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Heating uniformity and differential heating of insects in almonds associated with radio frequency energy

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ABSTRACT

Radio frequency (RF) treatments have potential as alternatives to chemical fumigation for phytosanitary disinfestation treatments in the dried nut industry. To develop effective RF treatment protocols for almonds, it is desirable to determine heating uniformity and the occurrence of RF differential heating of insects. This study compared heating uniformity in almonds (Nonpareil) heated by RF and by forced hot air. A mathematical model suggested a 4.7 and 6.0 °C RF preferential heating of the target pest navel orangeworm (*Amyelois transitella* [Walker]) over almonds at heating rates of 5 and 10 °C min^{-1}, respectively, for the loss factor ratio of 183 at 27.12 MHz, when the heat transfer coefficient between insects and almonds was set at 500 W m^{-2} °C^{-1}. To validate the model, a gellan gel with dielectric properties similar to those of the target pest was used as a model insect. When almond kernels were heated at 27.12 MHz from 21 °C to 55 °C, the model insects were differentially heated about 4.6 °C and 5.6 °C higher than the kernel temperatures at heating rates of 5 and 10 °C min^{-1}, respectively. These values corresponded to a heating rate for the model insect of 1.2 times greater than that for almond kernels. Slight preferential heating of insects in almonds using RF energy would improve the efficacy of large-scale RF treatments.

1. Introduction

Over 750,000 tons of almonds were produced in 2010 in the United States, which is estimated to be worth over US$2.7 billion and nearly 64% of which is for export (USDA, 2012). A major problem in the production, processing and storage of almonds is infestation by various insects. Infestations often cause customer returns and loss of consumer confidence, and may result in legal or regulatory actions. With the restriction of methyl bromide use (UNEP, 1992), many almond processors in California are, instead, using hydrogen phosphide (phosphine) for postharvest phytosanitary treatments. But fumigation with phosphine requires at least two more days exposure than with methyl bromide to ensure insect kill, making phosphine not suitable for applications where a quick treatment is required. In addition, because some processors use phosphine at suboptimal rates, the resultant lack of control may result in increased resistance in pest populations (Zettler et al., 1989; Opit et al., 2012). Phosphine is also a toxic gas (USEPA, 2001), which creates safety concerns for workers. There is, therefore, a growing interest in developing non-chemical alternatives to fumigation for almonds.

Radio frequency (RF) heating has long been proposed as a potential alternative to chemical fumigation for postharvest insect control in agricultural commodities (Headlee and Burdette, 1929; Frings, 1952; Nelson and Payne, 1982; Tang et al., 2000; Lagunas-Solar et al., 2007). Little progress in developing successful commercial RF treatments was made in the 1990s mainly due to non-uniform heating (Hallman and Sharp, 1994; Nelson, 1996). The non-uniform heating in RF treated produce caused by variations in thermal properties and moisture contents in a non-uniform RF field (Wang et al., 2008) would result in either insect survival or thermal damage to treated commodities. Based on results with a laboratory-scale RF system used to control codling moth and navel orangeworm in walnuts, Wang et al. (2001a,b) added hot air heating and mixing to improve RF heating uniformity, leading to successful development of a large-scale RF treatment for disinfesting walnuts and other dry products (Wang et al., 2007a,b; Jiao et al., 2012; Pan

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et al., 2012). Similar research is desirable for determining heating uniformity in almonds using both hot air and RF energy.

An attractive feature of insect control using RF energy is the possible differential heating of insects in agricultural commodities. If the insects were heated faster than the commodities they infest, insects would reach a lethal temperature while the commodities would be heated to a lower temperature that does not cause quality loss. Based on measured dielectric properties, Nelson and Charity (1972) suggested that it would be possible to generate differential heating in rice weevil, *Sitophilus oryzae* (L.), in hard red winter wheat in a frequency range between 10 and 100 MHz. Wang et al. (2003a) reported, based on direct measurements using model insects made from both gellan gel and insect slurry, as well as from model predictions, that codling moth larvae were heated 1.4–1.7 times faster than walnut kernels at 27.12 MHz but no preferential heating was observed and predicted at microwave frequencies 915 MHz and above. Previous thermal death kinetic studies determined fifth-instar navel orangeworm (*Amyelois transitella* [Walker]) to be the most heat tolerant species and stage in almonds (Wang et al., 2002a,b; Johnson et al., 2003, 2004). Further research is needed to determine the differential heating of navel orangeworm in almonds, thus compensating for possible non-uniform heating and allowing development of practical RF treatments for the almond industry.

Objectives of this study were: 1) to determine the temperature distributions within almond kernels when subjected to forced hot air heating; 2) to explore the temperature uniformity of almonds in RF heating; and 3) to theoretically and experimentally determine the possible differential heating of model insects in in-shell almonds at different heating rates when subjected to 27.12 MHz RF heating.

2. Materials and methods

2.1. Heat transfer model

Temperature difference between insects and host commodities could result from differential heating caused by RF energy. Since insect thermal lethality is primarily a function of the final temperature experienced by the insects during RF heating, energy loss from the large commodity volume was neglected in the model, which only focused on the absorbed RF energy. However, significant thermal transfer may occur between insects and commodity because of the relatively small size of the insect body when compared to the commodity. If the geometry of insect larvae, such as the navel orangeworm, was characterized as a cylindrical shape, and agricultural commodities, such as almonds (*Nonpareil*), were heated uniformly over their volumes when the insects and commodity were exposed to the same RF field, the following energy balance equations can be established according to Wang et al. (2003a):

$$\begin{cases} \rho_i C_{pi} V_i \frac{dT_i}{dt} = P_i V_i - hA_i (T_i - T_a) \\ \rho_a C_{pa} \frac{dT_a}{dt} = P_a \end{cases} \tag{1}$$

where A_i is the insect body surface area (m^2); V_i is the insect body volume (m^3); C_{pi}, C_{pa} are the specific heat of the insect (3450 J kg^{-1} °C^{-1} for navel orangeworm larvae) and host commodity (2510 J kg^{-1} °C^{-1} for almond kernel), respectively; h is the heat transfer coefficient between insect and host commodity (W m^{-2} °C^{-1}); ρ_i, ρ_a are the density of insect (1000 kg m^{-3}) and host commodity (1015 kg m^{-3} for almond kernel; Aydin, 2003), respectively; P_i, P_a are the RF energy absorbed by the insect and the host commodity (W m^{-3}), respectively; t is the heating time (s); and T_i, T_a are the temperatures of the insect and the commodity (°C), respectively. The thermal energy that is converted from the RF field can be expressed as (Nelson, 1996):

$$P = 5.56 \times 10^{-11} \, fE^2 \varepsilon'' \tag{2}$$

where P is the thermal energy generated per unit volume (W m^{-3}) in a dielectric material; f is the frequency (Hz); E is the electric field intensity (V m^{-1}); and ε'' is the dielectric loss factor. Using the ratio of surface to volume of cylindrically shaped insects ($A_i/V_i = 4/D$) as assumed in similar heating models (Ikediala et al., 2000; Ben-Lalli et al., 2013) and combining Eqs. (1) and (2), the temperature difference between the insect and the host commodity can be derived from the following relationship (Wang et al., 2003a):

$$T_i - T_a = \frac{DP_a}{4h}\left(\frac{\varepsilon_i''}{\varepsilon_a''} - \frac{\rho_i C_{pi}}{\rho_a C_{pa}}\right)\left[1 - \exp\left(-\frac{4ht}{D\rho_i C_{pi}}\right)\right] \tag{3}$$

where D is insect body diameter (0.002 m for fifth-instar navel orangeworm larvae). According to Eq. (3), the temperature difference (T_i–T_a) increases with increasing dielectric loss factor ratio ($\varepsilon_i''/\varepsilon_a''$) and decreasing surface heat transfer coefficient (h). Based on data derived from Wang et al. (2003a), Fig. 1 shows that the loss factor of navel orangeworm larvae increased with increasing temperature and was much larger than that of almond kernels at 27 MHz. The measured loss factor ratio between them was 257 at 27 MHz and room temperature. A reasonable range of heat transfer coefficient value (100–900 W m^{-2} °C^{-1}) was selected to include both poor and good contact between insects and almond kernels (Dincer, 1997) with a heat transfer coefficient of around 50 W m^{-2} °C^{-1} for pure air heating (Tang et al., 2000) and 1000 W m^{-2} °C^{-1} for two metals in close contact with each other (Incropera and DeWitt, 1996). Using the model, the predicted differential heating between insects and almonds was plotted as a function of the dielectric loss factor ratio and the surface heat transfer coefficient and compared to the experimental values obtained using comparable RF power and heating times.

2.2. Heating uniformity

Heating uniformity is one of the important factors in developing a treatment protocol for postharvest insect control in almonds. A 2.5 kW tray drier (UOP8, Armfield Limited, UK) was first used to determine the heating uniformity of almonds under a forced hot air system, which consisted of an electric axial fan adjusted to

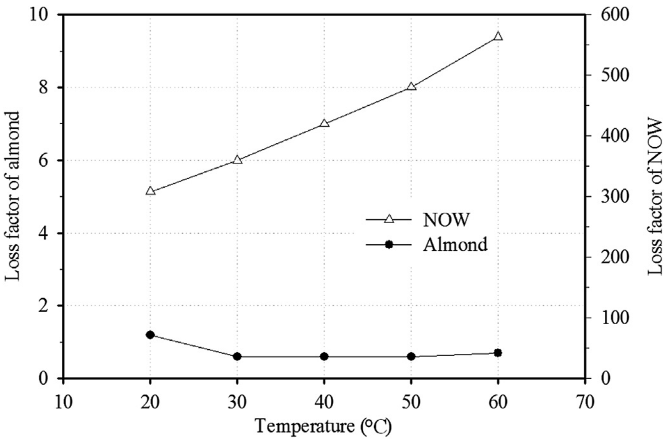

Fig. 1. Comparison of dielectric loss factors (ε'') of almond kernels and navel orangeworm (NOW) larvae as a function of temperature at 27 MHz (updated from Wang et al., 2003b).

maintain constant airflow velocity (1 m s^{-1}), volumetric airflow rate (0.08 m^3 s^{-1}), and a given air temperature. Almond samples were placed in the middle section of the air heating duct (28 cm × 28 cm). Temperatures of the air and of the interior of a shelled kernel, a kernel in an opened shell, and one in a closed shell were measured with thermocouples (Type-T, 0.8-mm diameter and 0.8 s response time, Omega Engineering Ltd, Stamford, CT, USA) placed through drilled holes during hot forced air heating and ambient air cooling. Similarly, five thermocouples were used to determine the temperature distribution during hot forced air heating and ambient air cooling within an 800 g sample of in-shell almonds in a plastic container (28 cm × 18 cm × 7 cm) with perforated bottom and side walls. The thermocouples were located in the middle layer of the container (Fig. 2). The temperature data were recorded every 5 s by a data logger (DL2e, Delta-T Devices Ltd., Cambridge, UK). Measurements were replicated twice.

A 6 kW, 27.12 MHz pilot-scale free-running oscillator RF system (COMBI 6-S, Strayfield International Limited, Wokingham, UK) was used in this study. A detailed description of the system can be found in Wang et al. (2002c). The RF heating uniformity test was also conducted with 800 g in-shell almonds in the same container described above, in which 4 temperatures in the 4 corners in the middle layer (Fig. 2) were measured by FISO fibre-optic sensors (UMI, FISO Technologies Inc., Saint-Foy, Quebec, Canada). This system had 20 Hz sampling rate, 0.01% temperature resolution and 0.5% accuracy of full-scale measurements. Measurements were repeated twice.

To determine the electrical current (or power) corresponding to the required heating rate for subsequent differential heating tests, 50 almonds in a single layer in the container described above were heated in the RF system and their temperatures monitored with fibre-optic sensors. The current was changed between 0.38 A and 0.5 A by adjusting the gap between the plate electrodes to obtain heating rates that ranged from 0 to 10 °C min^{-1}.

2.3. Measurements of differential heating

Because direct insertion of temperature probes into a live insect will cause loss of body fluid and the body diameter of some insects is smaller than that of the fibre-optic temperature sensors that must be used for temperature measurement in an RF field, temperature measurement in real insects is not reliable and inappropriate during RF heating. A model insect was thus developed by using a gellan gel at 0.17% salt solution, which had similar dielectric and thermal properties to those of insects. This method was proven to work well in experiments to validate differential heating of fifth-instar codling moth in walnuts (Wang et al., 2003a). Based on dielectric properties data (Wang et al., 2003b), although the dielectric constant and loss factor (80.2 and 307.8, respectively) of navel orangeworm larvae at 20 °C and 27.12 MHz were different from those (82.5 and 220.5, respectively) of the gellan gel, the dielectric loss factor for both had a similar trend that increased with increasing temperature. This difference would underestimate the differential heating of real insects in almonds, but the comparison of differential heating could be made in walnuts versus in almonds using the same gel. Details about preparing the gel and handling procedures are described in Wang et al. (2003a).

For each test run, two insect-size gellan gel cylinders were inserted into drilled holes in two almond kernels. Fibre-optic temperature sensors were inserted through drilled holes in the shell to measure almond kernel and gel temperatures. Probes were arranged in pairs: one of each pair measured the gel temperature, and the other measured almond kernel temperature. The two pairs of almonds were placed together in the centre of the container in a single layer of 800 g almonds to avoid uneven heating. Temperatures during RF heating and ambient air cooling were measured for heating rates of 5 and 10 °C min^{-1} and recorded at an interval of 5 s. Each test was repeated two times.

3. Results and discussion

3.1. Heating uniformity in hot air systems

Figure 3 shows temperature profiles in the single almond kernel with different shell conditions during hot air heating. Initially, all the kernel temperatures increased quickly but their heating rates decreased as kernel temperatures approached the air temperature (58 °C). Temperatures in the shelled kernel increased faster than the kernel with the opened shell followed by that with closed shell. It took 4.3, 6.7, and 8.7 min to achieve 50 °C for the shelled kernel, the kernel with opened shell, and with closed shell, respectively. Similar temperature trends were found in the cooling process. The almond temperature profile was similar to that for in-shell walnuts (Tang et al., 2000), but the time needed for almond kernels to achieve 50 °C was a little shorter than that for walnuts due to a reduction in heat transfer through the void within the walnut shell.

Figure 4 shows the temperature distributions of almond kernels at different positions in the container (800 g almond samples) when subjected to hot air heating and forced ambient air cooling. The kernel temperatures located upstream of the airflow (P1 and P4) increased faster than those downstream of the airflow (P3 and P5). The kernel temperature at the centre of the container (P2) was the lowest one among the 5 locations and took almost 49 min to

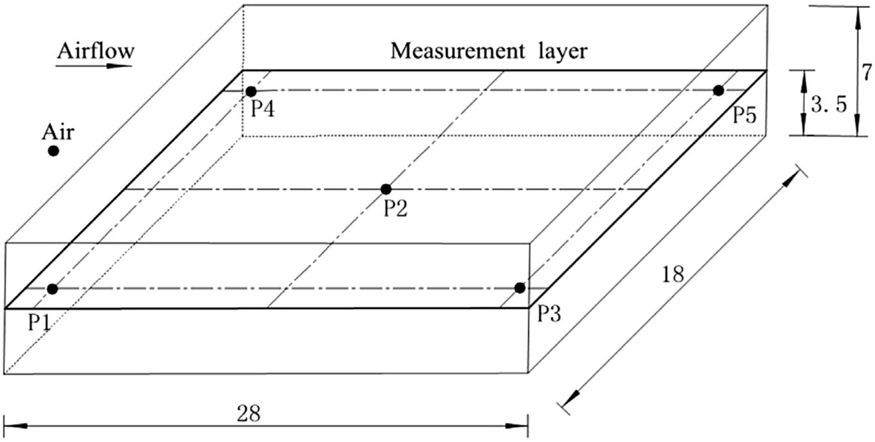

Fig. 2. Temperature sensor locations (P1–P5) in the middle layer of the sample container holding 800 g almonds for hot air heating (all dimensions are in cm).

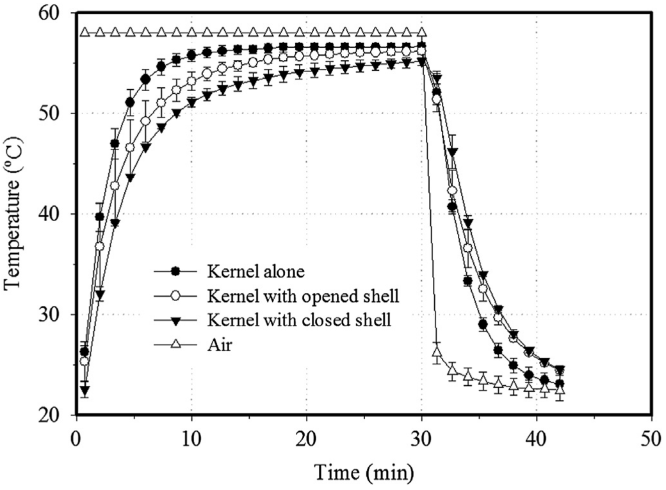

Fig. 3. Mean (±SD) temperatures in the centre of single kernels when subjected to hot air heating and forced ambient air cooling.

reach 48 °C. The results suggested that improved heating method and uniformity are needed.

3.2. Heating uniformity in RF systems

Temperature measurements taken from almond kernels in the centre of the sample during RF treatment (RF power = 1 kW, data not shown) showed that the almond kernel temperature increased linearly with process time, comparable to other fruit and dried nut commodities (Wang et al., 2001b, 2002c; Birla et al., 2004; Mitcham et al., 2004). It took about 7 min for the kernel temperatures to reach 67 °C, a significantly shorter heating time when compared to hot air heating (49 min). Increasing RF power input can further increase the heating rate, because RF energy interacts directly with almonds containing polar molecules and charged ions to generate heat volumetrically (Nelson, 1996; Wang et al., 2003b).

Figure 5 shows the kernel heating rate for 50 almonds in a single layer of the container as a function of the electrical current in the RF system. When the current was less than 0.38 A, no heating in almonds was observed. Heating rate increased as RF power increased. Heating rates from 0 to 9 °C min^{-1} were achieved within the almond kernels. The regression equation between heating rate (α, °C min^{-1}) and current (I, A) was $\alpha = -29.41 + 77.31 \times \text{I}$ with $R^2 = 0.99$. This function was used in subsequent differential heating tests to select the power needed to achieve the two targeted heating rates.

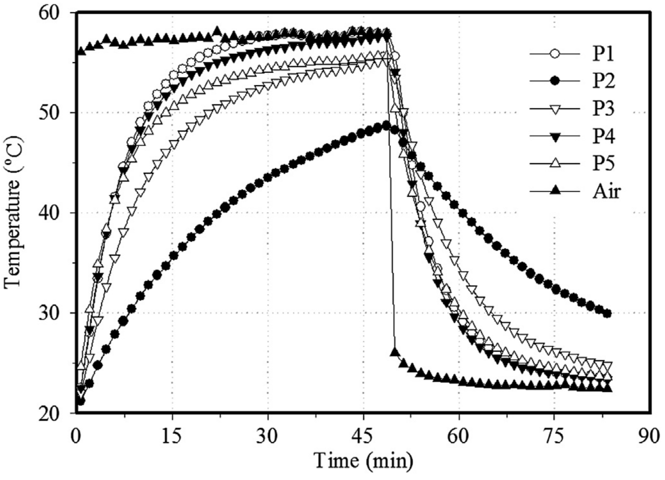

Fig. 4. Typical kernel temperatures of open-shell almonds at different positions in the sample container (indicated in Fig. 1) when subjected to hot air heating and forced ambient air cooling.

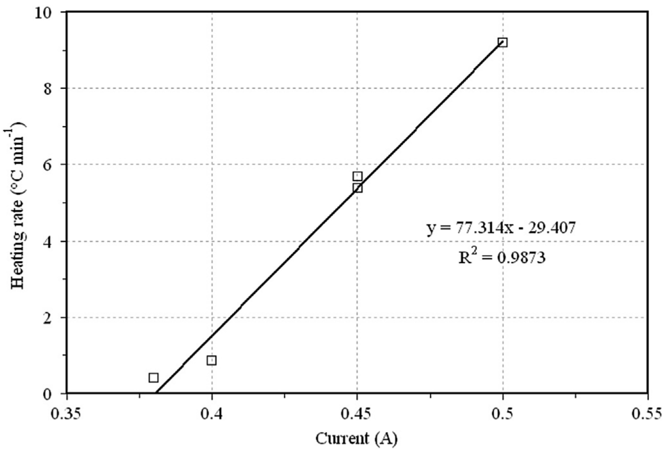

Fig. 5. Heating rate in almond kernel samples as a function of the electrical current in RF system.

Figure 6 shows the mean and standard deviation temperatures of almond kernels over four locations in one layer when heated in the RF system. The mean and standard deviation of measured temperatures in four kernels increased with heating time and reached 55.2 °C ± 3.1 °C at the end of the RF heating. Due to heat loss to the ambient air, the average almond kernel temperature decreased 13.5 °C in 5 min–41.7 °C ± 3.4 °C after the RF energy was turned off, indicating that cooling of almonds in ambient air was also faster than that of walnuts (less than 5 °C temperature decrease in the same time period, Wang et al., 2007a). This is due to the lack of large air voids within in-shell almonds. The non-uniform heating in RF systems suggested that the targeted almonds for subsequent differential heating tests should be placed close together. As with earlier walnut tests (Wang et al. 2002c, 2007a), these results also suggest that combining RF heating with hot forced air and possibly mixing of the product would improve heating uniformity and be helpful in developing an effective treatment protocol for post-harvest insect control without quality degradation.

3.3. Differential heating at 27.12 MHz RF systems

Figure 7 shows the predicted temperature difference between insects and almond kernels as a function of dielectric loss factor

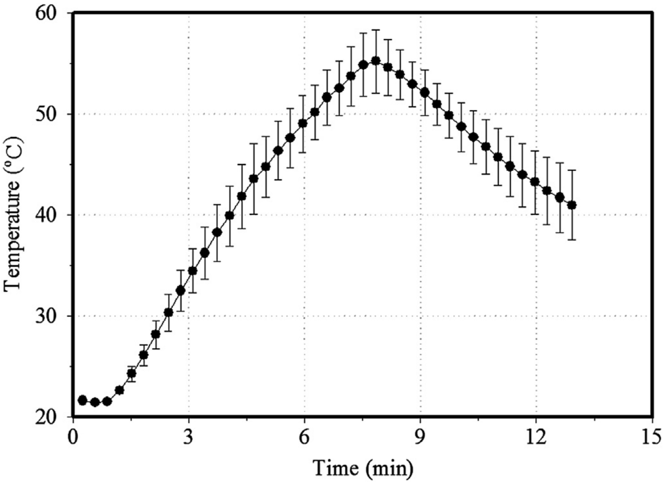

Fig. 6. Mean (±SD) values of 4 almond kernel temperatures in the 4 corners of the sample container when subjected to RF heating followed by 5 min ambient air cooling.

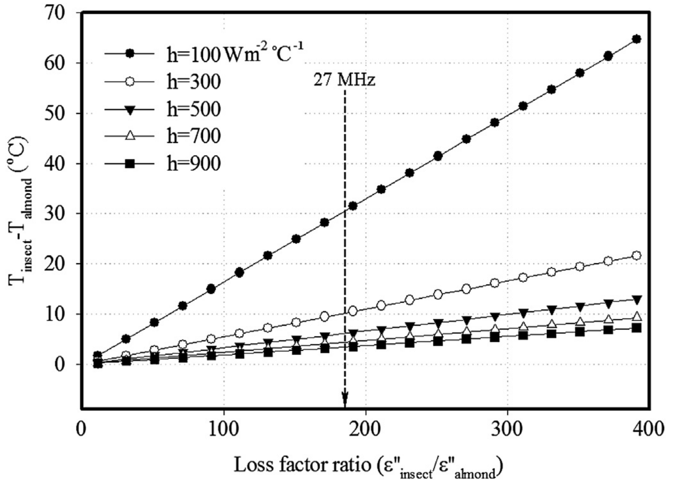

Fig. 7. Predicted temperature difference between insects and almonds as a function of dielectric loss factor ratios and heat transfer coefficients (h) after RF treatments at a heating rate of 10 °C min^{-1} for 3.4 min.

ratios (from 1 to 400) and heat transfer coefficients (from 100 to 900 W m^{-2} °C^{-1}) after 3.4 min RF heating at 10 °C min^{-1}. The temperature difference increased with increasing loss factor ratio, especially for the lowest heat transfer coefficient (100 W m^{-2} °C^{-1}). When the values of heat transfer coefficients were large (≥700 W m^{-2} °C^{-1}), the temperature difference was less than 9 °C even when the dielectric loss factor of the insect was 400 times larger than that of almonds. Given a heat transfer coefficient (h) of 500 W m^{-2} °C^{-1} at a loss factor ratio of 184 at 27.12 MHz, the temperature difference between insects and almond kernels was estimated from Eq. (3) to be about 6.1 °C, which was lower than that for walnuts (Wang et al., 2003a). The temperature difference between navel orangeworm larvae and almond kernels would increase to 8.5 °C while the loss factor ratio was 257 at 20 °C as shown in Fig. 1. This is a conservative estimation since the loss factor ratio would increase when the insect and almond were heated together. The differential heating comparison also suggests that the temperature difference between insect and kernel at 5 °C min^{-1} was 4.6 and 4.7 °C, respectively, for the experiment (Fig. 8) and simulation (Fig. 7).

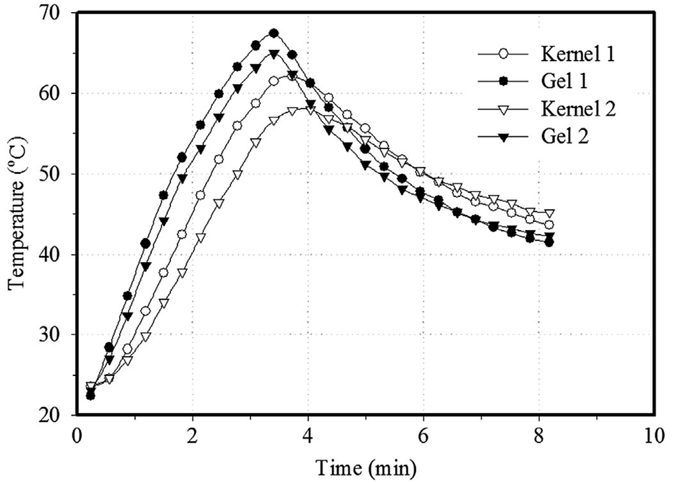

Fig. 8. Typical temperature profiles of almond kernels and gellan-gels (0.17% NaCl) when subjected to 27.12 MHz RF system followed by 5 min ambient air cooling.

Figure 8 shows a typical experimental temperature profile of gellan gel (size of a fifth-instar navel orangeworm) and almond kernels when heated in the 27.12 MHz system for 3.4 min at a heating rate of 10 °C min^{-1} and cooled in ambient air for 5 min. During the RF heating, gellan gel temperatures increased more rapidly than almond kernel temperatures, showing significant preferential heating of the gel. When almond kernel temperatures were raised to about 55 °C, the mean and standard deviation of temperature differences between the model insect and the kernel were 4.6 ± 1.9 °C and 5.6 ± 2.9 °C at heating rates of 5 and 10 °C min^{-1}, respectively. These mean temperature differences were close to the values (4.7 and 6.1 °C) predicted by Eq. (3) when the dielectric loss factor ratio (184) at 27.12 MHz and $h = 500$ W m^{-2} °C^{-1} were used. Both gel and kernel temperatures decreased rapidly as soon as the RF heating was stopped and gel temperatures were lower than kernel temperatures after 5 of ambient air cooling. Kernel temperatures dropped from 54.5 ± 0.7 °C and 55.1 ± 0.4 °C immediately after RF heating to 40.1 ± 1.0 °C and 42.1 ± 0.5 °C at the heating rates of 5 and 10 °C min^{-1}, respectively, during the 5-min ambient air cooling. Earlier studies on RF treatments of in-shell walnuts infested with fifth-instar codling moth also confirmed that the insects were preferentially heated at 27.12 MHz (Wang et al., 2001a, 2003a). In practical applications, this differential heating of insects in almonds should be maintained for a period of time after lethal temperatures were achieved. Suitable control of RF power could be used to maintain differential heating and obtain a desired temperature level for the pest. Therefore, this significant preferential heating of insects in almonds might be useful in developing postharvest RF treatments, helping to provide an adequate safety margin for pest control without causing thermal damage to product quality.

4. Conclusions

The slow and non-uniform heating of almonds found in hot air systems was improved with RF heating. The theoretical model developed to compare heating of insect pests and agricultural commodities predicted differential heating of navel orangeworm larvae in in-shell almonds using RF energy at 27.12 MHz. The predictions of the model were confirmed by direct temperature measurements using model insects made of gellan gel with dielectric properties and thermal properties similar to those of navel orangeworm larvae, and showed differential heating at heating rates of 5 and 10 °C min^{-1}. The mean temperature differences between model insects and almond kernels were 4.6 and 5.6 °C or 4.7 and 6.0 °C using experiments or simulation, at heating rates of 5 and 10 °C min^{-1}, respectively. Designing RF treatments to maintain differential heating and obtain optimum temperatures for both the pest and product would minimise the effect of non-uniform RF heating and ensure reliable control of insect pests without adversely affecting product quality.

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