DIFFERENTIAL HEATING OF INSECTS IN DRIED NUTS AND FRUITS ASSOCIATED WITH RADIO FREQUENCY AND MICROWAVE TREATMENTS

S. Wang, J. Tang, R. P. Cavalieri, D. C. Davis

ABSTRACT. *This research was conducted to provide a theoretical basis and experimental evidence to support the hypothesis that insect larvae can be preferentially heated in dry nuts and fruits by radio frequency (RF) heating for pest control. We selected codling moth larvae as the target insect and in–shell walnuts as the host material for this study, and focused our attention on one RF frequency (27 MHz) and one microwave frequency (915 MHz). Dielectric properties measurements showed that the loss factor ratio between codling moth larvae and walnut kernels at 20°C was 397 at 27 MHz and 4 at 915 MHz. The theoretical prediction for a 3 min treatment at 0.27 kW/kg suggested 12.0°C preferential heating of insect larvae for the loss factor ratio of 397 (corresponding to 27 MHz) and 0.1°C for the ratio of 4 (corresponding to 915 MHz), when the heat transfer coefficient between insects and walnuts was set at 500 W/m^2 °C. To prove differential heating predicted by the theoretical model, a gellan gel with dielectric properties similar to those of insects was used as a model insect. When walnut kernels were heated at 27 MHz from 20°C to 53°C, the model insects were differentially heated from 12.6°C to 21.2°C higher than the kernel temperature, depending on the power used and the treatment time. These values corresponded to a heating rate for the model insect of 1.4 to 1.7 times greater than that for walnut kernels. As predicted by the theoretical model, microwave heating at 915 MHz caused no differential heating of insects. Preferential heating of insects in dry nuts and fruits at radio frequencies can be used in developing thermal treatments to control insects without adversely affecting product quality.*

Keywords. *Codling moth, Dielectric properties, Differential heating, Microwaves, Radio frequencies, Walnuts.*

Dried nuts (including walnuts) and fruits are treated by chemical fumigation to control field and storage pests before being shipped to domestic and international markets. Because of increasing public concern about adverse impacts of chemical fumigation on humans and the environment, there is a heightened interest in developing non–chemical pest control methods, especially thermal methods. An important key to developing successful thermal treatments is to balance needs for a complete kill of insects with a minimal thermal impact on product quality. A common difficulty in using conventional hot–air disinfestation methods is the slow heating rate, non–uniform temperature distribution, and possible heat damage to heat–sensitive commodities (Hansen, 1992; Tang et al., 2000; Wang et al., 2001b). A more promising approach is to heat the commodity rapidly by radio frequency (RF) or microwave dielectric heating to control the insects in commodities (Nelson and Payne, 1982; Ikediala et al., 1999; Tang et al., 2000; Wang et al., 2001a). Tang et al. (2000) and Wang et al. (2002b) proposed thermal treatments based on RF energy to replace chemical fumigation to control the codling moth, *Cydia pomonella* (L.) (Lepidoptera: Tortricidae), and other insect pests in walnuts (*Juglans regia* L.).

Electromagnetic energy in RF (1 to 300 MHz) or microwave (300 to 30,000 MHz) heating has been studied to control insects in other commodities for many years. Headlee and Burdette (1929) reported results for determining lethal exposures for honeybees in a 12 MHz RF field. They observed that frequency, time, and voltage gradient were three important factors in killing insects. An attractive feature of insect control using an electromagnetic field is the possibility that the insects may be heated at a faster rate than the dry nuts and fruits they infest. If this were true, then the insects would reach a lethal temperature while the product would be heated to lower temperatures that do not cause quality loss. By exploring differences in the rate of heating between insect pests and host materials during RF or microwave heating, we can potentially reduce the time and the product temperature needed for effective treatments, thereby reducing adverse effects on product quality and enabling a greater throughput of product in a processing plant.

In general, temperature rise in insects and agricultural commodities when exposed to the same electromagnetic field depends not only on their dielectric properties but also

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on other physical properties, such as density and heat capacity. Frings (1952), Thomas (1952), and Watters (1962) pointed out that the dielectric loss factor of the insects must be higher than that of the host materials for possible differential heating. They concluded that there was little chance that the insects can be preferentially heated in fruits and vegetables. Based on dielectric properties measurements, 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. Nelson and Payne (1982) observed that an RF heating treatment at 40 MHz was more effective in killing pecan weevil, *Curculio caryae* (Horn) (Coleoptera: Curculionidae), in pecans than at a microwave frequency of 2450 MHz. Studies on dielectric heating treatments of rice weevils in wheat at 39 and 2450 MHz also showed that the lower frequency was much more effective in killing the insects (Nelson and Stetson, 1974), supporting possible selective heating of the insects (Nelson and Charity, 1972). To date, there exist no reported theoretical analyses backed with convincing experimental evidence to support the hypothesis that insect pests are differentially heated in commodities when they are subjected to an electromagnetic field.

The overall goal of this study was to establish a theoretical basis and provide convincing experimental evidence to prove or disprove the hypothesis that insect pests can be preferentially heated using electromagnetic energy. We selected in–shell walnuts as the commodity for study because of the imminent need to replace chemical fumigants for domestic and international markets, and we selected codling moth as the targeted insect pest because it is a quarantined insect pest in several countries, including Japan and South Korea. We focused on two frequencies: 27 MHz as a representative RF frequency, and 915 MHz as a typical frequency for microwaves. These frequencies are allocated in the U.S. for industrial, scientific, and medical applications. The specific objectives of this study, therefore, were: (1) to establish a theoretical basis for possible differential heating of insects in walnuts, (2) to determine dielectric properties of codling moth larvae and walnut kernels as a function of temperature and frequency, (3) to develop a gellan gel that has the same dielectric properties as targeted insects so it can be used as a model insect to make direct temperature measurement possible, and (4) to experimentally validate the theoretical prediction of the possible differential heating of the model insects in in–shell walnuts when subjected to RF (27 MHz) and microwave (915 MHz) treatments.

Materials and Methods

The degree of differential heating of insects in host commodities depends on the difference in the conversion of electromagnetic energy into thermal energy and the rate of heat transfer within the commodities. A thorough analysis requires the consideration of both processes.

Heat Transfer Model

The geometry of insect larvae, such as the codling moth, can be characterized as a cylindrical shape. Agricultural commodities (e.g., walnut kernels) and insect larvae are assumed to heat uniformly over their volumes when the insects and agricultural commodities are exposed to the same electromagnetic (RF or microwave) field. Assuming negligible heat loss from the commodities as compared to insects, the insect temperature, T_i (°C), and commodity temperature, T_w (°C), are governed by the following energy balance equations, respectively:

$$\begin{cases} \rho_i C_{pi} V_i \dfrac{dT_i}{dt} = P_i V_i - h A_i (T_i - T_w) \\ \rho_w C_{pw} \dfrac{dT_w}{dt} = P_w \end{cases} \qquad (1)$$

where

A_i = insect body surface area (m^2)
V_i = insect body volume (m^3)
C_{pi} = specific heat of insect (3450 J/kg °C for codling moth larvae)
C_{pw} = specific heat of host commodity (2510 J/kg °C for walnut kernel)
h = heat transfer coefficient between insect and host commodity (W/m^2 °C)
ρ_i = density of insect (1000 kg/m^3)
ρ_w = density of host commodity (900 kg/m^3 for walnut kernel)
P_i = electromagnetic energy absorbed by insect (W/m^3)
P_w = electromagnetic energy absorbed by host commodity (W/m^3)
t = heating time (s).

The thermal energy that is converted from the electromagnetic field can be expressed as (Nelson, 1996):

$$P = 5.56\times10^{-11} f E^2 \varepsilon'' \qquad (2)$$

where

P = thermal energy generated per unit volume (W/m^3) in a dielectric material
f = frequency (Hz)
E = electric field intensity (V/m)
ε'' = dielectric loss factor.

Using the ratio of surface to volume of cylindrically shaped insects ($A_i/V_i = 4/D$), assuming no losses from the ends of the cylinders, and combining equations 1 and 2, the temperature difference between insects and the host commodity can be obtained by the following relationship:

$$T_i - T_w = \frac{DP_w}{4h}\left(\frac{\varepsilon''_i}{\varepsilon''_w} - \frac{\rho_i C_{pi}}{\rho_w C_{pw}}\right)\left[1 - \exp\left(-\frac{4ht}{D\rho_i C_{pi}}\right)\right] \qquad (3)$$

where D is insect body diameter (0.002 m for fifth–instar codling moth larvae). According to equation 3, the temperature difference is dependent on the dielectric loss factor ratio ($\varepsilon_i''/\varepsilon_w''$) and the surface heat transfer coefficient (h), among other factors (i.e., heat capacities of the two materials, and size of the insect pest).

Dielectric Properties

As shown in equation 3, the dielectric loss factor ratio between insects and walnuts ($\varepsilon_i''/\varepsilon_w''$) is an important factor that determines the differential heating of insects in walnuts. In this study, this ratio was determined by measuring the dielectric properties of insects and walnuts.

Dielectric Properties Measurement System

It is well known that dielectric properties of biomaterials change with temperature (Herve et al., 1998). The dielectric properties of walnuts, insects, and/or gellan gel were determined with a coaxial probe technique (Engelder and Buffer, 1991) over the frequency range from 1 to 1800 MHz and at temperatures between 20°C and 60°C in 10°C increments. A custom–built test cell (20 mm in inner diameter and 25 mm in height) for sample temperature control was connected with an impedance/material analyzer (model 4291B, Hewlett Packard, Santa Clara, Cal., with Innovative Measurement Solutions software). The sample was confined in a stainless steel cell to allow the coaxial probe to fit into the cell and to be in close contact with the sample (fig. 1). The sample temperature was controlled by circulating water from a temperature–controlled water bath (model 1157, VWR Scientific Products, Niles, Ill.) through the cell jacket. The sample temperature was measured by a type–T thermocouple (0.8 mm diameter and 0.8 s response time) and used as a feedback for the water bath. The circulating water was adjusted to a rate of 15 L/min, and the sample temperature was raised to a desired level at each step in 10 min.

Before making dielectric properties measurements, the impedance analyzer (Hewlett Packard, Santa Clara, Cal.) was calibrated with a standard air–short–triple deionized water calibration procedure. Typical error of the system was 5%. Dielectric properties of butyl alcohol at 20°C were measured to validate the accuracy of the system because dielectric properties of this solution are well documented (Garg and Smyth, 1965). The dielectric constant and loss factor of the butyl alcohol obtained by Garg and Smyth (1965) were compared with those measured in this study at 20°C before the dielectric properties measurements were made on insects, gellan gel, and walnut kernels.

Dielectric Properties Measurement Procedure

Fifth–instar codling moth larvae were reared at the USDA–ARS Yakima Agricultural Research Laboratory in Wapato, Washington, and shipped overnight to Washington State University for dielectric properties measurement and RF treatment tests. Prior to dielectric properties measurements, the larvae were placed in a vial (27 mm diameter) and minced to obtain 30 cm^3 of slurry, which was used to fill the measurement cell (fig. 1). Tests with the larvae slurry were conducted as quickly as possible to minimize degradation of the hemolymph and other constituents. Walnut kernels were powdered with a blender. An adequate amount of kernel powder was pressed into the cell to reduce the voids between the probe and the sample. Dielectric properties data for insects and walnuts were determined in duplicate.

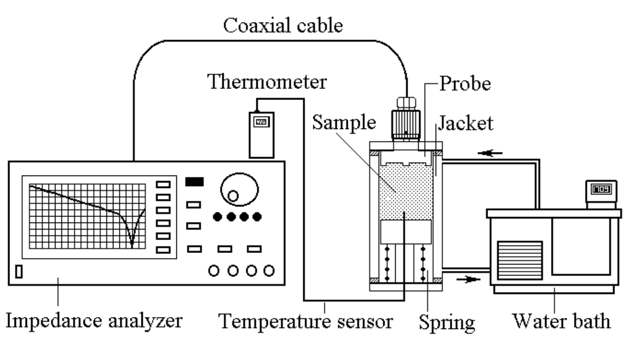

Figure 1. Schematic diagram of the dielectric properties measurement system (not to scale).

Temperature Uniformity

Before determining preferential heating of insects in walnuts when exposed to RF or microwave heating, we first determined temperature uniformity of twenty in–shell walnuts during RF heating. A 6 kW, 27 MHz pilot–scale RF system (COMBI 6–S, Strayfield International, Wokingham, U.K.) was used for heating of walnuts (fig. 2). Samples were placed between two parallel plate electrodes. The separation of the electrodes was changed to adjust RF power coupled to the sample. Twenty in–shell walnuts were placed in one layer on a plastic supporter made of polyvinyl chloride (PVC). Kernel temperatures of five walnuts, one located in the center and four at the corners of the supporter were measured by using fiber–optic sensors (UMI, FISO Technologies, Saint–Foy, Quebec, Canada). The sensors were inserted through pre–drilled holes in the shell. This system had 20 Hz sampling rate, 0.01% temperature resolution, and 0.5% accuracy of full–scale measurement.

Measurement of Preferential Heating

Model Insect Development

We developed model insects because inserting temperature probes into a live insect caused loss of body fluid, which would affect the accuracy of insect temperature measurements. Our model insect was a gellan gel having dielectric properties and thermal properties similar to those of codling moth larvae. In preparing the gel, gellan gum powders (Kelcogel, Kelco Division, Merck and Co., San Diego, Cal.) were dispersed in deionized water with a magnetic stirrer. Based on previous work (Ikediala et al., 2002), a 0.17% salt solution was added to the gel to produce dielectric properties similar to insects. The gellan dispersion was heated to 90°C so that polymers were fully dissolved. Calcium chloride was added to the hot gellan gum solution, and the gel was formed upon cooling by air at ambient temperature. Mechanical and gelation properties of gellan gel have been discussed in detail in Tang et al. (1995, 1996, 1997). Dielectric properties of the gellan gel samples were measured by the same procedure used for insects to confirm that the resulting gel had dielectric properties similar to the codling moth larvae over the temperature range from 20°C to 60°C.

Temperature Measurement

For each test run, two insect–size gellan gel cylinders were secured in voids of kernels. The two halves of the walnut shells were then glued together to simulate an intact walnut.

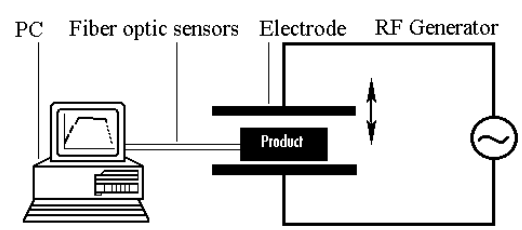

Figure 2. Schematic diagram for radio frequency treatments on in–shell walnuts for temperature uniformity and differential heating tests.

Fiber optic temperature sensors (UMI, FISO Technologies Inc., Saint–Foy, Quebec, Canada) were inserted through pre–drilled holes in the shell to measure walnut kernel and gel temperatures. Probes were arranged in pairs: one of each pair measured gel temperature, and the other measured walnut kernel temperature in each walnut shell. To validate the temperature difference between walnut kernels and insects, a small amount of insect slurry was also made from about 5 to 8 codling moth larvae and sealed with PE film. Temperatures of both the insect slurry and the walnut kernel during the RF heating were recorded at an interval of 1 s.

A pilot–scale microwave system (Model IV–5, Microdry Inc., Crestwood, Ky.) was used to study the differential heating of insects in walnuts at 915 MHz. The same procedure was followed as was used for the RF system. The tests were repeated twice.

Results and Analyses

Dielectric Properties

Figure 3 shows the dielectric constant (ε′) and loss factor (ε″) of the butyl alcohol at 20°C obtained in this study and by Garg and Smyth (1965). Similarly shaped dielectric properties curves and a peak loss factor at about 250 MHz were observed in both studies. Our measurement agreed reasonably well with the published data, with largest relative differences between the two measurements being 18.7% and 18.3%, respectively, for the dielectric constant and loss factor (at 250 MHz). This comparison demonstrates that the measurement results obtained by the impedance analyzer were reliable and the sample size in the cell was adequate for dielectric properties measurements.

The dielectric loss factor (ε″) of fifth–instar codling moths measured at five temperatures is shown in figure 4. The loss factor decreased with increasing frequency, reaching about 12 at 1800 MHz. The loss factor of codling moth larvae increased with temperature, especially at low frequencies. This was due mainly to the increase in ionic conduction at high temperatures (Tang et al., 2002). Increasing dielectric loss factor with temperature often results in a well known phenomenon, commonly referred to as "thermal runaway" (Metaxas and Meredith, 1983, pp. 54–56), in which a preferentially heated subject in an electromagnetic field accelerates heating as its temperature rises.

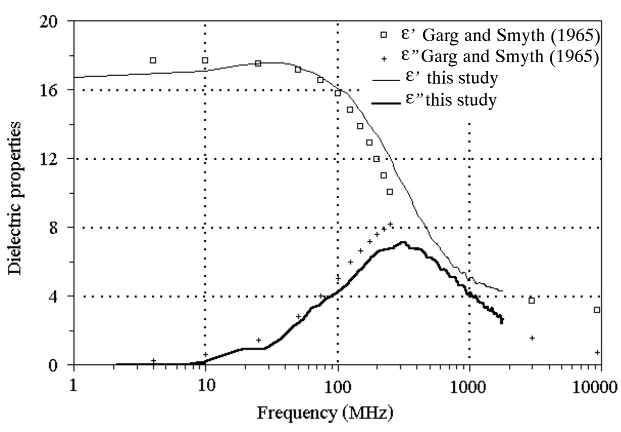

Figure 3. Dielectric constant (ε′) and loss factor (ε″) of butyl alcohol at 20°C obtained by Garg and Smyth (1965) and this study.

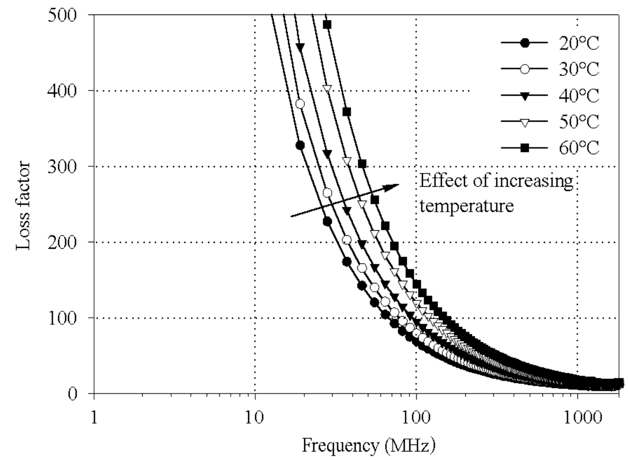

Figure 4. Dielectric loss factor of codling moth larvae (slurry) at five temperatures (means of two replicates).

Figure 5 shows the loss factor of walnut kernels over the frequency range from 1 to 1800 MHz at five temperatures. The ε″ values were less than 1 at frequencies below 100 MHz. The ε″ values peaked in the range between 500 and 1000 MHz. The peak value of ε″ for walnut kernels decreased with increasing temperature, during which the frequency corresponding to the peak ε″ shifted to a higher value. This temperature–dependent trend is typical of polar molecules (Feng et al., 2002). At any selected frequency in the tested range, the loss factor of the walnut kernel generally decreased with increasing temperature. That is, for a given electromagnetic field intensity, higher temperature walnuts will absorb less energy than cooler ones, resulting in improved heating uniformity.

Compared to codling moth larvae, the loss factor values of walnuts were much smaller because of high oil content and less moisture in walnut kernels. It is clear from figures 5 and 6 that the difference in the value of the ε″ between codling moth larvae and walnut kernels was much larger at lower frequencies than at microwave frequencies, suggesting a better potential for preferential heating of insects in walnuts when using lower frequency treatments.

Table 1 presents the mean and standard deviation values of the dielectric constant and the loss factor of codling moth

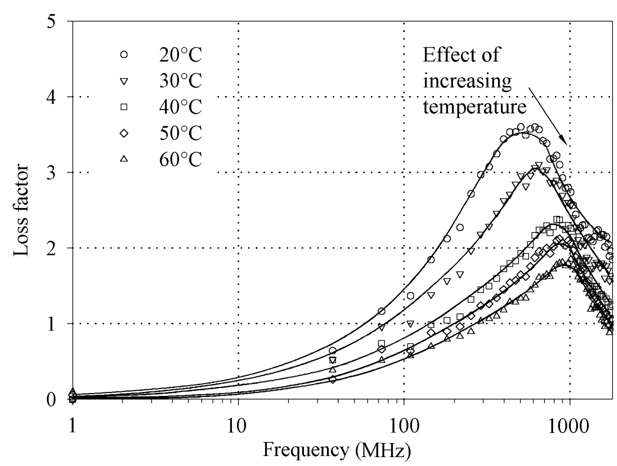

Figure 5. Dielectric loss factor of walnut kernels as a function of frequency at five temperatures (means of two replicates).

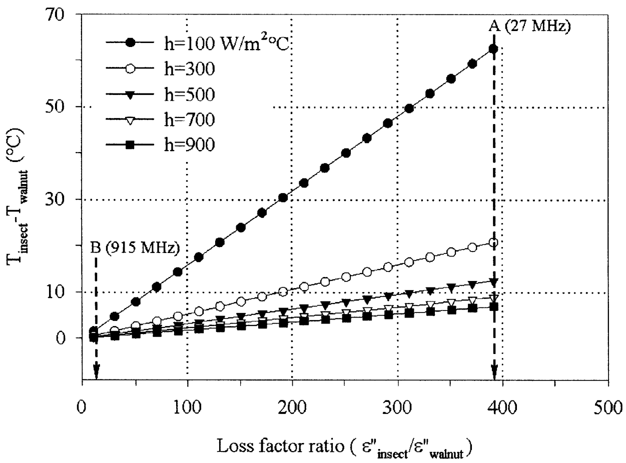

Figure 6. Predicted temperature difference between insects and walnuts as a function of dielectric loss factor ratios and heat transfer coefficients (*h*) after treatments at 0.27 kW/kg for 3 min.

larvae, gellan gel, and walnut kernels at five temperatures and five frequencies. Gellan gel with 0.17% salt content had a slightly smaller loss factor than codling moth larvae at all tested temperatures. Therefore, using this gellan gel as model insects would slightly underestimate the temperature difference between the insect and the walnut. The loss factors of codling moths and gellan gel at 27 MHz increased with increasing temperature, suggesting that both materials at high temperatures enhanced the heating due to increasing energy absorption. The loss factor ratio of gellan gel to walnut kernels at 20°C was 397 at 27 MHz and 4 at 915 MHz. The ε'' values for codling moth (11.7 to 19.1), gellan gel (7.9 to 10.8), and walnut kernels (1.8 to 2.8) varied a little at 915 MHz for temperatures from 20°C to 60°C.

Predicted Temperature Differences

Figure 6 shows the predicted temperature difference between insects and walnut kernels as a function of dielectric loss factor ratios (from 1 to 400) and heat transfer coefficients (from 100 to 900 W/m^2 °C) after 3 min dielectric heating at 0.27 kW/kg. The range of loss factor ratio depicted in figure 6 covered the measured values for insects and walnuts at 27 MHz (point A) and 915 MHz (point B). The most reasonable values of heat transfer coefficients were selected based on poor and good contacts between insects and walnut kernels (Dincer, 1997). The heat transfer coefficient was around 50 W/m^2 °C for pure air heating (Tang et al., 2000) and 1000 W/m^2 °C for two metals in close contact with each other (Incropera and DeWitt, 1996). The temperature difference increased with increasing loss factor ratio, especially for the smallest heat transfer coefficient (100 W/m^2 °C). When the values of heat transfer coefficients were large ($\geq$700 W/m^2 °C), the temperature difference was less than 8°C even when the dielectric loss factor of the insect was 400 times larger than that of walnuts. When the heat transfer coefficient (*h*) was 500 W/m^2 °C, the temperature difference between insects and kernels was about 12.7°C and 0.1°C, respectively, at loss factor ratios of 397 (for 27 MHz) and 4 (for 915 MHz). The prediction also suggested that the temperature difference at 915 MHz was 0.3°C even when the loss factor of the insect was 10 times larger than that of walnuts. It is clear from this example that the difference between loss factors of insect pests and host commodities cannot be used as the only criterion to predict preferential heating. The above analysis also suggests that preferential heating of insect larvae is likely to occur at 27 MHz, not at 915 MHz.

Experimental Temperature Uniformity

Figure 7 shows the walnut kernel temperature profiles at five locations in one layer when heated at 27 MHz at a power intensity of 0.6 kW/kg. The mean and standard deviation of measured temperatures in five kernels were 52.2°C ±1.0°C at the end of the heat treatment. Due to heat loss to the ambient air, the average walnut kernel temperature dropped to 48.9°C ±1.4°C in 3.3 min after RF energy was turned off. The temperature of the walnut in the center (position 3) was slightly higher than that of those at the four corners. The data presented in figure 7 about temperature variation in walnut kernels provided baseline information for us to evaluate preferential heating of insects.

Table 1. Dielectric properties (mean ±SD) of codling moth larvae (slurry), gellan gel (0.17% NaCl) and walnut kernel at five temperatures and frequencies.

Material	Temp. (°C)	Dielectric Constants at Indicated Frequency (MHz) 27	40	100	915	1800	Loss Factor at Indicated Frequency (MHz) 27	40	100	915	1800
Codling moth	20	71.5 ±0.9	64.9 ±0.9	56.3 ±0.1	47.9 ±0.2	44.5 ±0.1	238.1 ±0.1	163.3 ±0.4	68.5 ±0.3	11.7 ±0.1	12.0 ±0.2
	30	71.5 ±0.1	63.9 ±0.2	54.1 ±0.9	45.9 ±0.9	42.9 ±0.9	277.8 ±8.5	190.2 ±5.4	79.4 ±2.0	12.5 ±0.4	11.7 ±0.3
	40	73.8 ±0.1	64.5 ±0.1	53.2 ±0.6	44.6 ±0.6	41.6 ±0.4	332.4 ±16.3	227.5 ±10.5	94.7 ±3.9	13.9 ±0.5	11.9 ±0.3
	50	79.3 ±1.1	68.5 ±1.6	54.9 ±1.5	45.6 ±1.5	42.7 ±1.5	422.5 ±5.9	288.6 ±4.4	119.6 ±1.9	16.5 ±0.3	13.2 ±0.3
	60	84.5 ±2.5	71.5 ±2.9	55.6 ±2.6	45.0 ±2.4	41.9 ±2.2	511.3 ±26.6	349.1 ±18.3	144.4 ±7.5	19.1 ±1.0	14.2 ±0.7
Gellan gel	20	82.5 ±0.3	81.9 ±0.3	79.2 ±0.6	77.8 ±0.6	77.6 ±1.1	220.5 ±2.7	149.2 ±1.7	59.8 ±0.5	7.9 ±2.9	9.8 ±1.1
	30	80.5 ±0.5	79.5 ±0.5	76.7 ±0.9	75.4 ±1.0	75.3 ±1.4	256.8 ±3.5	173.8 ± 2.3	69.4 ±1.3	8.2 ±3.0	8.8 ±1.0
	40	78.1 ±0.2	77.0 ±0.3	73.9 ±0.8	72.6 ±0.9	72.6 ±1.4	301.5 ±2.1	203.8 ±1.6	81.3 ±1.0	8.9 ±3.0	8.3 ±1.0
	50	76.0 ±0.0	74.5 ±0.1	71.3 ±0.5	70.0 ±0.8	70.1 ±1.3	346.6 ±0.5	234.1 ±0.7	93.4 ±0.7	9.8 ±3.1	8.1 ±1.1
	60	74.1 ±0.2	72.2 ±0.1	68.8 ±0.5	67.4 ±0.8	67.5 ±1.3	393.6 ±1.7	265.7 ±1.5	105.8 ±1.0	10.8 ±3.1	8.2 ±1.1
Walnut kernel	20	4.9 ±0.0	4.8 ±0.0	4.3 ±0.2	2.2 ±1.6	2.8 ±0.7	0.6 ±0.0	0.7 ±0.1	1.2 ±0.1	2.8 ±0.1	1.7 ±0.2
	30	5.0 ±0.1	4.9 ±0.1	4.4 ±0.1	2.1 ±0.3	2.9 ±0.2	0.5 ±0.1	0.6 ±0.1	0.9 ±0.1	2.7 ±0.1	1.4 ±0.2
	40	5.1 ±0.1	5.1 ±0.1	4.5 ±0.1	3.0 ±0.1	3.2 ±0.0	0.4 ±0.0	0.6 ±0.1	0.7 ±0.1	2.3 ±0.1	1.1 ±0.2
	50	5.2 ±0.1	5.1 ±0.0	4.6 ±0.0	3.4 ±0.0	3.5 ±0.0	0.3 ±0.1	0.5 ±0.1	0.6 ±0.0	2.0 ±0.0	1.1 ±0.1
	60	5.3 ±0.0	5.2 ±0.0	4.7 ±0.0	3.8 ±0.0	3.7 ±0.0	0.4 ±0.1	0.5 ±0.0	0.5 ±0.0	1.8 ±0.0	1.0 ±0.1

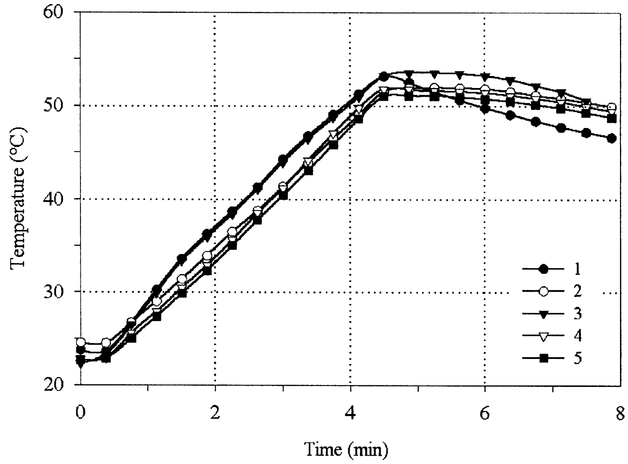

Figure 7. Walnut kernel temperatures at five different locations (position 3 is in the center) in one layer when subjected to 27 MHz heating (P = 0.6 kW/kg).

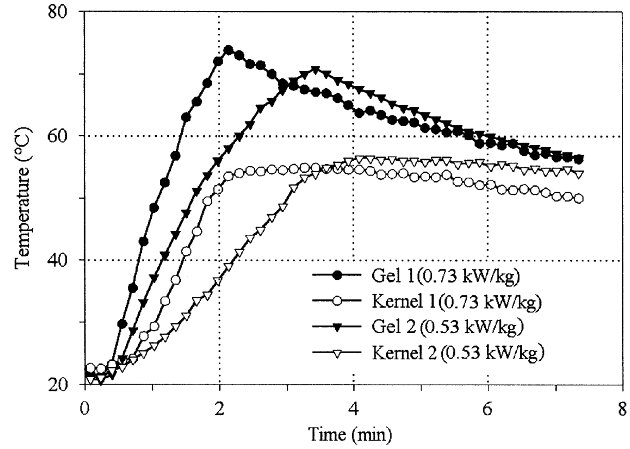

Figure 9. Typical temperature profiles of walnut kernels and gellan gel (0.17% NaCl) when subjected to 0.73 kW/kg and 0.53 kW/kg at 27 MHz.

Measured Differential Heating at 27 MHz

Figure 8 shows a typical temperature–time history of gellan gel (size of a fifth–instar codling moth larvae) and walnut kernels when heated in the 27 MHz system at a power level of 0.53 kW/kg. At the beginning of the 5 min heating, the gellan gel temperature increased much more rapidly than the walnut kernel temperature, showing significant preferential heating of the gel. As the heating progressed, the heating rate of the gel gradually decreased, probably due to cooling by evaporation of water. The gel temperature decreased rapidly once the RF heating was stopped after the 5 min RF heating. The walnut kernel temperature, on the other hand, increased linearly with heating time, and then remained constant or decreased slightly after the RF power was turned off. The mean and standard deviation values for the final temperature difference between the gellan gel and walnut kernels were 12.6°C and 0.9°C, respectively. The mean temperature difference was close to the value of 12.0°C predicted by equation 3 when the dielectric loss factor ratio (397) at 27 MHz and h = 500 W/m^2 °C were used. The heating rate for gellan gel was 1.4 to 1.5 times faster than that for walnut kernels. Figure 9 shows the differential heating of the gellan gel in walnut kernels at two RF power levels. The final temperature difference between the gellan gel and the walnut kernel increased from 15.9°C to 21.2°C, and the corresponding heating rate for the gellan gel increased from 1.4 to 1.7 times that for walnut kernels, when the RF power was increased from 0.53 to 0.73 kW/kg. Therefore, high RF power enhanced the differential heating of the model insect in walnuts due mainly to reduced total heat loss from the gel in the short period of time to reach the desired final temperature.

Figure 10 shows a temperature–time history for codling moth larvae (a slurry made from 5 to 8 fifth–instar codling moth larvae) and walnut kernels when subjected to the 27 MHz heating at 0.67 kW/kg. We again observed preferential heating of insects in walnuts; the temperature difference between insects and walnut kernels was as high as 14.3°C ±1.1°C. The heating rate for the insect slurry was 1.4 to 1.5 times faster than for walnut kernels. This further confirms that the insects were indeed preferentially heated in walnuts at 27 MHz. Although the dielectric loss factor of insects was several hundred times larger (238 vs. 0.6 at 20°C) than walnut kernels at 27 MHz, we only detected 1.4 to 1.7 times preferential heating of insects in walnuts. As suggested in our prediction model, this was the result of the larger specific heat and higher density of insects compared to the walnuts, and the large surface–to–volume ratio of the insect body that results in significant heat loss to walnut kernels.

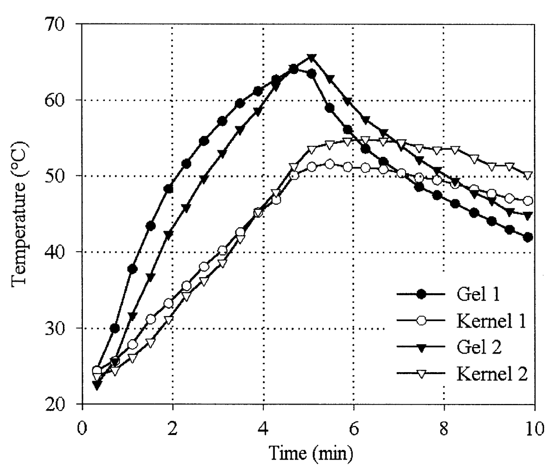

Figure 8. Typical temperature profiles of walnut kernels and gellan gel (0.17% NaCl) when subjected to 27 MHz heating (P = 0.53 kW/kg).

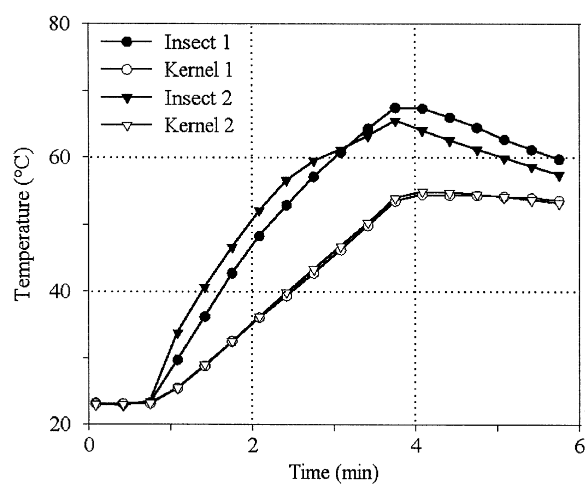

Figure 10. Typical temperature profiles of walnut kernels and codling moth slurry when subjected to 27 MHz (P = 0.67 kW/kg).

Measured Differential Heating at 915 MHz

Figure 11 shows the temperature–time history of the gel and walnut kernels when subjected to 915 MHz heating with a power of 0.33 kW/kg, which was the maximum microwave power that we were able to couple into the sample with our unit. Even though the dielectric loss factor of the model insects was 4 times larger than walnut kernels ($\varepsilon_i'' / \varepsilon_w'' = 4$) at 915 MHz, there was no detectable preferential heating of insects in walnuts. In fact, in all cases the walnut kernel temperature was very close to that of the gel at the end of the microwave heating. The mean and standard deviation values of the temperature difference between the gel and the walnut kernel were –1.4°C and 2°C, respectively. This was consistent with what we predicted by equation 3 when the dielectric loss factor ratio (4) at 915 MHz and h = 500 W/m^2 °C were used (fig. 6). The above observations suggest that preferential heating did not occur at microwave frequencies. Nelson and Payne (1982) also stated that dielectric heating at 40 MHz should be more effective in killing pecan weevil in pecans than heating at 2450 MHz.

Results from RF Treatments of Infested Walnuts

Our earlier studies on RF treatments of in–shell walnuts infested with fifth–instar codling moths also support the hypothesis that insects are preferentially heated at 27 MHz. Table 2 summarizes measured walnut kernel temperatures and observed insect mortalities under two different treatment conditions in a 27 MHz pilot–scale system. For a 2 min RF treatment at 0.27 kW/kg, the mean, standard deviation, and minimum final temperatures of walnut kernels were 42.6°C, 2.5°C, and 39°C, respectively (Wang et al., 2001a). For a 3 min RF treatment with the same power intensity, the mean, standard deviation, and minimum final temperatures of walnut kernels were 53.3°C, 3.6°C, and 49°C, respectively. If insects had the same initial temperature as that of walnut kernels, then based on previously determined thermal death kinetic data reported by Wang et al. (2002a), we would expect a mortality range of 10% to 20% for the 2 min RF treatment and 70% to 100% for the 3 min RF treatment after a 5 min holding period. But instead, we observed 78.6% ±6% mortality for the 2 min RF treatment and a consistent 100% mortality for the 3 min RF treatment. The much higher observed mortalities can only be explained by preferential heating of insects, because there is no reported evidence that RF energy at 27 MHz or in this vicinity has any nonthermal lethal effect on insects. Based on thermal death time kinetic data provided by Wang et al. (2002a), we estimate that codling moths should have experienced at least 7°C higher mean temperature than the measured mean kernel temperature in the 2 min RF treatments (>1.3 times the heating rate of walnut kernels) to reach the observed 78.6% ±6% mortality, and 10.5°C in the 3 min treatments to reach the observed 100% mortality.

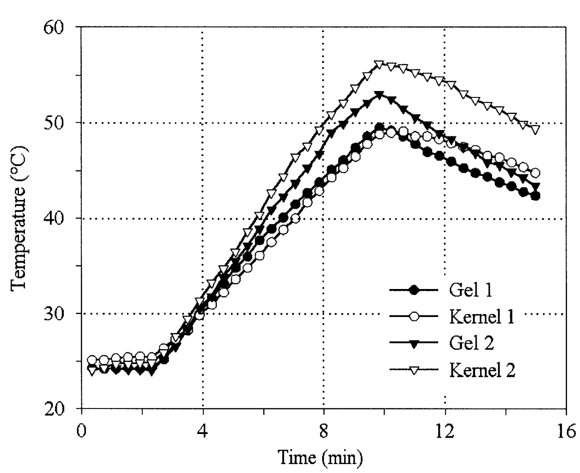

Figure 11. Typical temperature profiles of walnut kernels and gellan gel (0.17% NaCl) when subjected to 915 MHz heating (P = 0.33 kW/kg).

It is evident that significant preferential heating of insects in walnuts can be used to our advantage when developing insect control treatments with RF energy to provide an adequate safety margin for insect pest control without causing thermal damage to product quality. It also allows us to design short–time processes to reduce the use of RF energy and increase product throughput.

The dielectric properties, size, and thermal capacitance of many economically important insect pests, such as Indianmeal moth, Mexican fruit fly, and navel orangeworm, are similar to those of codling moth (Wang et al., 2003), while the thermal and dielectric properties of dried fruits and nuts are generally similar (Feng et al., 2002; Wang et al., 2003). The loss factor of those insects is about two orders of magnitude larger than that of dried fruits and nuts at an RF frequency range between 20 and 40 MHz. We, therefore, expect differential heating of those insect pests in dried commodities when treating with RF energy. However, the dielectric loss factor of insect pests is less than one order of magnitude larger than or very close to that of fresh fruits at RF and microwave frequencies (20 to 2450 MHz) (Wang et al., 2003), so it is very unlikely that insects will be selectively heated in fresh products.

Conclusions

We developed a theoretical model based on heat transfer and dielectric heating to predict preferential heating of insect pests in agricultural commodities. This model was used to predict differential heating of codling moths in dried in–shell walnuts at 27 and 915 MHz frequencies. Direct temperature measurements with model insects made of gellan gel with dielectric properties and thermal properties similar to those of codling moth larvae and tests with larger bodies of insect slurry revealed 1.4 to 1.7 times greater heating of insects than walnuts at 27 MHz. We predicted and detected no preferential heating of codling moth larvae at 915 MHz. Insect mortalities in earlier studies, in which infested in–shell walnuts were treated with 27 MHz RF energy, could be explained only by preferential heating of insects with insect heating rates at least 1.3 times those of walnuts.

Table 2. Mortality of fifth–instar codling moth larvae after radio frequency treatments at 27 MHz on infested walnuts (Wang et al., 2001a).

Treatments (heating/ holding)	Measured Kernel Temp. (°C)			Insect Mortality (%)	
	Mean	SD	Min.	Observed	Estimated[a]
2 min/5 min	42.6	2.5	39.0	78.6	10 to 20
3 min/5 min	53.3	3.6	49.0	100	70 to 100

[a] Based on walnut temperature.

We conclude that differential heating of insects in walnuts does occur at 27 MHz but not at 915 MHz. The differential heating makes possible the development of practical RF treatments that the industry can use to overcome possible non–uniform RF heating and ensure reliable control of insect pests in dried nuts and fruits without damaging product quality.

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