INDUSTRIAL-SCALE RADIO FREQUENCY TREATMENTS FOR INSECT CONTROL IN LENTILS

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A 27.12 MHz, 6 kW radio frequency (RF) unit with a built-in hot air system was used to conduct industrial scale-up disinfestation treatments. An electrode gap of 14 cm and conveyor belt speed of 7.5 m/h was chosen. Results showed that heating uniformity was acceptable, and there was no significant product quality changes after continuous hot air assisted RF treatment. The average heating efficiency of the RF system was 76.5% and throughput was 208.7 kg/h. Measurements from the RF system provided sufficient data to develop an industrial-scale RF process.

Keywords: Radio frequency (RF), Heating uniformity, Quality, Efficiency, Throughput

INTRODUCTION

Lentil (*Lens culinaris*) is an important rotational legume in the north-western United States, especially Washington State (Wang et al., 2010). Disinfestation treatments for agricultural products are necessary to meet postharvest phytosanitary regulations before export to several markets such as India and Latin American countries (USADPLC, 2007). Since the conventional disinfestation method used the chemical fumigant methyl bromide was banned in developed countries in 2005 due to its damage to the ozone layer (Wang and Tang, 2004), an alternative non-chemical quarantine treatment is urgently required.

RF heating has been used to control different insects for various agricultural commodities (Nelson, 1996; Nelson and Payne, 1982; Tang et al., 2000). Wang et al. (2001, 2002) developed RF treatments for control of insects in in-shell walnuts, and scaled-up the treatment to an industrial conveyorized RF system for disinfesting in-shell walnuts with acceptable product quality (Wang et al., 2006a, 2007a, b). Recently, Wang et al. (2010) developed a RF disinfestation treatment protocol to control cowpea weevils in legumes with acceptable quality of legumes. Only 5-7 min were needed to get the central temperature of 3 kg legumes to 60°C from room temperature, and heating uniformity was improved by adding forced hot air and movement of samples. However, the previous study was conducted with small amount of samples in batch mode. To make this RF treatment available for industrial applications, continuous processes and scale-up tests need to be considered.

Heating uniformity is a key factor and main consideration in scaling-up the proposed RF treatment protocol (Wang et al., 2007a). Factors resulting in non-uniform heating during RF treatments include non-uniform electromagnetic field distribution and variations of product moisture content and thermal properties. There are many practical methods used to minimize the non-uniform RF heating, i.e. adding forced hot air to the product surface to reduce the energy change between the product surface and surrounding air, sample movement, rotation or mixing during RF treatment and immersing products into water (Birla et al., 2004, Wang et al., 2006b, 2007a., 2010). Product quality is also important for effective RF treatments in developing industrial-scale disinfestation technology.

The objectives of the current study were (1) to determine the RF processing parameters (electrode gap and conveyor belt speed), (2) to investigate the RF heating uniformity in lentils, (3) to evaluation the product quality after RF treatments; (4) to estimate the heating efficiency and throughput of RF treatment process.

MATERIALS AND METHODS

RF and hot air heating systems

A 27 MHz 6 kW RF unit (COMBI 6–S, Strayfield International, Wokingham, U.K.) combined with a customized auxiliary hot air system using a 5.6 kW electrical strip heater and a blower fan (Fig. 1) was used to heat the lentils. A conveyor belt system (TOSVERT-130 G2+, Toshiba International Corp., Houston, TX) build into the RF unit was used to move the samples at different speeds to simulate a continuous process. A detailed description of the RF system can be found in Wang et al. (2010). Plastic polypropylene containers (0.40 L × 0.23 W × 0.10 H m^3) with perforated side and bottom walls were used to allow hot air to pass through the lentils (George Brocke & Sons, Inc., Kendrick, ID, USA.)

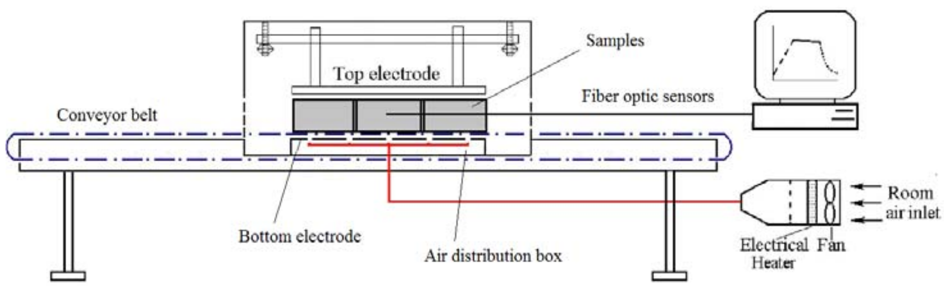

Fig. 1. Schematic view of the 6 kW, 27.12 MHz RF unit with hot air and temperature measurement systems (adapted from Wang et al., 2010)

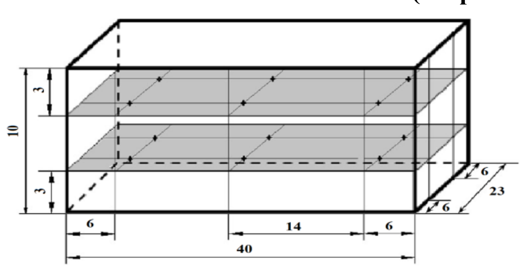

Fig. 2. Dimensions (cm) of the plastic container and the location of 12 thermocouples (+) used for temperature measurement

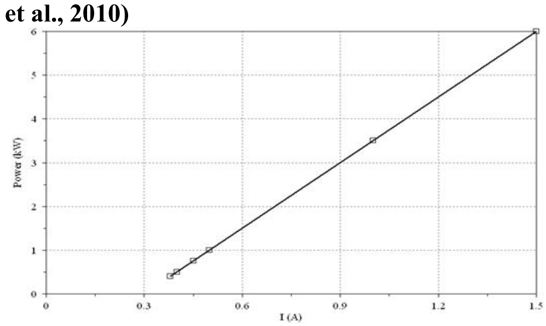

Fig. 3. The relationship between output power and electrical current of the current 6 kW RF unit

Determining electrode gap and speed of conveyor belt

The top electrode in the RF unit can be adjusted up and down to vary the electrical current and RF power (Fig. 3). Since the dimension of the top electrode was 69 L× 50 W cm^2, three plastic containers can be put together between the electrodes for RF heating. To develop a continuous RF treatment protocol, the electrode gap and speed of conveyor belt should be determined first. Three plastic containers filled with lentils (each with 6.4 kg) were placed on the conveyor belt between two electrodes to obtain a general relationship between electrode gaps and electric currents. The electrode gap range of 13.5–17.0 cm was considered. After setting the electrode gap at 17.0 cm, RF power was turned on and the electric current was immediately recorded. This procedure was repeated when the electrode gap was reduced to the next level until a gap of 13.5 cm was reached. Under stationary conditions, the sample temperature at the geometric center of the middle container was recorded by FISO optic sensor (UMI, FISO Technologies Inc., Saint-Foy, Quebec, Canada) during RF heating without forced hot air. The time needed for the center temperature of the middle container to reach 60°C from ambient temperature (22.3°C) was recorded. When the electrode gap and heating time are fixed, the speed of conveyor belt can be easily calculated by using electrode length divided by heating time.

Heating uniformity evaluation

To simulate continuous RF processing, eight containers filled with lentils were placed on the conveyor belt and passed between the RF electrodes. The electric current became unstable as the first container moved between the electrodes, but it would stabilize once the third container was completely between the electrodes, and became unstable again as the last three containers move out from between the electrodes. The electric current was recorded every 30 seconds while the eight containers pass between the electrodes. The fourth and fifth containers were subjected entirely to stable RF power conditions and used to evaluate product quality. Heating uniformity was obtained only from the temperature distribution of the fifth container. After RF treatment, the surface temperature of the fifth container was immediately measured by a digital infrared camera (Thermal CAMTM SC-3000, FLIR Systems, Inc., North Billerica, MA, USA), and the interior temperature at 12 positions (Fig. 2) was measured by using a Type-T thermocouple thermometer (Model 91100-20, Cole-Parmer Instrument Company, Vernon Hill, IL, USA). The treatment was replicated three times. The average and standard deviation (SD) values of the surface and interior sample temperatures were used to evaluate the RF heating uniformity.

Quality analysis

Moisture content, color and germination were selected as the parameters to evaluate lentil quality. All those quality parameters were measured before and after the RF treatment. Based on the treatment protocol required for insect control in lentils (Wang et al., 2010), the RF treated samples was held under 60°C forced hot air for another 10 min, and followed by natural forced air cooling for 20 min in a thin layer to minimize the influence of RF heating on the product quality.

The moisture contents of lentils were determined by the vacuum oven drying method. Lentils were first ground in coffee grinder, 2-3 g flour samples were placed in aluminum dishes and then dried in a vacuum oven (ADP-31, Yamato Scientific America Inc., Santa Clara, CA, USA) at 130°C and 75-85 kPa for 1 h (AOAC, 2002). Germination rate of lentil seeds was determined by immersing 60 lentil seeds in water first for one day at room temperature, then taking out and holding them on germination paper saturated with distilled water in Petri dishes for two days in the dark under ambient conditions. Each dish had 20 lentil seeds. Finally, geminated seeds were counted and the germination rates were calculated. The color of lentils was determined by a computer version system (CVS), a detailed description of the system and measurement procedures can be found elsewhere (Kong et al., 2007). About 200 g lentil seeds were placed on a 2 cm thick black plate at the bottom of a shooting tent. The images taken by the digital camera were analyzed by Adobe Photoshop software. The color values observed from Photoshop (L, a, b) were converted to CIE LAB (L*, a* and b*) values using the following formulas (Kong et al., 2007):

$$L^* = L/2.5 \quad (1)$$

$$a^* = 240a/255 - 120 \quad (2)$$

$$b^* = 240b/255 - 120 \quad (3)$$

Heating efficiency and throughput

The average heating efficiency for industrial RF system was calculated based on the continuous treatment process. The electric current would become stabilized as the fourth container moved into the RF system, this stable current was used to estimate the RF input power *P(I)* according to the relationship shown in Fig. 3. The RF heating efficiency (η, %) was calculated as the ratio of the total energy absorbed by the lentils (P_{output}, W) to the power input (P_{input}, W) (Wang et al., 2007a):

$$\eta = \frac{P_{output}}{P_{input}} \times 100\% = \frac{mC_p\left(\Delta T/\Delta t\right)}{P(I) + Ah(T_a - \overline{T_s})} \times 100\% \quad (4)$$

where m is the mass of lentils in kg treated in a time period Δt (s), C_p is the specific heat of lentils, C_p=1732 $J/kg°C$ at room temperature (Jiao et al., 2011), ΔT is the sample temperature changes, A is the surface area exposed to the hot air, h is the convective heat transfer coefficient, h=28 $W/m^2°C$ (Wang et al., 2007a), T_a is the hot air temperature (60°C), and $\overline{T_s}$ is the average surface temperature.

The throughput of the RF treatment (M, kg/h) was calculated by (Wang et al., 2007a):

$$M = vNm \quad (5)$$

where v is the conveyor belt speed in m/h, N (#/m) is the number of containers within a unit of length and m (kg) is the mass of lentils per container.

RESULTS AND DISCUSSION

Determination of electrode gap and conveyor belt speed

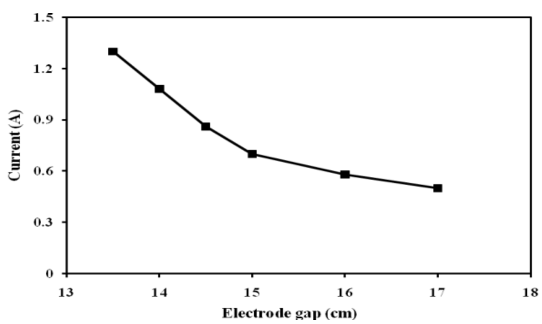

Fig. 4. The relationship between the electrical current and electrode gap with three containers filled with lentils without movement and forced hot air

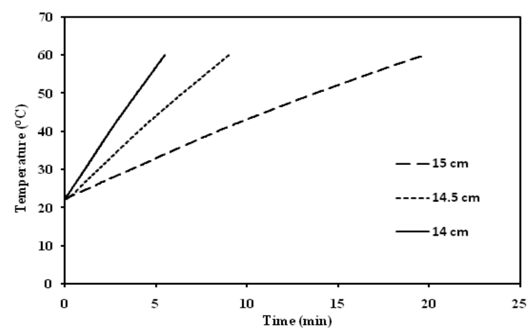

Fig. 5. Temperature-time histories of the RF heated lentils in the geometric center of the middle container under three different electrode gaps without movement and forced hot air

Fig. 4 shows the influences of electrode gap on electric current when the three containers filled with lentils were placed between RF electrodes without movement and forced hot air. In the range of the tested electrode gaps (13.5-17 cm), electric current decreased with increasing electrode gap. Fig. 5 shows the lentil temperature changes at the geometric center of the middle container during RF heating at the three selected electrode gaps of 14, 14.5 and 15 cm., The times required to raise the temperature from 22.3°C to 60°C were about 5.5, 10 and 20 min under the electrode gaps 14, 14.5 and 15 cm, respectively. To get high throughputs in industrial applications, the small electrode gap (14 cm) corresponding to a relatively short heating time (5.5 min) was selected for RF disinfestation treatments of lentils. According to the required heating time, the speed of conveyor belt was set to 7.5 m/h.

Table 1. Temperature (mean±SD) distribution of lentils after RF and hot air treatment

RF treatment	Surface temperature (°C)	Interior temperature (°C)
Rep-1	58.3±1.6	60.4±0.5
Rep-2	60.1±1.9	60.0±1.2
Rep-3	59.6±1.9	60.2±1.2

Heating uniformity evaluation

Table 1 lists the average surface and interior temperatures and SD values of lentils in the fifth container after RF treatments. Fig. 6 shows the typical thermal image of the surface temperature distribution in this container. The surface and interior temperature uniformity was better than that reported by Wang et al., (2010), which was probably caused by the continuous process and eliminating the edge overheating in the larger container that exactly fitted into the electrode size according to computer simulation results reported by Tiwari et al., (2011).

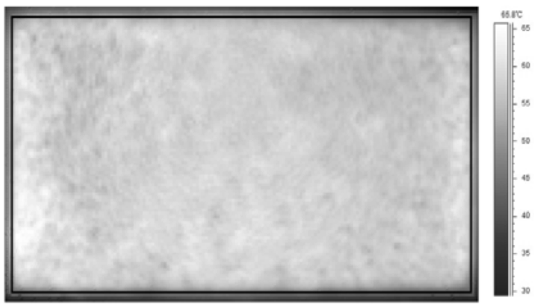

Fig. 6. Thermal image of the surface of the fifth container filled with lentils after RF and hot air treatment

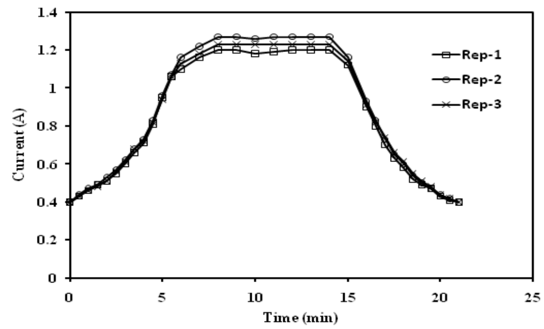

Fig. 7. The electric current change profile when 8 containers pass through the RF unit electrodes

Quality evaluation

Table 2 lists the quality values of lentils before and after hot air assisted RF treatments. For all three quality parameters, there were no significant differences before and after RF treatments. The results show that the current RF and hot air treatment maintained lentil quality, which was in good agreement with Wang et al. (2007b, 2010). The initial color values (L^*, a^* and b^*) were slightly different with the reported data by Wang et al. (2010), which were probably caused by different moisture contents. According to these results, continuous RF disinfestation treatment can be used to control insects in lentils while maintaining good product quality.

Table 2. Lentils quality (mean ± SD) before and after hot air assisted RF treatment

Treatment	Moisture content (% w.b.)	Germination (%)	Color		
			L^*	a^*	b^*
Control	6.90 ± 0.03^a	98.33 ± 0.98^a	55.96 ± 13.29^a	6.84 ± 3.26^a	37.60 ± 5.83^a
RF and hot air	6.65 ± 0.07^a	96.67 ± 0.98^a	55.67 ± 13.56^a	6.86 ± 3.25^a	37.57 ± 6.28^a

RF heating efficiency and throughput

Fig. 7 shows the current changes during RF treatment as 8 containers filled with lentils pass through the RF unit at the speed of 7.5 *m/h*. The stable currents from three replicates were 1.20, 1.27 and 1.23 A, so the corresponding input powers were 4.5, 4.8 and 4.6 kW, respectively. RF system heating efficiency was estimated to be 79.0%, 73.6% and 76.9% based on Eq. (4), resulting in the average heating efficiency of 76.5%. This heating efficiency was comparable with the value (79.5%) reported by Wang et al. (2007a) and higher than the value (60%) found for laboratory-scale RF treatment (Wang et al., 2006a). The calculated throughput of RF units was 208.7 *kg/h* according to Eq. (5) for the continuous treatment. This throughput could be improved by using larger power RF systems or multiple small systems in parallel.

CONCLUSIONS

A 27.12 MHz, 6 kW RF unit with built-in hot air and conveyor belt system was used to scale-up the proposed disinfestation treatment protocol. The electrode gap (14 cm) was chosen and the speed of conveyor belt was set to 7.5 *m/h*. Heating uniformity was evaluated based on the surface and interior temperatures after the temperature of lentils raised to 60°C by the hot air assisted RF treatment. The experiment results showed that the heating uniformity was acceptable and the quality of RF treated lentils had no significant changes. The RF system heating efficiency and throughput were 76.5% and 208.7 kg/h, respectively. This study provided a solid basis in developing an industrial-scale RF process.

ACKNOWLEDGMENTS
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