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Industrial-scale radio frequency treatments for insect control in lentils

S. Jiao [b], J.A. Johnson [c], J. Tang [b], S. Wang [a,b,*]

[a] Northwest A&F University, College of Mechanical and Electronic Engineering, Yangling, Shaanxi 712100, China
[b] Department of Biological Systems Engineering, Washington State University, Pullman, WA 99164-6120, USA
[c] USDA-ARS-San Joaquin Valley Agricultural Sciences Center, 9611 S. Riverbend Avenue, Parlier, CA 93648, USA

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ABSTRACT

Radio frequency (RF) treatments are considered to be a potential postharvest technology for disinfesting legumes of internal seed pests such as the cowpea weevil. After treatment protocols are shown to control postharvest insects without significant quality degradation, it is important to scale-up laboratory RF treatments to industrial level applications. A 27.12 MHz, 6 kW RF unit with a built-in forced hot air system was used to conduct industrial scale-up studies. A treatment protocol was designed to provide 100% cowpea weevil mortality combined RF with forced hot air to heat product to 60 °C for 10 min, followed by forced ambient air cooling for 20 min. An electrode gap (14.0 cm) was chosen based on the electric current and heating time, and conveyor belt speed was set to 7.5 m/h. Heating uniformity was evaluated by measuring post-treatment surface temperatures with a thermal image camera and interior temperatures with thermocouples. Changes in moisture content, color and germination were used to evaluate treatment effects on product quality. Finally, the RF system heating efficiency and throughput were calculated. Results showed that heating uniformity and quality of lentils in continuous RF treatment with hot air and movement were acceptable, the average heating efficiency of the RF system was 76.5% and throughput was 208.7 kg/h. The average energy efficiency and throughput of the RF system provided sufficient data to develop an industrial-scale RF process as an alternative to chemical fumigation.

1. Introduction

Lentil (*Lens culinaris*) is an important rotational legume in the north-western United States, especially Washington State (USADPLC, 2010). Disinfestation treatments for agricultural products are necessary to meet postharvest phytosanitary regulations before export to international markets, such as India, Korea, Spain, and Latin American countries (USADPLC, 2007). Since the Montreal Protocol (UNEP, 1992) in 2005 largely banned conventional disinfestation methods using methyl bromide fumigation in developed countries due to damage to the ozone layer, an alternative non-chemical quarantine treatment such as radio frequency (RF) heating is urgently required (Wang and Tang, 2004).

RF heating has been studied for control of different insects for various agricultural commodities (Nelson and Payne, 1982; Nelson, 1996; Tang et al., 2000; Marra et al., 2009; Gao et al., 2010). Lagunas-Solar et al. (2007) showed that RF treatment controlled insects in rough rice with no significant quality changes. Wang et al. (2001, 2002) and Mitcham et al. (2004) developed pilot scale RF treatments for control of codling moth and navel orangeworm in in-shell walnuts, and scaled up the treatment procedure using 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) reported a RF disinfestation treatment protocol at 60 °C for 10 min to completely control cowpea weevils in legumes (chickpea, lentil and green pea) with acceptable product quality, based on their dielectric properties (Guo et al., 2008, 2010; Jiao et al., 2011a). With RF heating, only 5–7 min were needed to bring the central temperature of 3 kg legumes to 60 °C from room temperature, the 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 a batch mode; studies are needed to prove that this RF treatment is suited for continuous processes that can handle large quantities of legumes in commercial applications.

Heating uniformity is an important consideration in scaling-up any proposed RF treatment protocol. Factors resulting in non-uniform heating during RF treatments include non-uniform

* Corresponding author. Northwest A&F University, College of Mechanical and Electronic Engineering, Yangling, Shaanxi 712100, China. Tel.: +86 29 87092391; fax: +86 29 87091737.
E-mail addresses: shaojinwang@nwsuaf.edu.cn, shaojin_wang@wsu.edu (S. Wang).

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electromagnetic field distribution and variations of product moisture content and thermal properties (Wang et al., 2007a). Several practical means can be used to minimize non-uniform RF heating, i.e. adding forced hot air to the product surface to reduce the energy exchange between the product surface and surrounding air, sample movement, rotation or mixing during RF treatment and immersing products into water for fresh fruits (Birla et al., 2004; Wang et al., 2006b, 2007a, 2010; Tiwari et al., 2008; Sosa-Morales et al., 2009; Gao et al., 2010). For dry commodities such as lentils, optimizing temperature uniformity during RF treatments by adding hot air and movement along a conveyor belt could be very helpful in ensuring complete insect mortality throughout the bulk of the product.

Industrial-scale RF treatments must maintain product quality. Moisture content, germination and color have been selected as quality parameters to evaluate the quality changes of lentils under improved heating uniformity (Wang et al., 2010). Based on tests of small samples treated in batches, Wang et al. (2010) reported acceptable quality of lentils after RF disinfestation treatments. But for continuous treatments of large amount of samples, the quality changes may be different and need to be determined.

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 (moisture content, color and germination) after RF treatments, (4) to estimate the heating efficiency and throughput of the RF treatment process.

2. Materials and methods

2.1. RF and hot air heating systems

A 27 MHz 6 kW RF unit (COMBI 6–S, Strayfield International, Wokingham, U.K.) was used to heat the lentils in combination with a customized auxiliary hot air system using a 5.6 kW electrical strip heater and a blower fan (Fig. 1). A conveyor belt system (TOSVERT-130 G2+, Toshiba International Corp., Houston, TX) was built into the RF unit 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). Lentil samples were treated in plastic polypropylene containers (0.40 L × 0.23 W × 0.10 H m^3) with perforated side and bottom walls (Fig. 2) to allow hot air to pass through the lentils (George Brocke & Sons, Inc., Kendrick, ID, USA.).

2.2. Determining electrode gap and conveyor belt speed

The height of the top electrode in the RF unit was adjustable to change the electrical current and RF power (Fig. 3), which was provided by Strayfield International, Wokingham, U.K. for the power calibration curve using water loads. The dimension of the top electrode was 69 L × 50 W cm^2, allowing three plastic containers to be heated simultaneously between the electrodes. To develop a continuous RF treatment protocol, the optimal electrode gap and conveyor belt speed was determined first. Three plastic containers filled with 6.4 kg lentils were placed on the stationary conveyor belt between the electrodes to obtain a general relationship between the electrode gap and electric current. An electrode gap range of 13.5–18.0 cm was considered. After setting the electrode gap at 18.0 cm, RF power was turned on and the electric current was immediately recorded. This procedure was repeated until the electrode gap was incrementally adjusted to a minimum of 13.5 cm. Based on the measured electric current, electrode gaps of 14.0, 14.5 and 15.0 cm were selected for subsequent heating tests. With the conveyor belt stationary and without forced hot air, the sample temperature at the geometric center of the middle container was recorded with a FISO optic sensor (UMI, FISO Technologies Inc., Saint-Foy, Quebec, Canada) during RF heating. The time needed for the center temperature of the middle container from ambient temperature (22.3 °C) to 60 °C was recorded. The conveyor belt speed was calculated by dividing the electrode length by the resulting heating time.

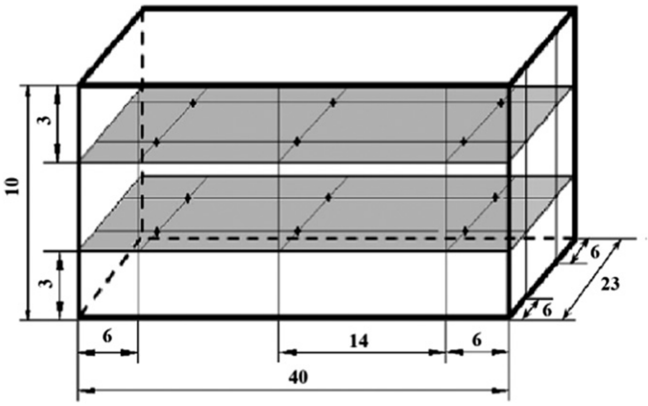

Fig. 2. Dimensions of the plastic container and the location of 12 thermocouples (+) used for temperature measurement (all dimensions are in cm).

2.3. Heating uniformity evaluation

The insect disinfestation treatment proposed by Wang et al. (2010) uses product heating to 60 °C with RF and 60 °C hot forced air, followed by maintenance of the target temperature for 10 min using hot forced air alone. The temperature uniformity of this treatment was evaluated at two points; immediately after the target temperature was reached, and after the 10 min maintenance. To do this, eight containers filled with lentils were placed on the

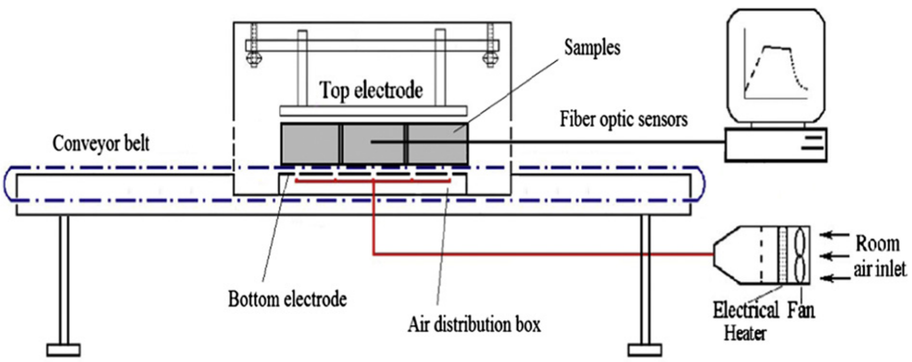

Fig. 1. Schematic view of the 6 kW, 27.12 MHz RF unit with hot air and temperature measurement systems (adapted from Wang et al., 2010).

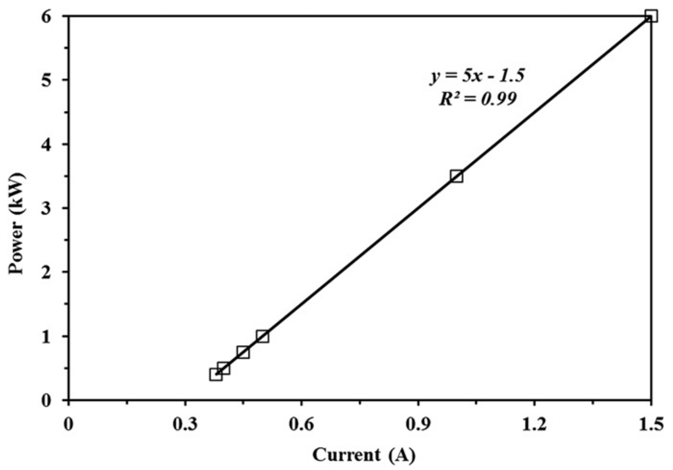

Fig. 3. The relationship between the output power and electrical current of the 6 kW RF unit obtained by Strayfield International, UK using water loads.

conveyor belt and passed between the RF electrodes set at the optimal gap determined above. Forced 60 °C (±1 °C) air was added to improve temperature uniformity. The electric current increased as the first container moved between the electrodes, but stabilized once three containers were completely located between the electrodes, and finally decreased as the last three containers moved out from between the electrodes, similar to what were reported in Wang et al. (2007a, b). The electric current was recorded every 30 s while the eight containers passed between the electrodes. The fourth and fifth containers experienced the most stable RF power conditions.

Heating uniformity was evaluated from temperature measurements taken from the fifth container. Surface temperatures were immediately measured after reaching the target temperature with a digital infrared camera (Thermal CAMTM SC-3000, FLIR Systems, Inc., North Billerica, MA, USA) having an accuracy of ±2 °C. After 2 s for the surface temperature measurement, the interior temperature at 12 positions (Fig. 2) was measured with a Type-T thermocouple thermometer (Model 91100-20, Cole-Parmer Instrument Company, Vernon Hill, IL, USA) having an accuracy of ±0.2 °C and 0.8 s response time (Wang et al., 2010). In a separate test, similar temperature measurements were made after the containers were heated to the 60 °C target temperature and then maintained at that temperature for 10 min using hot air alone. The target temperature treatment was replicated three times and the 10 min maintenance treatment was replicated twice.

The average and standard deviation (SD) values of the surface and interior sample temperatures for each replicate were used to calculate the temperature uniformity index (UI) and the average UI with SD values were used to evaluate heating uniformity. The UI (λ) was derived experimentally from product temperature measurements during the heating process and has been successfully used to evaluate RF heating uniformity (Wang et al., 2005, 2010), which can be calculated by the following equation (Wang et al., 2005):

$$\lambda = \frac{\Delta\sigma}{\Delta\mu} \quad (1)$$

where $\Delta\sigma$ is the rise in SD of sample temperature and $\Delta\mu$ is the rise in mean sample temperature over treatment time.

2.4. Quality analysis

Moisture content, color and germination were selected as the parameters to evaluate lentil quality before and after the RF treatments. Based on the treatment protocol proposed for insect control in lentils (Wang et al., 2010), the RF treated samples were 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 (<1 cm) 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 a 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). The samples were placed in desiccators with $CaSO_4$ and brought to room temperature before weighing. There were three replicates for each measurement.

Germination rate of lentil seeds was determined by immersing 60 lentil seeds in water at room temperature for one day. Seeds were then transferred to Petri dishes (20 seeds/dish) lined with germination paper saturated with distilled water. Dishes were held for two days in the dark under ambient conditions. Geminated seeds were counted and germination rates calculated.

The color of lentils was determined by a computer vision system (CVS), composed of a lighting system, a Nikon D70 digital camera with 18–70 mm DX Zoom Nikkor lens, and a desktop computer with Adobe Photoshop CS2 software (version 8.0, Adobe Systems Inc., SanJose, CA, USA). 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 mm 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 (Briones and Aguilera, 2005):

$$L^* = \frac{L}{2.5} \quad (2)$$

$$a^* = \frac{240a}{255} - 120 \quad (3)$$

$$b^* = \frac{240b}{255} - 120 \quad (4)$$

$L*$, $a*$ and $b*$ indicate for each sample the lightness of the color, its position between red and green, and between yellow and blue,

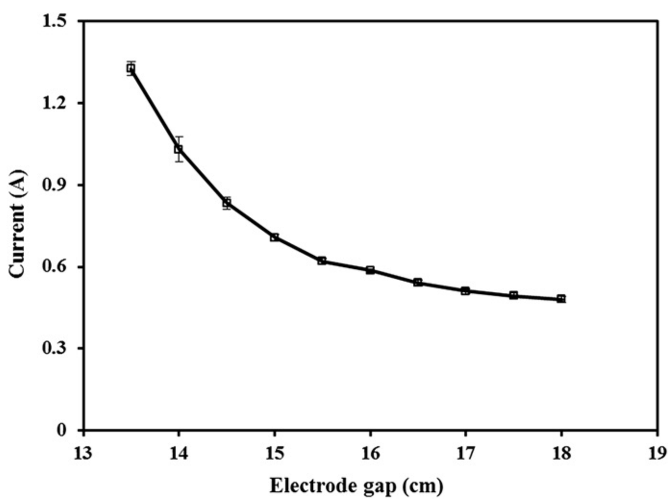

Fig. 4. The relationship between the electrical current and electrode gap with three containers filled with lentils without movement and forced hot air.

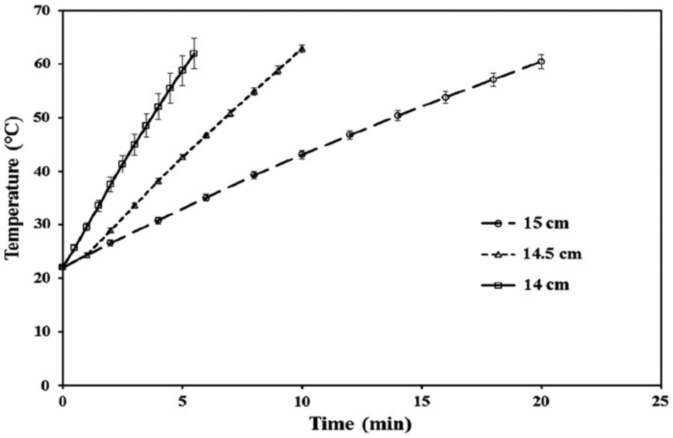

Fig. 5. Temperature-time histories of the RF heated lentils in the geometric center of the middle container under three different electrode gaps without movement and forced hot air.

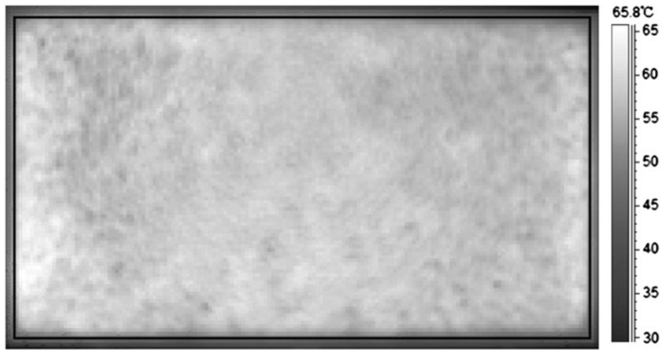

Fig. 6. Thermal image of the surface of the fifth container filled with lentils after RF and hot air treatment.

respectively. In CIE LAB, $L*$ ranges from 0 to 100, and $a*$ and $b*$ from −127 to +128, but in Photoshop program, these values are encoded between 0 and 255, so it is necessary to convert to CIE LAB values using the above equations.

Mean values and standard deviations were calculated from replications for each quality parameter (moisture content, germination rate and color). Where there were significant differences ($P < 0.05$), means were separated using least significant difference (LSD) *t*-test for each quality parameter before and after RF treatment.

2.5. Heating efficiency and throughput

Average heating efficiency calculations for the industrial RF system were based on a continuous treatment. The electric current became stabilized as the fourth container moved into the RF system, and 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):

$$\eta = \frac{P_{\text{output}}}{P_{\text{input}}} \times 100\% = \frac{mC_p\left(\Delta T/_{\Delta t}\right)}{P(I) + Ah(T_a - \overline{T}_s)} \times 100\% \quad (5)$$

where m is the mass of lentils in kg treated in a time period Δt (s), C_p is the specific heat of lentils, and equals 1732 J/kg °C at room temperature (Tang et al., 1991;Jiao et al., 2011b), ΔT is the change in mean sample temperature (°C), A is the surface area exposed to the hot air, h is the convective heat coefficient, estimated to be 28 W/m^2 °C for hot air over a plate (Ozisik, 1985), T_a is the air temperature (60 °C), and $\overline{T}_s$ is the average surface temperature in °C.

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

$$M = vNm \quad (6)$$

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.

3. Results and discussions

3.1. Determination of electrode gap and conveyor belt speed

Figure 4 shows the influences of the electrode gap on electric current when three plastic containers filled with lentils were placed between RF electrodes without movement and forced hot air. In the range of the tested electrode gaps (13.5–18.0 cm), electric current decreased with increasing electrode gap. Fig. 5 shows the lentil temperature change at the geometric center of the middle container during RF heating for three selected electrode gaps of 14.0, 14.5 and 15.0 cm, with times required to raise the temperature from 22 °C to 60 °C for each gap being about 5.5, 10 and 20 min, respectively. Shorter heating times correspond to higher throughputs, and thus are desired, but heating uniformity could be adversely affected by too rapid heating. To obtain relatively high throughputs with acceptable heating uniformity in industrial applications, an electrode gap of 14.0 cm corresponding to a relatively short heating time (5.5 min) was selected for RF disinfestation treatments of lentils. The speed of the conveyor belt was therefore set to 7.5 m/h.

3.2. Heating uniformity evaluation

Table 1 lists the average and SD values of surface and interior temperatures and the corresponding temperature UI values of

Table 1
Comparisons of temperature distribution (mean ± SD) and uniformity index (UI) of lentils after RF heating with different conditions over replicates (Rep).

Temperature distribution and UI	After target temperature reached			After 10 min maintenance	
	Rep-1	Rep-2	Rep-3	Rep-1	Rep-2
Surface temperature (°C)	59.6 ± 1.9	60.1 ± 1.9	58.3 ± 1.6	59.5 ± 1.2	59.2 ± 1.1
Interior temperature (°C)	60.4 ± 0.5	60.0 ± 1.2	60.2 ± 1.2	60.7 ± 1.0	60.5 ± 1.1
Surface temperature UI	0.055	0.054	0.048	0.035	0.032
Mean ± SD	0.052 ± 0.004			0.034 ± 0.002	
Interior temperature UI	0.014	0.034	0.034	0.028	0.031
Mean ± SD	0.027 ± 0.012			0.030 ± 0.002	

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

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

[a] In each column, same letter indicates that means were not significantly different ($P > 0.05$) between the control and RF treatments based on t-test.
[b] L^*—lightness, a^*—position between red and green, b^*—position between yellow and blue.

lentils in the fifth container measured after reaching the target temperature and after the 10 min maintenance. Average surface temperatures were a little lower than 60 °C, probably caused by heat loss during measurement. SD values for surface temperatures were a little higher than that of interior temperatures after the target temperature was reached, but all the SD values were less than 2 °C, indicating relatively uniform temperature distribution. After the 10 min maintenance, the SD values of surface and interior temperatures were very close. The UI for surface temperature after the 10 min maintenance was lower than that after the target temperature was reached, indicating improved uniformity caused by the extended hot air. The surface and interior temperature uniformity was comparable to that reported by Wang et al. (2010) even though much larger samples were used in the current study. Fig. 6 shows little or no overheating along the top and bottom edges of the image, corresponding to the sides of the container that abut the neighboring containers on the conveyor belt. This is an improvement over tests using single container (Wang et al., 2010). Computer simulation has shown that as container size approaches electrode size, RF energy distribution is improved and better temperature uniformity achieved (Tiwari et al., 2011), which would explain these results.

3.3. Quality evaluation

Results from the quality studies are presented in Table 2. For all quality parameters, there were no significant differences before and after RF treatments ($P > 0.05$). The results showed that the RF and hot air treatments 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 from the data reported by Wang et al. (2010); this was probably caused by different moisture contents in treated samples. According to these results, continuous RF disinfestation treatment can be used to control insects in lentils while maintaining good product quality.

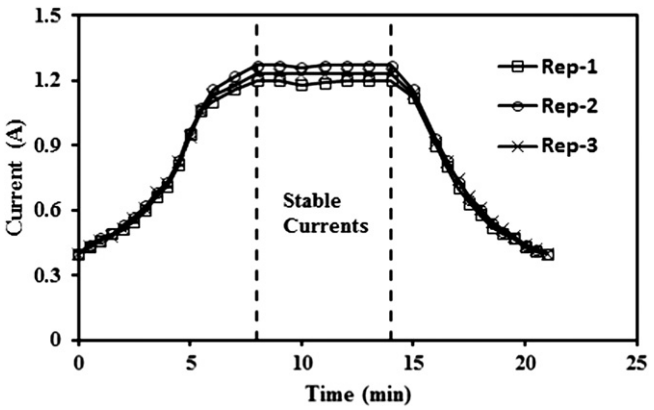

Fig. 7. The electric current change profile when 8 containers passed through the RF unit electrodes with the gap of 14.0 cm.

3.4. RF heating efficiency and throughput

Figure 7 shows the current changes during RF treatment as 8 containers filled with lentils pass through the RF unit with an electrode gap of 14.0 cm at a conveyor belt speed of 7.5 m/h. For the three replicates currents were stable at 1.20, 1.27 and 1.23 A. According to the relationship between current and power input (Fig. 3) the input powers were 4.5, 4.8 and 4.6 kW, respectively. Based on Eq. (5), the RF system heating efficiency was estimated to be 79.0%, 73.6% and 76.9%, resulting in an 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 6 kW RF units was 208.7 kg/h for the continuous treatment according to Eq. (6). This throughput could be improved by using RF systems with greater power or multiple small systems in parallel.

4. Conclusion

A 27.12 MHz, 6 kW radio frequency (RF) unit with a built-in conveyor belt system and customized auxiliary forced hot air system was used to conduct industrial scale-up disinfestation studies. The experiment results showed that the heating uniformity was acceptable and the quality parameters (moisture content, color and germination) of RF treated lentils had no significant changes when electrode gap and conveyor belt speed were set to 14.0 cm and 7.5 m/h, respectively. The average heating efficiency and throughput of the RF system were 76.5% and 208.7 kg/h, respectively. The heating efficiency was acceptable and the throughput can be improved by using larger power RF units or multiple small systems in parallel. This study provided a solid basis in developing an industrial-scale RF process as an alternative to chemical fumigation.

Acknowledgments

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