

# Industrial-scale radio frequency treatments for insect control in walnuts I: Heating uniformity and energy efficiency

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## Abstract

Conducting industrial-scale confirmatory treatments is the final step in developing commercially and environmentally sound insect control technologies for in-shell walnuts using radio frequency (RF) energy as an alternative to chemical fumigation. Improving heating uniformity of in-shell walnuts in the industrial process is essential to ensure insect control without quality degradation. An industrial-scale 27 MHz, 25 kW RF system was used to determine the heating uniformity of in-shell walnuts. Non-uniform vertical temperature distributions were measured in the RF unit, indicating that mixing and circulated hot air were needed to obtain the required treatment uniformity. Using a uniformity index derived experimentally for the RF unit, we showed that a single mixing of the walnuts was required to optimize heating uniformity. The predicted standard deviation of walnut surface temperatures was verified experimentally. The average energy efficiency of two RF units in series was estimated to be 79.5% when heating walnuts at 1561.7 kg/h. This study provided the basis for subsequent evaluations of treatment efficacy and product quality needed in developing an industrial-scale RF process to control insect pests in walnuts.

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## 1. 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). Currently, use of MeBr is restricted to quarantine applications, requiring industries to apply for yearly critical use exemptions for phytosanitary postharvest treatments. Such restrictions on the use of MeBr fumigation have forced the multi-billion dollar nut industries in the USA and other developed countries to seek alternatives for control of postharvest insect pests. Because the future of alternative chemical fumigants such as phosphine and sulfuryl fluoride is uncertain (USEPA, 1998; Fields and White, 2002) and public concern over pesticide residues in consumer products is high (Govindasamy et al., 1997), 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, 2002; Mitcham et al., 2004). However, it is important to transfer laboratory research results to industrial-scale applications.

RF energy has long been used in studies to kill insect pests 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 can be used for industrial postharvest insect control. Most early research on RF insect control has focused on stored grain pests in small laboratory RF units (Nelson and Whitney, 1960). 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, 2002) developed a successful laboratory-scale RF treatment to disinfest in-shell walnuts using a systematic approach based on the thermal death kinetics of the

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targeted insects (Johnson et al., 2004), dielectric properties of walnuts (Wang et al., 2003b), differential heating of insects in walnuts (Wang et al., 2003a) and the thermal responses of walnuts (Buranasompob et al., 2003). RF treatments provide a major advantage over hot air heating for in-shell walnuts, because of significant thermal resistance in the porous walnut shell and the in-shell void that hinder the transfer of thermal energy from external hot air to the walnut kernel. Our earlier results have shown that it would take more than 40 min to raise in-shell kernel temperature to within 5 °C of the final set temperature when heated from 20 to 53 °C by air, whereas only 4 min are required with RF energy for the same temperature rise (Wang et al., 2001a). However, those previous studies were conducted with laboratory systems in a batch mode, and commercial treatments based on RF energy need to be studied as continuous processes 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 a thorough mixing of the nuts between RF exposures (Wang et al., 2005). The number of mixings needed can be calculated from the required insect mortality level, and from the minimum and average final product temperatures selected for the proposed treatment (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 needed between RF exposures to minimize the effect of walnut orientation and position.

The objectives of this study were: (1) to determine the heating uniformity in the industrial-scale RF system; (2) to determine the number of mixings needed for industrial-scale RF treat-

ments to meet the required insect control for in-shell walnuts; (3) to determine the treatment parameters in developing commercial postharvest insect treatments; (4) to estimate the heating efficiency and throughput of the continuous RF process.

## 2. Materials and methods

### 2.1. Description of industrial-scale RF systems

A 25 kW, 27 MHz industrial-scale RF system (Model S025/T, Strayfield International Limited, Wokingham, UK) (Fig. 1) was used in 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 to 400 mm. Adjustable conveyor belt speeds from 4.8 to 57 m/h provided different product residence times and corresponding throughputs. The total treatment and heating times were calculated from the belt speed and the lengths of the RF cavity and the two electrodes.

The RF system was equipped with an auxiliary hot air system that helped to maintain walnut surface temperature. 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 and 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 cooling of the RF triode tube gradually increased in air temperature with the warm-up time and treatment periods.

The control screen of the RF system displayed the electrical current being used, but not RF power. A correlation between the output RF power and electrical current of the RF unit was derived experimentally with a water load and provided by the manufacturer (Fig. 2). The initial current when the RF cavity was empty varied from 0.34 to 0.44 A, depending upon the gap between the electrodes. The maximum current could reach 3.5 A

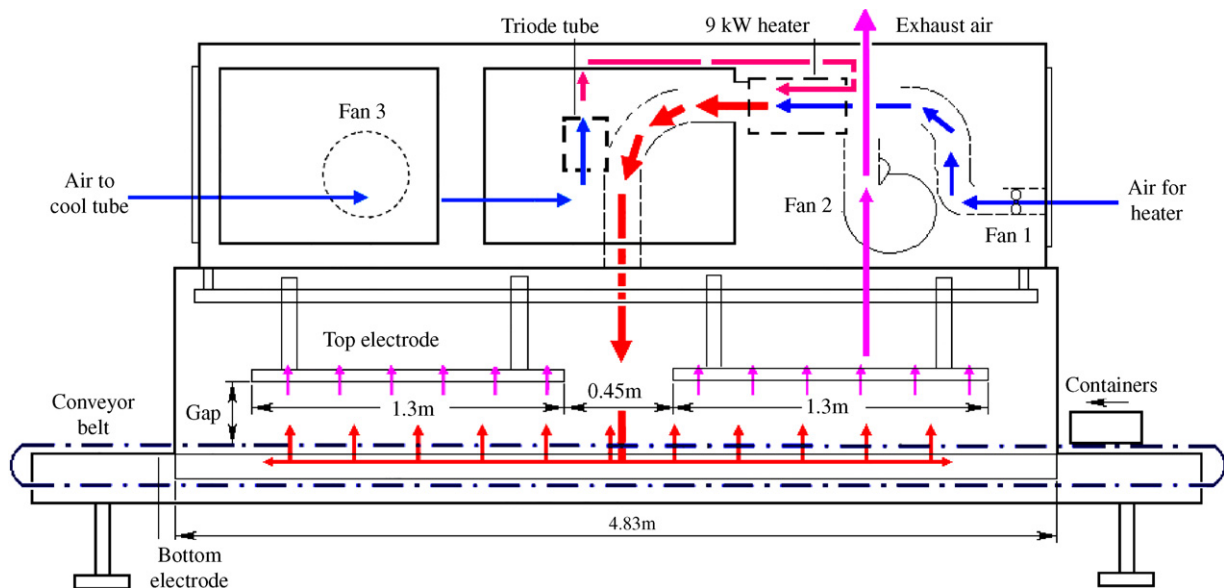


Fig. 1. Schematic view of the industrial-scale 25 kW, 27.12 MHz radio frequency (RF) unit showing the two pairs of plate electrodes and the hot air system.

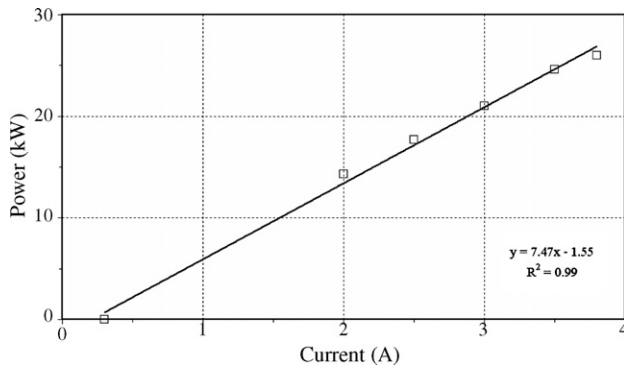


Fig. 2. Correlation between output power and electrical current of the RF unit.

with a maximum load of walnuts. Exceeding this current value either by overloading or by reducing the electrode gap would result in unstable heating, tripping an automatic cut-off of electric power to the RF unit and possibly causing a mismatch in frequency between the applicator and the generator.

### 2.2. Horizontal and vertical heating uniformity using polyurethane foam

Heating uniformity tests were first conducted in the RF unit using seven polyurethane foam sheets. The conveyor belt was set at maximum speed (57 m/h) to obtain the highest throughput possible, the electrode gap was set at 260 mm, and the hot air system was off. The sheets (0.91 m  $L \times$  0.60 m  $W \times$  0.03 m  $H$  each) were stacked on top of each other on the conveyor belt. The surface temperatures were measured with a digital infrared camera (Thermal CAM<sup>TM</sup> SC-3000, FLIR Systems, Inc., North Billerica, MA, USA) having an accuracy of  $\pm 2^\circ\text{C}$ . Immediately upon removal from the RF system, the thermal images were taken of the upper surface of each sheet, beginning with the top sheet working towards the bottom. The total measurement time for the seven sheets was about 30 s. From each of the thermal images, 45,056 individual surface temperature data points were collected from the final surface temperatures of the foam sheet and were used for statistical analyses (Wang et al., 2005). The test was repeated twice.

### 2.3. Determining the number of mixings

Because of the intrinsic field pattern imposed by the RF electrodes, non-uniform heating of the treated product occurred even on a moving conveyer belt. Vertical and lateral (back to front) uneven heating could only be reduced by stirring or mixing the product after each pass of the load through the system. A mathematical model based on normal distributions of product temperatures against probability density frequency was developed to predict the required number of mixings during RF treatments to ensure a desired degree of uniformity (Wang et al., 2005). The minimum number ( $n$ ) of mixings can be expressed as:

$$n = \frac{(\mu_T - \mu_0)^2 \lambda^2}{(L - \mu_T/z_p)^2 - \sigma_0^2} - 1 \quad (1)$$

where  $\mu_0$  and  $\sigma_0$  represent the mean and standard deviation ( $^\circ\text{C}$ ), respectively, of the initial product temperature;  $\mu_T$  and  $L$  the desired mean and minimum temperature ( $^\circ\text{C}$ ), respectively, for insect control;  $\lambda$  the uniformity index; normal score  $z_p$  is determined by probability  $p$  based on the desired level of insect mortality.

The uniformity index,  $\lambda$ , in Eq. (1) is a parameter unique to a specific RF unit and the treated product (in-shell walnuts in this study) in a fixed configuration. It is derived experimentally from product temperature measurements during treatment, using the following equation:

$$\lambda = \frac{\Delta\sigma}{\Delta\mu} \quad (2)$$

where  $\Delta\sigma$  is the rise in standard deviation of product temperature and  $\Delta\mu$  is the rise in mean product temperature over the treatment time.

Tests were conducted before the walnut harvest season to determine the uniformity index for a single high-density polyethylene container (0.6 m  $\times$  0.4 m  $\times$  0.22 m) with perforated bottom and sidewalls and a continuous process (17 containers) using stored walnuts from the previous season (11 kg per container). Surface temperatures of the top layer of walnuts in the container were measured with the Thermal CAM<sup>TM</sup> digital infrared camera before and after RF heating. The infrared camera was first calibrated against a thin Type-T thermocouple thermometer (Model 91100-20, Cole-Parmer Instrument Company, Vernon Hill, IL, USA) with an accuracy of  $\pm 0.2^\circ\text{C}$  and 0.8 s response time. Based on the calibration, we selected 0.92 for the emissivity of the walnut surface. Details on measurement procedure and the precision of this camera can be found for washed walnuts after RF heating (Wang et al., 2006).

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  $60^\circ\text{C}$  hot air; with or without water washing of nuts before treatment; with or without one mixing of the nuts between two RF exposures. Mixing was achieved by a single pass through a riffle-type sample splitter (SP-1, Gilson Company, Inc., Lewis Center, OH, USA), dividing the treated nuts into two representative samples which were then added back to the treatment container. Preliminary tests of the mixing process showed that nuts were redistributed evenly throughout the sample after mixing. To prepare washed walnuts, nuts were rinsed in commercial rotating drum washers for 2 min using tap water at ambient temperature. For all conditions, surface temperature measurements were made during three replicated treatments. The uniformity index for unwashed, moving nuts with added hot air but without mixing was used to determine the desired mixing number for further tests.

Once the minimum number of mixings was determined, the standard deviation for the final walnut surface temperature distributions was calculated as follows (Wang et al., 2005):

$$\sigma = \sqrt{\sigma_0^2 + \frac{(\mu_T - \mu_0)^2 \lambda^2}{(n + 1)}} \quad (3)$$

The predicted values obtained by Eq. (3) were validated using measurements made during tests using newly harvested, unwashed walnuts with the appropriate number of mixings. The tests were conducted with one container heated in the RF machine and with 17 containers to simulate a full-load continuous process. Detailed procedures for RF treatments and walnut surface temperature measurements on the selected containers in the full-load continuous process can be found elsewhere (Wang et al., 2007).

#### 2.4. Heating efficiency and throughput

The average heating efficiency for the industrial RF system was calculated over the whole series of full-load tests, during which 17 containers of product were passed through the RF unit on the conveyor belt, mixed, and then passed through the RF unit a second time. This process simulated the proposed commercial system, which would pass product through two RF units in series, mixing the nuts in between. The electrical current drawn by the RF unit was lowest at the beginning of each test when there were no containers between the electrodes. The current then increased as containers moved into the system and eventually stabilized after the first container reached the far edge of the second pair of electrodes. This stable current value was used to estimate the RF power input based on the relationship shown in Fig. 2.

Heating efficiency was estimated from temperature measurements taken in two selected containers in each treatment run. The selected containers were #9 and #12, both of which entered the system after the current was stabilized. Detailed information on container arrangement is provided in Wang et al. (2007). Tests were made on six different days, with two runs (A and B) each day for a total of 12 runs.

Temperatures of the walnut shell and kernel varied during RF treatments due to their differences in moisture content and thermal properties. The rise in walnut shell and kernel temperatures was assumed to be the result of RF heating plus surface heating by the added hot air. Heat loss from the nuts to the surrounding environment during the mixing was assumed to be negligible because of the short time (<1 min) and low heat conduction through the high air content within the walnut shell (Wang et al., 2001b).

The power input ( $P_{\text{input}}$  in W) was estimated by adding the displayed RF power [ $P(I)$  in W] estimated from Fig. 2 with the calculated convective heat energy from the hot air. The heating efficiency ( $\eta$ , %) was calculated as the ratio of the total energy absorbed by the walnuts ( $P_{\text{output}}$ , W) to the power input ( $P_{\text{input}}$ , W):

$$\eta = \frac{P_{\text{output}}}{P_{\text{input}}} \times 100 = \frac{m_k C_{p,k} (\Delta T_k / \Delta t) + m_s C_{p,s} (\Delta T_s / \Delta t)}{P(I) + Ah(T_a - \bar{T}_s)} \times 100 \quad (4)$$

where  $A$  is the walnut surface area ( $1.83 \text{ m}^2$ ) exposed to the hot air and equals the total RF chamber length (3.05 m) multiplied by the container width (0.6 m),  $C_{p,k}$  and  $C_{p,s}$  the specific heat of

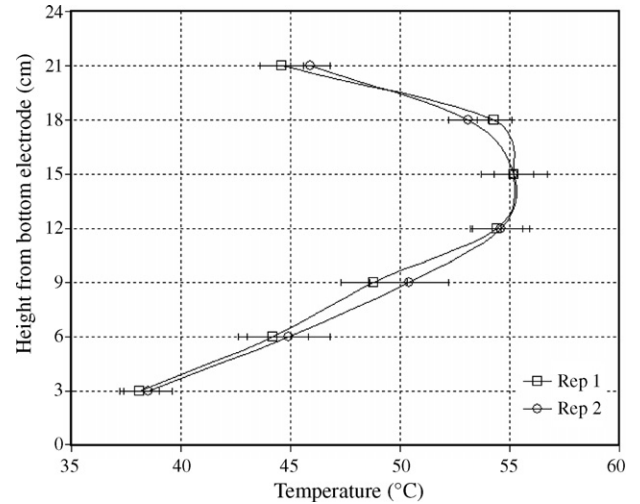


Fig. 3. The average and standard deviation values of surface temperature profiles as a function of height of polyurethane foam sheets after RF treatments (two replicates).

walnut kernel ( $2510 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$ ) and shell ( $1530 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$ ), respectively (Lavialle et al., 1997),  $h$  the convective heat coefficient which was estimated to be  $28 \text{ W m}^{-2} \text{ }^\circ\text{C}^{-1}$  for hot air over a plate (Ozisik, 1985),  $m_k$  and  $m_s$  the total mass of walnut kernel and shell, respectively, treated in a time period  $\Delta t$  (s),  $T_a$  the hot air temperature ( $^\circ\text{C}$ ),  $\bar{T}_s$  the average walnut surface temperature during the RF heating ( $^\circ\text{C}$ ) and  $\Delta T_k$  and  $\Delta T_s$  are the temperature increases in the walnut kernel and shell ( $^\circ\text{C}$ ).

The throughput of the treatment was estimated as:

$$M \text{ (kg/h)} = \nu Nm \quad (5)$$

where  $\nu$  (m/h) is the conveyor belt speed,  $N$  (#/m) the container numbers within a unit of length and  $m$  (kg) is the mass of walnuts per container.

### 3. Results and discussion

#### 3.1. Heating uniformity of polyurethane foam

Fig. 3 shows the measured average surface temperature of polyurethane foam sheets at different heights from the bottom electrode after passing through the 25 kW RF unit at 57 m/h. The surface temperature of the foam sheets was repeatable when the electrode gap and conveyor belt speed were maintained the same. The highest surface temperatures were found in the second, third and fourth layers from the top. Surface temperatures of the top and bottom three layers were lower than those of the middle probably because both top and bottom layers were exposed to ambient air. The surface temperature at the bottom layer was a little lower than that of the top layer, likely due to be increased heat loss from the bottom caused by close contact with the cooler bottom electrode plate. The horizontal surface temperature variations were small in each layer and the standard deviation ranged from 0.9 to 1.9  $^\circ\text{C}$ . These results suggested that the mixing process and added hot air were needed to improve the vertical heating uniformity.



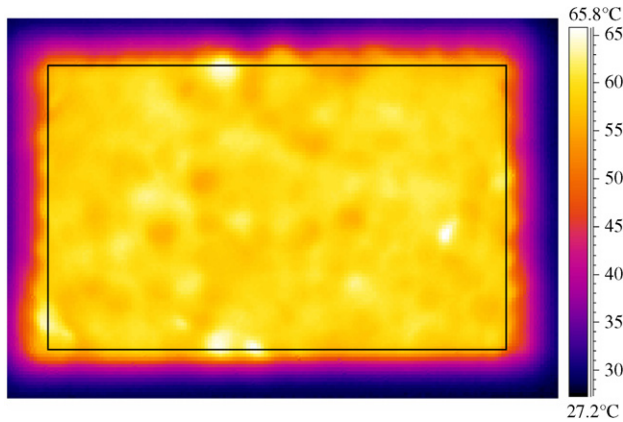


Fig. 4. Surface temperature (top view) distributions of in-shell walnuts obtained by infrared thermal imaging after full-load RF heating with one mixing. The boundary lines define the area in which temperature data were used for statistical analyses.

### 3.2. Determination of mixing number and validation of the uniformity prediction

Fig. 4 shows a typical walnut surface temperature distribution obtained by thermal imaging after RF treatments. The surface temperature data within the boundary field shown in the figure were used for statistical analyses. The mean values of the uniformity index  $\lambda$ , initial mean surface temperature  $\mu_0$ , and initial surface temperature standard deviation  $\sigma_0$  over three replicates for unmixed nuts on the moving conveyor belt and with added hot air were 0.087, 25.7 and 0.2 °C, respectively.

The normal score  $z_p$  for an insect mortality level of probit 9 ( $P=0.000032$ ), desired for quarantine security, is  $-4.0$  (Wang et al., 2005). Based on our earlier studies, the minimum exposure required to achieve probit 9 mortality for the most heat resistant pest in walnuts, fifth-instar navel orangeworm, *Amyelois transitella* (Walker) (Lepidoptera: Pyralidae), was 6 min at 52 °C (Wang et al., 2002). These studies also showed that after RF heating, walnut kernel temperature dropped only 1 °C after 5 min at ambient temperatures. Taking into account the observed post-treatment temperature variability and the slow cooling rate of the heated nuts, the mean and lowest surface temperatures for an effective treatment were selected to be 60 and 52 °C. After inputting these parameters, the minimum number of mixings was determined from Eq. (1) to be 1.2. Therefore, we decided to use one mixing between two RF exposures for further experiments to meet the requirements for insect control at the probit 9 level.

Table 1 shows the uniformity index (Eq. (2)) of stored walnuts after RF heating under different operational conditions. The smaller the uniformity index, the better the RF heating uniformity. It is clear that movement on the conveyor belt and a single mixing improved RF heating uniformity as indicated by gradual reductions in  $\lambda$  values. 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. Washed walnuts had the most non-uniform heating among these treatments even with movement, added hot air and mixing.

Table 1

The heating uniformity index of stored in-shell walnuts after RF treatments using different operational conditions

Treatments					Uniformity index ( $\lambda$ )
Walnuts	Container no.	Moving	Mixing	Hot air	
Unwashed	1	No	No	No	0.103 ± 0.017
Unwashed	1	Yes	No	No	0.087 ± 0.005
Unwashed	1	Yes	No	Yes	0.083 ± 0.012
Unwashed	1	Yes	Yes	Yes	0.061 ± 0.012
Unwashed	17	Yes	Yes	Yes	0.062 ± 0.012
Washed	1	Yes	Yes	Yes	0.143 ± 0.023

The large moisture variations in washed walnut shells might have caused severe uneven heating in those samples. Therefore, we chose not to consider using RF treatments for washed walnuts and focused on efficacy tests before washing or after drying.

A comparison was made between the experimentally derived standard deviation in walnut surface temperatures after RF treatment with one mixing and those predicted by Eq. (3) (Fig. 5). The agreement between the predicted and experimental values was acceptable ( $R^2=0.79$ ) for practical industrial applications, showing that industrial-scale RF treatments could meet the treatment design criteria of an average walnut surface temperature of 60 °C and a minimum surface temperature of 52 °C for 5 min exposure. The corresponding operational parameters for this 25 kW RF system were an electrode gap of 280 mm, one mixing between two exposures, hot air at 60 °C and a conveyor belt speed of 57 m/h.

### 3.3. RF heating efficiency and throughput

Fig. 6 shows a summary of the estimated heating efficiency for the continuous RF treatment with a full load, calculated over six treatment days and 12 complete runs. The RF energy efficiency ranged from 72 to 85% with an average value of 79.5%.

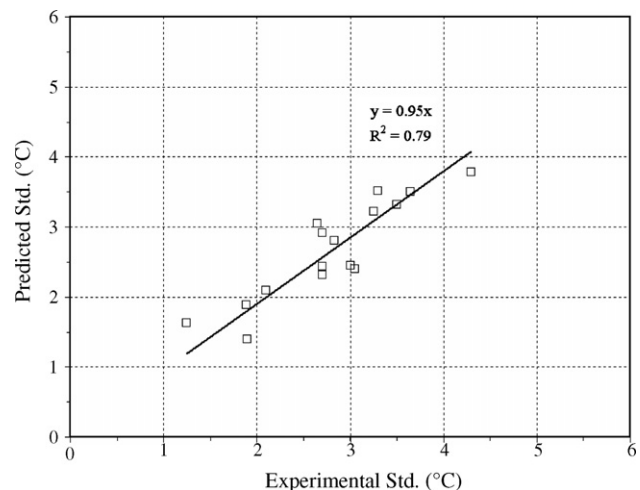


Fig. 5. Correlation between predicted and experimental standard deviations of the walnut surface temperatures after one mixing between two RF treatments.

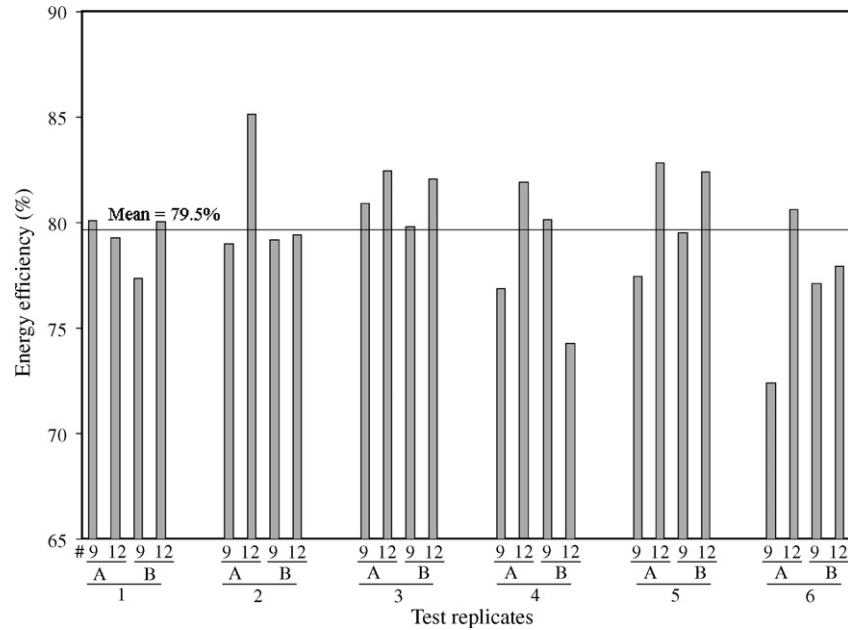


Fig. 6. The mean heating efficiency of the RF unit estimated for two containers (#9 and #12), and two passes (A and B) through the 25 kW RF unit for six full-load tests.

The variations in heating efficiency were probably caused by the different walnut moisture contents and different ambient conditions for different days. The heating efficiency in this study was higher than that (60%) found for laboratory-scale RF treatment (Wang et al., 2006).

The throughput of two 25 kW RF units in series at a belt speed of 57 m/h was 1561.7 kg/h for tests with a continuous product stream. The throughputs could be increased by using multiple 25 kW or larger systems arranged in series, with appropriate mixing in between to improve heating uniformity. But the overall operational parameters (product temperature and exposure) in this study can still be applied. The mean total energy for the RF power and hot air was estimated to be 19.2 kW inputted for the six full-load tests in each of two RF units at 1561.7 kg/h. After including the power (1.75 kW) for conveyor belt and fans, the overall unit electrical consumption for the processed walnuts was 0.0268 kWh/kg. Based on average retail electricity price in California of US\$ 0.1/kWh for industrial uses in 2005 (CEC, 2005), the total electrical cost was US\$ 4.19/h for two 25 kW RF units in series and the hot air heating system or US\$ 0.0027/kg for treating the walnuts. Using the 1995 cost for MeBr (US\$ 2.86/kg), Aegerter and Folwell (2001) estimated the unit cost of MeBr fumigation for walnuts to be from US\$ 0.00059/kg for large chambers (170 tonnes per fumigation) to US\$ 0.00079/kg for small chambers (34 tonnes per fumigation). When the 2005 cost of MeBr (US\$ 9.7/kg) was applied to the same estimates, this unit fumigation cost became US\$ 0.0020–0.0027/kg. The electrical cost of the RF treatments was comparable to that of MeBr fumigation for commercial in-shell walnut treatments. Since the capital, labor and depreciation costs depend upon the design, the capacity, the location, and year when they were built, a real cost comparison study is needed in the future for a complete economic analysis.

#### 4. Conclusions

Heating uniformity and energy efficiency studies are among the most essential engineering steps in developing industrial-scale RF treatments for postharvest insect control in walnuts. We found that heating uniformity was improved through the movement of product on the conveyor belt and by adding hot air. Uniformity was improved even further by a single mixing of the product between two RF exposures, resulting in a treatment schedule that has been shown to meet phytosanitary and product quality requirements for unwashed or dried nuts (Wang et al., 2007). Using the treatment schedule developed during this study for our 27 MHz, 25 kW industrial RF system, the average heating efficiency for two similar RF units in series was estimated to be 79.5% when treating walnuts at 1561.7 kg/h. Although there are significant capital costs for the initial installation of an RF system, energy costs per kg of treated product is comparable to the current cost of MeBr fumigation. The determined experimental conditions support further efficacy studies of disinfesting walnuts of target pests without affecting product quality.

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