Postharvest Biology and Technology 58 (2010) 225–231

Contents lists available at ScienceDirect

Postharvest Biology and Technology

journal homepage: www.elsevier.com/locate/postharvbio

Almond quality as influenced by radio frequency heat treatments for disinfestation

M. Gao[a], J. Tang[b], Y. Wang[c], J. Powers[d], S. Wang[b,*]

[a] College of Life Science, Yangtze University, Jingzhou, Hubei 434025, China
[b] Department of Biological Systems Engineering, Washington State University, 213 L.J. Smith Hall, Pullman, WA 99164-6120, USA
[c] College of Food Science and Engineering, Northwest A&F University, Yangling, Shaanxi 712100, China
[d] School of Food Science, Washington State University, PO Box 646376, Pullman, WA 99164-6376, USA

ARTICLE INFO

Article history:
Received 23 March 2010
Accepted 20 June 2010

Keywords:
Almond
Heating uniformity
Phytosanitary
Postharvest quality
RF

ABSTRACT

Increased regulation of chemical fumigants has forced the almond industry to seek alternatives for postharvest control of insect pests in raw almonds. This paper reports developments of non-chemical treatment for postharvest disinfestation of almonds using radio frequency (RF) energy. A pilot-scale 27 MHz RF unit was used to evaluate effects of a RF treatment protocol on quality attributes in treated in-shell and shelled almond samples. The RF treatment protocol used 0.75 kW RF power, a forced hot air at 63 °C, back and forth movements on the conveyor at 0.56 m/min, and single mixing, which all improved the final heating uniformity. RF treatments sharply reduced the heating time from 86 and 137 min for hot air heating to only 6.4 and 8.8 min for the center of 1.5 kg in-shell and 2.4 kg shelled almond samples to reach 63 °C, respectively. Almond quality was not affected by the RF treatments because peroxide values, fatty acid and kernel color of treated almonds were better than or similar to untreated controls after 20 d at 35 °C, simulating 2 years of storage at 4 °C. RF treatments did not significantly affect the kernel moisture content of both types of almonds but reduced the moisture content in the shell. RF treatments may hold great potential to replace chemical fumigation for disinfesting almonds.

1. Introduction

Almond is one of the most valuable edible nuts in the world with distinctive taste, nutrient and texture. Almonds are a leading horticultural export for the United States, with about 70% of the total crop shipped for export to more than 80 countries (ABC, 2005). A major problem in the production, processing and storage of almonds is insect infestation that creates barriers to export. Indianmeal moth (*Plodia interpunctella*), navel orangeworm (*Amyelois transitella*) and red flour beetle (*Tribolium castaneum*) are recognized as main pests of harvested almonds. Infested almonds are not easily detected by external inspection, leading to customer returns and loss of consumer confidence, and may result in legal or regulatory actions.

Postharvest phytosanitary treatments are often required to completely control insect pests before the products are moved through marketing channels to areas where the pests do not occur (Heather et al., 2008). Most almond processors in California use hydrogen phosphide (phosphine) for postharvest phytosanitary treatments, but use of phosphine at suboptimal rates may result in increased resistance in pest populations (Zettler et al., 1989). As a toxic gas, phosphine also presents safety concerns for workers (USEPA, 2001). Due to actions by the Montreal Protocol (UNEP, 1992), methyl bromide is no longer available to the almond industry for postharvest phytosanitary treatments. In addition, because of the rapidly growing market for organic almonds, there is an increasing interest in finding non-chemical alternatives to chemical fumigation for almonds.

Several non-chemical alternative methods have been suggested to control insect pests in agricultural commodities, including ionizing radiation, cold storage, controlled atmospheres, and combination treatments (Fleurat-Lessard, 1990; Johnson et al., 1997, 1998; Johnson and Marcotte, 1999; Heather et al., 2008). All of these methods would require substantial capital investment and alteration of existing facilities. For example, cold storage and controlled atmospheres require lengthy treatment times for disinfestation, which may not be acceptable for many important markets. Irradiation treatments often lead to live insects found by inspectors or consumers in the treated product because the applied doses do not immediately kill treated insects (Hallman and Miller, 1994; Hallman, 1999; Saour and Makee, 2004; Heather et al., 2008). To date, irradiation is not accepted by the organic industry and

* Corresponding author at: Washington State University, Biological Systems Engineering, PO Box 646120, Pullman, WA99164-6120, USA. Tel.: +1 509 335 7950; fax: +1 509 335 2722.
E-mail address: shaojin_wang@wsu.edu (S. Wang).

0925-5214/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.postharvbio.2010.06.005

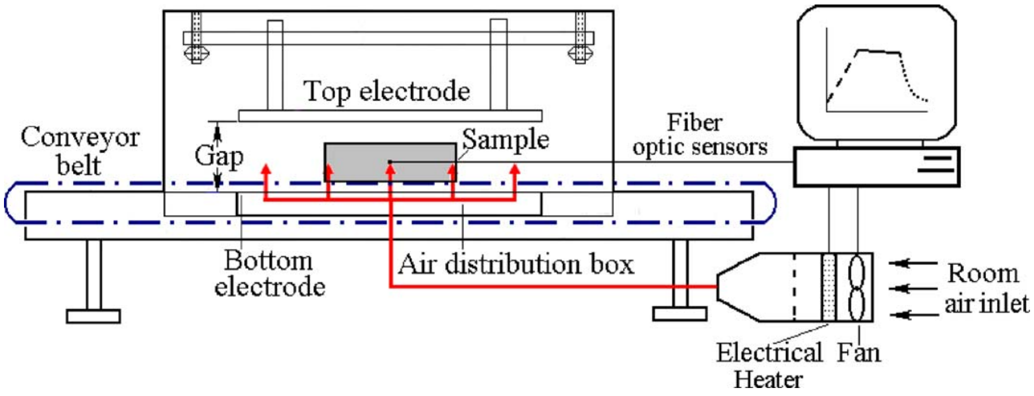

Fig. 1. Schematic view of the pilot-scale 6 kW, 27.12 MHz radio frequency (RF) unit showing the two-pair plate electrodes, conveyor belt and the hot air system (Wang et al., 2010).

approvals for almond irradiation are not in place in many countries, such as the EU, Japan, and Taiwan.

Thermal treatments that rely on heated circulating air or steam are used to a limited extent to control insect pests in agricultural commodities (USDA-APHIS-PPQ, 2009). A common and major difficulty with hot air or steam heating methods is the slow rate of heat transfer in bulk almonds due to high resistance to conductive heat transfer, resulting in lengthy treatments (Wang and Tang, 2007). The small thermal conductivity of the porous almond shell and the in-shell void further hinders the transfer of thermal energy from the hot air to the kernel center (Wang et al., 2001b). Temperature and time combinations required to kill the target insects may exceed those conditions that may cause thermal damage to almonds or reduce shelf life. To shorten treatment time and minimize thermal impact on product quality, it is desirable to quickly deliver thermal energy to every part of the bulk product in which insect pests may reside.

Industrial radio frequency (RF) systems have been used in the food processing, textile and wood processing industries. RF treatments would have the advantage of rapid and volumetric heating of almonds because of the direct interaction between RF energy and the whole almond mass. RF energy has been suggested for control of postharvest insects in other agricultural commodities (Hallman and Sharp, 1994; Nelson, 1996; Tang et al., 2000). Recently, Lagunas-Solar et al. (2007) reported RF control of insects in rough rice with acceptable quality. RF treatments have also been successfully used in research on control of codling moth (Wang et al., 2001a) and navel orangeworm (Wang et al., 2002b, 2007a,b; Mitcham et al., 2004) in in-shell walnuts. It is our intention to expand studies of RF energy for control of the insect pests in almonds.

Thermal death kinetic data of the targeted insects in almonds are critical to the development of effective RF treatments. The thermal resistance of Indianmeal moth, navel orangeworm and red flour beetle in almonds has been reported (Wang et al., 2002a; Johnson et al., 2003, 2004). The results suggest that fifth-instar navel orangeworm is the most heat resistant life stage at temperatures above 50 °C among the three studied insects, and is completely killed at 54 and 58 °C by holding at 1.5 and 0.1 min, respectively.

Commercially viable RF phytosanitary treatments for almonds must retain product quality. Temperatures experienced by almonds during RF treatments influence their quality and marketability. Because of the potential of nut kernels to undergo rapid oxidative and hydrolytic rancidity at elevated temperatures (Wang et al., 2002b), the main quality parameters of concern in this study included peroxide values (PV, mequiv./kg), fatty acids (FA, % oleic) and kernel color. Buranasompob et al. (2003, 2007) reported that hot air heating of shelled walnut and almond kernels at 60 °C for up to 10 min did not increase rancidity compared to untreated samples. Mitcham et al. (2004) observed that final kernel temperatures around 75 °C did not alter walnut quality after RF treatments. Thus, almond quality as influenced by RF treatments holds great potential for developing practical postharvest phytosanitary methods under the improved heating uniformity.

The objectives of this study were to compare the temperature–time history of in-shell and shelled almonds when subjected to hot air and RF heating, to develop an effective cooling method for RF heated almonds, to study the RF heating uniformity in almonds using hot air surface heating, moving and mixing, and finally to evaluate almond quality after RF treatments and storage.

2. Materials and methods

2.1. RF and hot air heating systems

To explore effects of RF heating on almond quality, a pilot-scale RF system (COMBI 6-S, Strayfield International, Wokingham, U.K.) with a maximum power of 6 kW at 27 MHz was used together with a hot air system (5.6 kW) for surface heating (Fig. 1). A detailed description of the RF unit, the hot air and conveyor systems can be found in Wang et al. (2010). The RF power coupled into the almond samples was adjusted by changing the gap between the top and bottom electrodes to achieve an appropriate heating rate. A perforated conveyor belt above the bottom electrode was moved from the center to the right end of the top electrode and then back to the left end of the electrode at 0.56 m/min during RF heating to simulate a continuous process. A plastic container (25.5 cm × 15 cm × 10 cm) with perforated screens on the side and bottom walls constructed from 12.7 mesh nylon screen with 0.14 cm openings (9318T27, McMaster-Carr Supply Company, Los Angeles, CA, USA) was used to allow hot and room air to pass through the samples for surface heating and cooling. The hot air system provided forced hot air (air temperature of 60 °C at an air speed of 0.7 m s^{-1} in the RF cavity) into the RF cavity through an air distribution box under the bottom electrode (Fig. 1).

2.2. Materials and electrode gap determination

In-shell and shelled almonds (Nonpareil) were obtained from Almond Board of California, Modesto, CA, USA. For full loads in the container, samples of 1.5 and 2.4 kg (10 cm thick) were used for in-shell and shelled almond samples, respectively. To determine the appropriate gap between the electrodes for RF treatments, four gaps, 11.5, 12.0, 12.5 and 13.0 cm, for in-shell almonds and three gaps, 10.5, 11.0 and 11.5 cm, for shelled samples were tested under stationary conditions without hot air heating. Ambient room temperature was used as the initial sample temperature for each test.

The central sample temperature in the container was measured during RF heating using a FISO optic temperature sensor (UMI, FISO Technologies Inc., Saint-Foy, Quebec, Canada) having an accuracy of ±0.5 °C. The final gap was fixed based on the target heating rate (6–8 °C/min) of samples with two replicates.

2.3. Comparisons of temperature profiles of almonds between RF and hot air heating

After the tests described above, the most appropriate gaps were used for temperature profile comparisons, heating uniformity improvement and protocol development. To achieve complete control of the most heat resistant insect, the fifth-instar naval orangeworm, the temperature and time combination exceeding 58 °C for 1 min holding was selected. When taking into consideration the non-uniformity in RF treated products, the target sample temperature of 63 °C was used to develop the treatment protocol. The container was placed in the center of the RF bottom electrode for both hot air and hot air assisted RF heating. The central sample temperature in the container was measured by the FISO fiber optic sensor during heating with forced hot air at 63 °C and stationary hot air assisted RF treatments. The hot air velocity in the RF cavity was about 1 m/s measured by a rotating vane anemometer (LCA 6000, AIRFLOW Instrumentation, Buckinghamshire, UK). The measurement was stopped when the sample center temperature reached 63 °C.

2.4. Determination of cooling methods

Cooling is an important part of effective treatment protocols since slow cooling may result in quality degradation of the RF or hot air heated products and reduce throughput of the industrial-scale treatments. Almond samples preheated for 3 h with hot air at 63 °C were used to determine appropriate cooling methods. In-shell almonds with 10 and 5 cm depth, and shelled samples with 10 cm, 5 cm depth, and a single layer held in the plastic container were subjected to ambient natural and ambient forced air cooling. The natural and forced air cooling was obtained by placing the container in ambient room air and applying a cross airflow driven by a fan, respectively. The measured air velocities on the sample surface were about 0.2 and 1.0 m/s for the natural and forced air cooling, respectively. The sample temperature in the center was recorded until the sample temperature dropped to 30 °C. The best cooling method was selected according to the shortest cooling time and further used to develop the RF treatment protocol.

2.5. Heating uniformity tests

The RF heating uniformity depends on practical treatment conditions, such as with or without forced hot air, with or without movement on the conveyor belt, and with or without mixing. To develop a potential treatment protocol and evaluate effects of RF treatments on product quality, the optimized heating uniformity should be first determined. Full loads of both almond types were heated in the RF system to compare the temperature distribution in the container. The container movement started from the left edge to the right edge of the electrode (Fig. 1), moved back to the right edge at 0.56 m/min until the end of RF heating. The forced hot air at 63 °C was provided through the perforated bottom of the electrode and the conveyer. A single mixing was included in the middle of the RF treatment time. Mixing was done outside the RF cavity by hand in a large container (55 cm × 40 cm × 14 cm). After mixing for 20 s, the samples were returned to the treatment container and placed back into the RF system for the remainder of the treatment time. The mixing process took less than 1 min. Before and immediately after RF treatments, the sample surface temperatures were mapped with a thermal imaging camera (Thermal CAM^{TM} SC-3000, N. Billerica, MA) having an accuracy of ±2 °C. Each thermal image took less than one second. The 45,056 surface temperature data in the treated area were used for estimating the mean and standard deviation values. Ten almonds were randomly selected below the surface of the container for interior kernel temperature measurements using a thin 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. Each test was repeated twice.

To determine the optimal heating uniformity, a heating uniformity index, λ, was used to compare the difference of the above operational means. The heating uniformity index has been applied to determine acceptable treatment conditions for walnuts and legumes (Wang et al., 2007a, 2010). It is defined as the ratio of the rise in standard deviation of product temperature to the rise in mean product temperature during treatment (Wang et al., 2005). It can be derived experimentally from product temperature measurements over a surface or a volume using the following equation (Wang et al., 2008):

$$\lambda = \frac{\sqrt{\sigma^2 - \sigma_0^2}}{\mu - \mu_0} \qquad (1)$$

where μ_0 and μ are initial and final mean almond temperatures (°C), and σ_0 and σ are initial and final standard deviations (°C) of almond temperatures over treatment time, respectively.

2.6. Treatment protocol development

To achieve the required insect control in almonds, the minimum product temperature in treated almonds was set up at 58 °C plus 2 min holding to achieve the complete kill of the target insects (Johnson et al., 2004). The quality of the RF and hot air treated almonds were compared based on the developed treatment protocol. The previously determined electrode gap was used for heating 1.5 and 2.4 kg with 10 cm thickness of in-shell and shelled almond samples in the RF system together with the back and forth movement at 0.56 m/min, hot air heating at 63 °C and a single mixing. After reaching 63 °C at the center of the container, the RF system was turned off and the almond samples were held in hot air for 2 min. As a comparison, the in-shell and shelled almond samples in the plastic containers were heated to 63 °C in forced hot air. Both RF and hot air treated almond samples were cooled to 30 °C with the pre-determined method. The untreated samples were considered as controls. Treated samples were sealed in plastic bags for quality evaluations. Each treatment was replicated three times.

2.7. Almond quality evaluations

Before and after hot air and RF treatments, the quality of almond samples taken from each treatment was evaluated immediately and after accelerated shelf life storage. The almond quality parameters evaluated include PV, FA, color and moisture contents. The accelerated shelf life storage tests were conducted in an incubator at 35 °C and 30% relative humidity (RH) for 10 and 20 d to simulate commercial storage at 4 °C for 1 and 2 years, respectively. The storage time at 35 °C was calculated based on a Q_{10} value of 3.4 for lipid oxidation (Taoukis et al., 1997) and was validated by real-time storage experiments (Wang et al., 2006). The PV and FA values were determined by the oil pressed from the treated almond samples using methods Cd 8b-90 and Ca 5a-40 of the American Oil Chemists Society (AOCS, 1997b, 2003). Detailed measurement procedures and calculation of PV and FA values can be found elsewhere (Wang et al., 2001a).

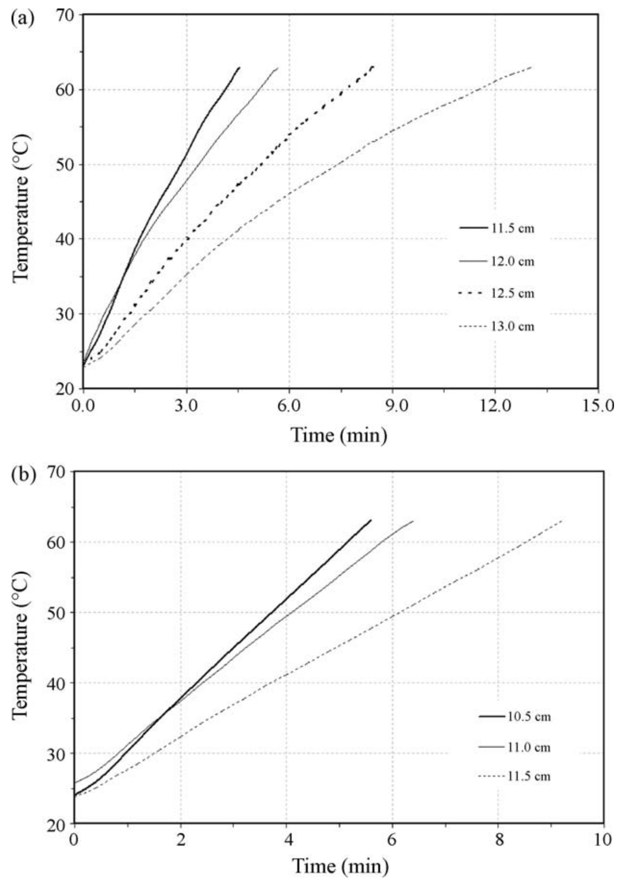

Fig. 2. Temperature–time histories of the RF heated in-shell (a) and shelled (b) almonds in the center of the 10-cm thick container as a function of the electrode gap without movement, hot air heating, and mixing.

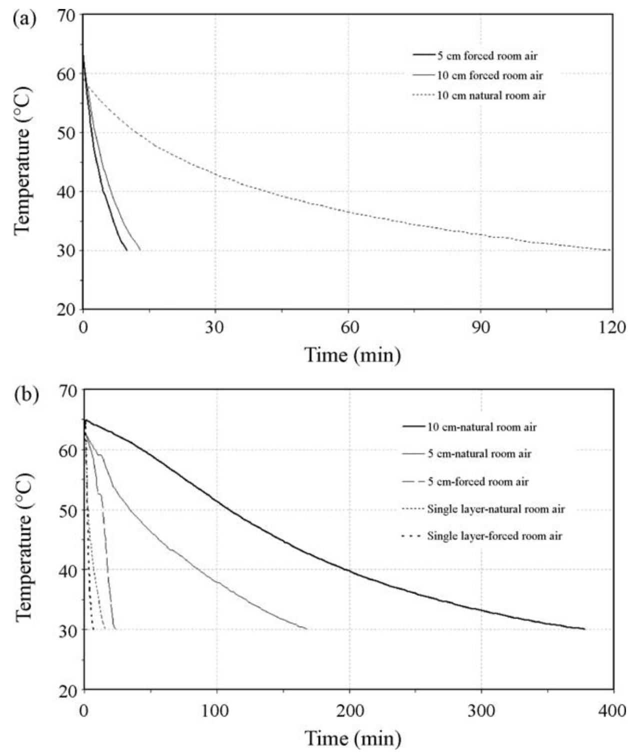

Fig. 3. Cooling curves of in-shell (a) and shelled (b) almonds in the sample center as a function of sample thickness under natural and forced room air cooling.

Almond kernel color was measured with a computer vision system (CVS) as described in detail by Wang et al. (2010). Color images of 30 almond kernel skin and core color per treatment were captured and stored in the computer using Adobe Photoshop (CS, Adobe Systems Inc., USA). These color values were then converted to Hunter L (darkness), a (green-red), and b (blue-yellow) parameters.

In-shell almond samples taken before and after hot air and RF treatments were cracked manually for collection of the shells and kernels. Shell and kernel were ground into meal using a coffee grinder (ID557, Mr Coffee, Guangzhou, China) and then passed through a No. 18 mesh (16 Tyler). The moisture content was determined using standard oven methods Ca 2d-25 of the American Oil Chemists Society (AOCS, 1997a).

Mean values and standard deviations were calculated from the replicates for each hot air and RF treatment. The mean values were compared and separated using least significant (LSD) t-test using the variance procedure (Microsoft office Excel 2003) at a significant level of $P = 0.05$.

3. Results and discussion

3.1. Heating rate as influenced by the electrode gap

Fig. 2 shows the temperature–time history of in-shell (a) and shelled (b) almond samples in the container center during RF heating as a function of the electrode gap. The heating rate of both almond samples increased with decreasing electrode gap, which corresponds to the increased power in the RF systems. The RF heating rate of in-shell almonds was larger than that of shelled samples. Fast heating rate may result in RF non-uniformity. But slow heating rate reduces the throughput of the treatments. Electrode gaps of 12 and 11 cm were considered appropriate and therefore selected for in-shell and shelled almonds to achieve the heating rates of 7.7 and 6.3 °C/min. The corresponding RF powers were 0.75 and 0.70 kW for in-shell and shelled almonds, respectively.

3.2. Heating and cooling profiles

Cooling temperature–time histories in the sample center for both in-shell and shelled almonds as influenced by the sample thickness and cooling methods are shown in Fig. 3. About 120 and 380 min were needed for the 10 cm deep in-shell and shelled almond samples to cool from 63 to 30 °C in natural room air, respectively. The cooling time decreased sharply with reducing sample thickness and when introducing forced air. For in-shell almonds, it took only 10 min to cool 5-cm deep samples to 30 °C with forced air, which could be used after thermal treatments. But this was not enough for shelled almonds, due to reduced voids in the sample volume. Single layer with forced room air made the cooling time for shelled samples to be 7 min, which could be applied in a continuous RF process in the nut industry.

Fig. 4 shows typical temperature–time histories at the center of a 10 cm thick in-shell and shelled almond samples when subjected to 63 °C forced hot air and RF heating followed by the best cooling determined above. Forced air heating to 63 °C of in-shell and shelled almond samples took about 86 and 137 min, respectively. These long times were probably caused by the poor heat conduction within the bulk low-moisture almond samples. The reduced voids in shelled almonds reduced air flow and increased heating time. RF heating dramatically reduced the heating time to 6.4 and 8.8 min for the same-size in-shell and shelled almond samples, respectively. The shorter RF heating time for in-shell almonds was probably caused by higher power absorption as indi-

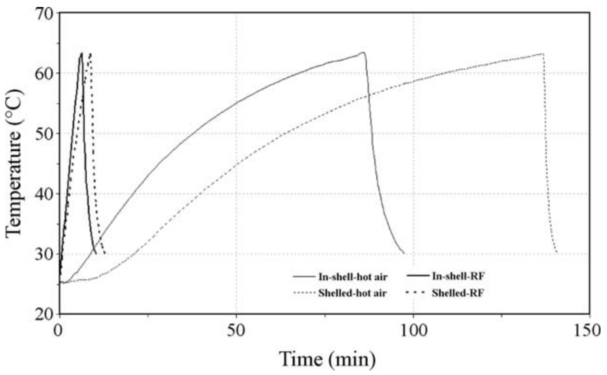

Fig. 4. Typical temperature–time histories of in-shell and shelled almonds in the center of a 10 cm thick container in hot air heating at 63 °C as compared with stationary hot air assisted RF heating of shelled (gap = 11 cm) and in-shell (gap = 12 cm) almonds followed by forced room air cooling in single layer samples.

cated in Fig. 2. The significantly reduced heating time demonstrated the advantage of rapid RF heating as compared to conventional heating.

3.3. Heating uniformity in RF treated almonds

Table 1 summarizes a detailed comparison of the temperature distribution and uniformity index values of the in-shell and shelled almonds on the surface and the interior layers after RF heating under different conditions. Hot air increased the surface almond temperature, resulting in better heating uniformity. Mixing reduced slightly the mean temperature due to heat loss. Generally, hot air, movement and mixing all improved the RF heating uniformity in both almond samples as indicated by gradual reduction in the uniformity index value. Finally, the mean temperatures after RF treatment together with hot air, movement and mixing were higher than 58 °C, which might meet the requirements for complete insect control in almonds (Table 1). The surface temperatures taken by the thermal imaging camera were comparable to the interior layer temperatures obtained by thermocouples, although variability of surface temperatures was larger than that of interior layer ones. The heating uniformity index values were similar to those found for walnuts (Wang et al., 2005, 2007a), but slightly larger than those observed for legumes with smaller particle sizes (Wang et al., 2010). In this study, therefore, the treatment protocol was developed using the integrated RF treatments with hot air, movement and mixing.

3.4. Almond quality

Table 2 shows the moisture contents in the almond kernel and shell before and after hot air and RF treatments. RF treatments did not significantly affect the kernel moisture content in both types of almonds ($P > 0.05$). But hot air treatments significantly reduced the kernel moisture content in shelled almonds ($P < 0.05$). Both the hot air and RF treatments resulted in significant reduction in the shell moisture content ($P < 0.05$).

Table 3 summarizes the results of almond quality evaluations during accelerated storage after hot air and RF treatments. Mean PV and FA values increased with storage time for both control and treated almonds. Hot air and RF treatments did not significantly affect the PV and FA values of both almonds immediately after treatment (0 d) and stored at 35 °C for 10 d ($P > 0.05$) except for the FA values in the shelled samples stored at 35 °C for 10 d ($P < 0.05$). All PV and FA values for the control and treated samples increased with storage time and most increases were significant ($P < 0.05$). The mean PV values of hot air and RF treated in-shell almonds decreased from 0.38 to 0.47 mequiv./kg for controls to below 0.36 mequiv./kg after accelerated storage for 10 and 20 d ($P < 0.05$). Similar reduction was also observed in RF treated walnuts (Wang et al., 2002b). This might be due to possible inactivation of the lipoxygenase enzymes by heat treatments (Buranasompob et al., 2003). For both in-shell and shelled almonds, the final PV and FA values during accelerated storage for up to 20 d remained within the acceptable range (PV < 1.0 mequiv./kg and FA < 0.6%) used by industry for good almond quality.

The color results show that *L*-, *a*- and *b*-values of kernel skin color and core color (*L*-values) decreased slightly after hot air and RF treatments and then increased after storage (Table 3). However, there were no significant differences ($P > 0.05$) in *L*-, *a*- and *b*-values of in-shell and shelled almond kernel skin color among the treatments and after storage. *L*-Values of almond cores for both types of almonds were above 86 after hot air and RF treatments. Accord-

Table 1
Comparisons of the temperature and heating uniformity index (mean ± SD over 2 replicates) of the in-shell and shelled almonds after RF heating with different conditions.

Almond	No hot air heating	With hot air heating	With movement	With hot air + movement	With hot air + movement + mixing
Surface temperatures (°C)					
In-shell	58.5 ± 3.9	60.9 ± 2.6	58.5 ± 3.8	62.4 ± 2.3	60.6 ± 2.1
Shelled	58.2 ± 2.9	65.7 ± 2.4	61.0 ± 3.1	68.2 ± 2.5	65.2 ± 2.0
Surface heating uniformity index					
In-shell	0.110 ± 0.002	0.071 ± 0.017	0.108 ± 0.005	0.060 ± 0.001	0.058 ± 0.002
Shelled	0.083 ± 0.000	0.058 ± 0.016	0.082 ± 0.001	0.057 ± 0.000	0.046 ± 0.009
Interior layer kernel temperature (°C)					
In-shell	58.1 ± 2.1	58.2 ± 1.3	59.3 ± 1.8	60.0 ± 1.2	59.1 ± 1.1
Shelled	64.5 ± 4.7	61.9 ± 3.1	62.5 ± 2.7	66.4 ± 3.1	64.9 ± 1.9
Interior layer kernel uniformity index					
In-shell	0.060 ± 0.002	0.034 ± 0.004	0.050 ± 0.001	0.033 ± 0.009	0.031 ± 0.004
Shelled	0.136 ± 0.059	0.075 ± 0.006	0.073 ± 0.039	0.071 ± 0.050	0.045 ± 0.004

Table 2
Moisture contents (mean ± SD over 3 replicates, % w.b.) of the kernel and shell in almonds before and after hot air and integrated radio frequency (RF) treatments.

Almond	Kernel			Shell		
	Control	Hot air	RF	Control	Hot air	RF
In-shell	3.86 ± 0.63a	3.23 ± 0.05a	3.23 ± 0.05a	6.44 ± 0.06a	3.67 ± 0.05b	4.50 ± 0.04b
Shelled	2.78 ± 0.42a	2.65 ± 0.06b	2.92 ± 0.06a	–	–	–

Different letters indicate that means are significantly different ($P < 0.05$) among different treatments.

Table 3
Storage quality characteristics (mean ± SD over 3 replicates) of shelled and in-shell almond kernels before and after treatments by hot air and integrated radio frequency (RF) heating.

Almond type	Shelled			In-shell		
Storage time (days) at 35 °C[a]	0	10	20	0	10	20
Peroxide value (mequiv./kg)[b]						
Control	0.24 ± 0.01aA	0.32 ± 0.07aA	0.67 ± 0.01aB	0.24 ± 0.03aA	0.38 ± 0.01aB	0.47 ± 0.02aC
Hot air	0.22 ± 0.02aA	0.34 ± 0.02aB	0.51 ± 0.05bC	0.24 ± 0.01aA	0.31 ± 0.03bB	0.36 ± 0.05bB
RF	0.21 ± 0.01aA	0.32 ± 0.02aB	0.45 ± 0.01cC	0.23 ± 0.06aA	0.24 ± 0.01cA	0.30 ± 0.02cB
Fatty acid (%)[b]						
Control	0.17 ± 0.02aA	0.24 ± 0.01aB	0.28 ± 0.01aC	0.11 ± 0.05aA	0.13 ± 0.03aA	0.20 ± 0.01aB
Hot air	0.24 ± 0.03aA	0.40 ± 0.03bB	0.40 ± 0.02bB	0.17 ± 0.01aA	0.21 ± 0.00bB	0.27 ± 0.03bC
RF	0.20 ± 0.02aA	0.23 ± 0.01aA	0.32 ± 0.00cB	0.15 ± 0.02aA	0.15 ± 0.01aA	0.26 ± 0.02bB
Kernel skin color						
L[c]						
Control	48.09 ± 2.70	48.07 ± 2.35	49.47 ± 2.18	58.76 ± 2.95	59.72 ± 3.39	61.54 ± 2.81
Hot air	46.83 ± 2.81	48.81 ± 2.63	50.48 ± 1.95	57.34 ± 3.76	61.65 ± 3.16	60.52 ± 2.77
RF	45.98 ± 2.91	48.21 ± 2.40	49.96 ± 2.40	57.75 ± 3.96	59.84 ± 3.60	63.42 ± 2.91
a						
Control	14.91 ± 0.80	15.24 ± 0.52	15.65 ± 0.85	12.57 ± 1.44	13.55 ± 2.11	13.51 ± 2.12
Hot air	13.77 ± 0.74	15.23 ± 1.09	17.87 ± 0.69	11.15 ± 1.82	12.06 ± 2.12	13.80 ± 1.70
RF	13.43 ± 0.99	15.30 ± 0.65	17.04 ± 0.67	11.61 ± 1.57	13.50 ± 2.25	12.14 ± 1.72
b						
Control	40.92 ± 1.90	41.37 ± 1.71	41.08 ± 1.58	47.29 ± 1.50	48.79 ± 1.69	49.67 ± 2.01
Hot air	40.07 ± 2.07	40.85 ± 1.95	42.19 ± 1.75	44.71 ± 1.91	47.48 ± 1.30	48.32 ± 1.46
RF	39.29 ± 2.18	41.42 ± 1.67	42.06 ± 1.92	46.42 ± 2.15	48.82 ± 1.85	49.52 ± 1.66
Kernel core color (*L*-value)						
Control	89.21 ± 1.34	88.49 ± 1.01	90.31 ± 1.13	87.68 ± 1.32	86.37 ± 1.20	88.53 ± 1.18
Hot air	89.14 ± 1.43	91.64 ± 1.04	92.37 ± 2.16	86.16 ± 1.63	89.62 ± 0.99	89.43 ± 1.08
RF	89.94 ± 1.80	88.44 ± 1.13	92.85 ± 1.06	86.88 ± 0.98	86.35 ± 1.21	90.15 ± 1.39

Different lower and upper case letters indicate that means are significantly different among treatments and storage time, respectively, at $P = 0.05$.
[a] 10 and 20 d at 35 °C to simulate 1 and 2 years storage at 4 °C, respectively.
[b] Accepted PV and FA values for good quality are less than 1.0 mequiv./kg and 0.6%, respectively.
[c] *L*-Value (lightness): 0 = black and 100 = white; good quality ≥ 40.

ing to almond industry standards, acceptable *L*-values for product color are >40. Consequently, the final color of the treated almonds would be acceptable to the almond industry.

4. Conclusions

An appropriate RF heating rate (6–8 °C/min) was obtained by adjusting the electrode gap for in-shell and shelled almonds. RF treatments provided fast and volumetric heating in almond samples as compared to hot air heating. RF heating uniformity was greatly improved by using 63 °C forced hot air, back and forth movement, and single mixing of the samples. After achieving the required heating uniformity, a RF treatment protocol was developed for pest control in almonds. The protocol consisted of RF heated to 63 °C, holding for 2 min in hot air, followed by forced room air cooling in a single layer for shelled or 5 cm layer for in-shell almonds. Almond quality was not affected by the RF treatments because PV, FA values and kernel color of treated almonds were better than or similar to untreated controls after 20 d at 35 °C simulating 2 years of storage at 4 °C. RF treatments did not significantly affect the kernel moisture content of both in-shell and shelled almonds, but reduced the moisture content of the shell. This RF technology may enhance sustainability and competitiveness of the almond industry in international markets if the treatment efficacy is validated in commercial settings.

Acknowledgements

This research was conducted by visiting scholars: Drs. M. Gao and Y. Wang in the Department of Biological Systems Engineering, Washington State University (WSU) and partially supported by grants from USDA-CSREES (2008-34103-19091). We thank Dr. G. Huang (Almond Board of California) for providing in-shell and shelled almond samples.

References

[ABC] Almond Board of California, 2005. California Almond Facts. ABC, Modesto, CA.
AOCS, 1997a. AOCS Official Method Ca 2b-25: Moisture and Volatile Matter Vacuum Oven Method, in Sampling and Analysis of Commercial Fat and Oils. AOCS, Washington, DC.
AOCS, 1997b. AOCS Official Method Ca 5a-40: Free Fatty Acids, in Sampling and Analysis of Commercial Fat and Oils. AOCS, Washington, DC.
AOCS, 2003. AOCS Official Method Cd 8b-90: Peroxide Value Acetic Acid-Isooctance Method, in Sampling and Analysis of Commercial Fat and Oils. AOCS, Washington, DC.
Buranasompob, A., Tang, J., Mao, R., Swanson, B.G., 2003. Rancidity of walnuts and almonds affected by short time heat treatments for insect control. J. Food Process. Pres. 27, 445–464.
Buranasompob, A., Tang, J., Powers, J.R., Reyes, J., Clark, S., Swanson, B.G., 2007. Lipoxygenase activity in walnuts and almonds. LWT-Food Sci. Technol. 40, 893–899.
Fleurat-Lessard, F., 1990. Effect of modified atmospheres on insects and mites infesting stored products. In: Food Preservation by Modified Atmospheres. CRC Press, Boca Raton, pp. 21–38.
Hallman, G.J., 1999. Ionizing radiation quarantine treatments against tephritid fruit flies. Postharvest Biol. Technol. 16, 93–106.
Hallman, G., Miller, W.R., 1994. Irradiation as an alternative to methyl bromide quarantine treatment for plum Curculio in blueberries. In: Proceedings from the 1994 International Conference on Methyl Bromide Alternatives and Emissions Reductions, Kissimmee, FL.
Hallman, G.J., Sharp, J.L., 1994. Radio frequency heat treatments. In: Sharp, J.L., Hallman, G.J. (Eds.), Quarantine Treatments for Pests of Food Plants. Westview Press, San Francisco, CA, pp. 165–170.
Heather, N.W., Hallman, G., Heather, N., 2008. Pest Management & Phytosanitary Trade Barriers. CABi Publishing, Cambridge, MA, p. 272.
Johnson, J.A., Marcotte, M., 1999. Irradiation control of insect pests of dried fruits and walnuts. Food Technol. 53, 46–51.

Johnson, J.A., Vail, P.V., Soderstrom, E.L., Curtis, C.E., Brandl, D.G., Tebbets, J.S., Valero, K.V., 1998. Integration of nonchemical, postharvest treatments for control of navel orangeworm (Lepidoptera: Pyralidae) and Indianmeal moth (Lepidoptera: Pyralidae) in walnuts. J. Econ. Entomol. 91, 1437–1444.

Johnson, J.A., Valero, K.A., Hannel, M.M., 1997. Effect of low temperature storage on survival and reproduction of Indianmeal moth (Lepidoptera: Pyralidae). Crop Prot. 16, 519–523.

Johnson, J.A., Valero, K.A., Wang, S., Tang, J., 2004. Thermal death kinetics of red flour beetle, *Tribolium castaneum* (Coleoptera: Tenebrionidae). J. Econ. Entomol. 97, 1868–1873.

Johnson, J.A., Wang, S., Tang, J., 2003. Thermal death kinetics of fifth instar *Plodia interpunctella* (Lepidoptera: Pyralidae). J. Econ. Entomol. 96, 519–524.

Lagunas-Solar, M.C., Pan, Z., Zeng, N.X., Truong, T.D., Khir, R., Amaratunga, K.S.P., 2007. Application of radio frequency power for non-chemical disinfestation of rough rice with full retention of quality attributes. Appl. Eng. Agric. 23, 647–654.

Mitcham, E.J., Veltman, R.H., Feng, X., de Castro, E., Johnson, J.A., Simpson, T.L., Biasi, W.V., Wang, S., Tang, J., 2004. Application of radio frequency treatments to control insects in in-shell walnuts. Postharvest Biol. Technol. 33, 93–100.

Nelson, S.O., 1996. Review and assessment of radio-frequency and microwave energy for stored-grain insect control. Trans. ASAE 39, 1475–1484.

Saour, G., Makee, H., 2004. Susceptibility of potato tuber moth (Lepidoptera: Gelechiidae) to postharvest gamma irradiation. J. Econ. Entomol. 97, 711–714.

Tang, J., Ikediala, J.N., Wang, S., Hansen, J.D., Cavalieri, R.P., 2000. High-temperature–short-time thermal quarantine methods. Postharvest Biol. Technol. 21, 129–145.

Taoukis, P.S., Labuza, T.P., Sagus, I.S., 1997. Kinetics of food deterioration and shelf-life prediction. In: Valentas, K.J., Rotstein, E., Singh, R.P. (Eds.), Handbook of Food Engineering Practice. CRC Press, Boca Raton, p. 374.

UNEP, 1992. Fourth Meeting of the Parties to the Mont Real Protocol on Substances that Deplete the Ozone Layer. Unite Nations Environment Program, Copenhagen, Denmark.

USDA-APHIS-PPQ, 2009. Treatment Manual: Interim Edition. U. S. Dept. Agric., Animal Plant Health Inspection Service, Plant Protection Quarantine, Riverdale, MD.

[USEPA] United States Environmental Protection Agency, August 2001. Toxicological Review of Acetone, NCESA-S-1093.

Wang, S., Ikediala, J.N., Tang, J., Hansen, J.D., Mitcham, E., Mao, R., Swanson, B., 2001a. Radio frequency treatments to control codling moth in in-shell walnuts. Postharvest Biol. Technol. 22, 29–38.

Wang, S., Monzon, M., Johnson, J.A., Mitcham, E.J., Tang, J., 2007a. Industrial-scale radio frequency treatments for insect control in walnuts: I. Heating uniformity and energy efficiency. Postharvest Biol. Technol. 45, 240–246.

Wang, S., Monzon, M., Johnson, J.A., Mitcham, E.J., Tang, J., 2007b. Industrial-scale radio frequency treatments for insect control in walnuts: II. Insect mortality and product quality. Postharvest Biol. Technol. 45, 247–253.

Wang, S., Tang J., 2007. Heating uniformity and differential heating of insects in almonds in radio frequency systems. In: 2007 ASABE Annual International Meeting, June 17–20, 2007, Minneapolis, Minnesota. Paper No. 076019. ASABE, St. Joseph, MI, USA. p. 10.

Wang, S., Tang, J., Cavalieri, R.P., 2001b. Modeling fruit internal heating rates for hot air and hot water treatments. Postharvest Biol. Technol. 22, 257–270.

Wang, S., Tang, J., Johnson, J.A., Hansen, J.D., 2002a. Thermal death kinetics of fifth-instar *Amyelois transitella* (Walker) (Lepidoptera: Pyralidae) larvae. J. Stored Prod. Res. 38, 427–440.

Wang, S., Tang, J., Johnson, J.A., Mitcham, E., Hansen, J.D., Cavalieri, R., Bower, J., Biasi, B., 2002b. Process protocols based on radio frequency energy to control field and storage pests in in-shell walnuts. Postharvest Biol. Technol. 26, 265–273.

Wang, S., Tang, J., Sun, T., Mitcham, E.J., Koral, T., Birla, S.L., 2006. Considerations in design of commercial radio frequency treatments for postharvest pest control in inshell walnuts. J. Food Eng. 77, 304–312.

Wang, S., Tiwari, G., Jiao, S., Johnson, J.A., Tang, J., 2010. Developing postharvest disinfestation treatments for legumes using radio frequency energy. Biosyst. Eng. 105, 341–349.

Wang, S., Yue, J., Chen, B., Tang, J., 2008. Treatment design of radio frequency heating based on insect control and product quality. Postharvest Biol. Technol. 49, 417–423.

Wang, S., Yue, J., Tang, J., Chen, B., 2005. Mathematical modeling of heating uniformity of in-shell walnuts in radio frequency units with intermittent stirrings. Postharvest Biol. Technol. 35, 97–107.

Zettler, J.L., Halliday, W.R., Arthur, F.H., 1989. Phosphine resistance in insects infesting stored peanuts in the southeastern United States. J. Econ. Entomol. 82, 1508–1511.