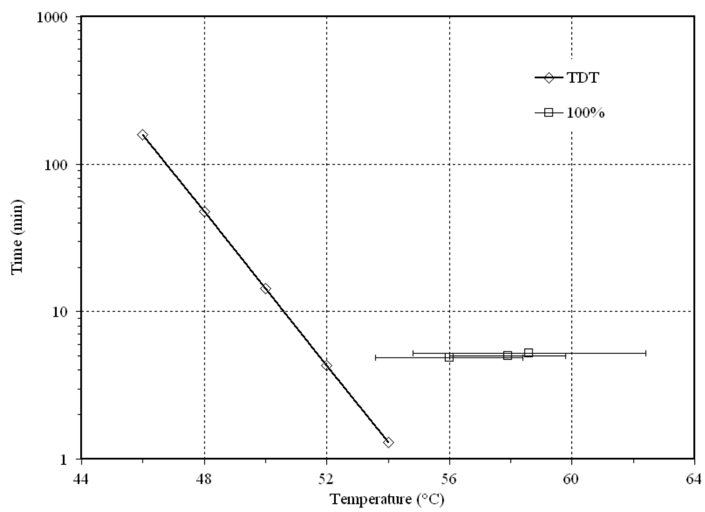

Fig. 3. Final walnut kernel temperature variations after three commercial RF treatments corresponding to 100% kill of fifth-instar navel orangeworm as related to the thermal death time (TDT) curve obtained from a previous study

Walnut quality

Table 3 summarizes the mean values and standard deviations of the PV, FA and color values of the control and the RF treated walnut samples that resulted in 100% kill. The mean PV values increased with the storage time for control and RF treated walnuts but FA values did not have the clear trend in terms of storage time. There was no statistically significant difference in PV and FA values between control and RF treated samples except for the PV values of dried walnuts stored at 35°C for 10 days ($P<0.05$). The final PV and FA values during accelerated storage of up to 20 days remained below the threshold values (PV<1.0 meq/kg and FA<0.6%) indicating good walnut quality. Hydrolytic rancidity increased slightly after storage, as indicated by increased FA values from 0 to 20 d at 35°C. The chemical quality evaluations confirmed earlier results in which RF heating did not increase rancidity after 10- and 20-day storage when the final walnut temperatures were raised to 53°C for 5 min (Wang et al., 2001a), 55°C for 10 min (Wang et al., 2002c), and 75°C for 5 min (Mitcham et al., 2004).

Table 3. Storage quality characteristics of in-shell walnuts treated with a commercial RF system

Storage time at 35°C (days)[z]	Peroxide value[y] (meq/kg)		Fatty acid[y] (%)		Kernel color (L value)[x]	
	Control	RF treated	Control	RF treated	Control	RF treated
0	0.04± 0.03a[w]	0.18± 0.29a	0.15± 0.07	0.19± 0.06	--	--
10	0.32± 0.21a	0.21± 0.03a	0.23± 0.07	0.24± 0.04	47.46± 1.04	46.55± 1.29
20	0.71± 0.41a	0.86± 0.26a	0.20± 0.02	0.20± 0.05	46.80± 0.97	45.76± 1.00

[z]10 and 20 days at 35°C simulate 1 and 2 years storage at 4°C
[y]Accepted peroxide value and fatty acid values for good quality are less than 1.0 meq/kg and 0.6%, respectively
[x]L value (lightness): 0 = black and 100 = white; good quality ≥40
[w]Different letters for peroxide values indicate that means are significantly different ($P<0.05$) between the control and RF treated walnuts.

The higher the L-values the lighter the product being tested. The kernel color became slightly darker after RF treatments and with increasing storage time, because the L-values were reduced a little (Table 3). However, the kernel color resulted in no statistically significant difference between untreated controls and RF treated walnuts for different storage times ($P>0.05$). The final color of the treated walnuts would still be acceptable for the walnut industry if the L-values were greater than 40.

Conclusions

The RF process is a technically feasible alternative to MeBr fumigation against insects in walnuts. The demonstrated ability of the method to control the most heat tolerant insect, navel orangeworms, yet not affect the quality of heat sensitive walnuts shows its potential as an environment-friendly pest control method for other low moisture commodities.

Acknowledgments

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