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Mathematical modelling of heating uniformity for in-shell walnuts subjected to radio frequency treatments with intermittent stirrings

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Abstract

Non-uniform heating caused by the different orientations and locations of in-shell walnuts may be a major problem in developing a large-scale radio frequency (RF) treatment for postharvest phytosanitary and quarantine regulations in international trade. A mathematical model was developed based on normal distributions of walnut temperatures against frequency to study the influence of the number of RF units and intermittent stirrings on heating uniformity. The model was validated by experiments with a good accuracy. It was determined by experiments that the rise in standard deviation of walnut temperatures at any time during RF heating increased linearly with the rise in mean temperature. The ratio, defined as uniformity index, depends upon the design of a RF unit, and has a significant influence on the number of stirrings needed to achieve the desired insect mortality. For a uniformity index value of 0.165, a minimum of two stirrings was needed to meet the different desired temperature distributions for insect controls, such as the lowest temperature of 48 °C and mean temperature of 67 °C for a 99.9968% mortality or the lowest temperature of 50 °C and mean temperature of 64 °C for a 99.9% mortality.

Keywords: Heating uniformity; Modelling; Radio frequency; Stirring; Walnuts

1. Introduction

A potential alternative disinfestation treatment involves using radio frequency (RF) energy. RF energy interacts directly with dielectric materials, such as walnuts, to generate heat by converting electromagnetic energy into thermal energy, thus sharply reducing the heating time (Tang et al., 2000). In hot air treatments of in-shell walnuts, however, the low thermal conductivity of the porous walnut shell and voids within the shell hinder the transfer of thermal energy from the hot air outside of the shell (Tang et al., 2000; Wang et al., 2001b). This results in long treatment times of up to 1–2 h and may cause severe quality loss due to lipid

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oxidation (Mate and Krochta, 1997). Based on studies of the thermal death kinetics of targeted insects (Wang et al., 2002a,b; Johnson et al., 2003), a pilot-scale treatment protocol using RF energy has been developed for postharvest insect control in in-shell walnuts without causing product losses (Wang et al., 2001a, 2002c). It is desirable however, to transfer this protocol from pilot-scale to large-scale industrial applications.

Many studies have been conducted to explore the feasibility of using electromagnetic energies to control insect pests in agricultural commodities (Headlee and Burdette, 1929; Frings, 1952; Nelson and Payne, 1982; Wang et al., 2002c). A complete kill of tobacco moth larvae, *Ephestia elutella* (Hubner) (Lepidoptera: Pyralidae), and cigarette beetles, *Lasioderma serricorne* (F.) (Coleoptera: Anobiidae), is achieved when heated by 2,450 MHz microwaves to 55 °C for 30 s (Hirose et al., 1970a,b). A study reported by Andreuccetti et al. (1994) demonstrates the possibility of using 2,450 MHz microwaves to kill woodworms by heating the larvae to 52–53 °C for less than 3 min. Several comprehensive reviews provide good sources of useful information about the susceptibility of various insect species to RF treatments (Hallman and Sharp, 1994; Nelson, 1996). However, previous studies focused only on small-scale RF treatment protocol development using very limited samples.

A major concern in developing a large-scale thermal treatment based on RF energy is the heating uniformity in the treated products. The non-uniformity problem has been found in small-scale RF treatments, such as in 20 in-shell walnuts (52.2 ± 1.0 °C) (Wang et al., 2003a) and in 8 oranges (51.6 ± 2.0 °C) (Birla et al., 2004). The walnut temperature variations after RF heating may result from the different properties and shapes of each individual walnut and the different locations of walnuts in a non-uniform electromagnetic field. Although it is impossible to eliminate non-uniform heating caused by physical differences among individual walnuts, we can minimise the position effects by stirring the walnuts during RF treatments. A continuos RF treatment can be designed using several RF units with stirrings in between. It is desirable to determine the appropriate number of RF units and stirrings needed to achieve the desired temperature distributions. This information will directly influence the efficacy of the treatment, capital cost and process time. An acceptable final temperature distribution is required to provide desired efficacy of the treatments and ensure minimum impact on the quality of in-shell walnuts over the entire volume. Our earlier studies have shown that the minimum exposures to achieve probit 9 of fifth-instar navel orangeworm, *Amyelois transitella* (Walker) (Lepidoptera: Pyralidae), require 151, 51, 17, 6 and 1 min at 46, 48, 50, 52 and 54 °C, respectively (Wang et al., 2002b), and that walnut quality is not affected by treatments of up to 60 °C for 10 min (Buranasompob et al., 2004) or 75 °C for 5 min (Mitcham et al., 2004). It is desirable to develop a large scale RF treatment process that controls insect pests but does not cause degradation of product quality. Up to now, there exist no reported theoretical analyses and experimental data to determine the number of stirrings needed to meet the temperature requirements in large-scale operations.

The objectives of this research were: (1) to develop a mathematical model that determines the number of stirrings needed for a given walnut temperature distribution in RF systems; (2) to validate the model by measuring walnut temperature distributions in a RF system; (3) to study the influence of important parameters on the desired number of RF units with stirring for insect control.

2. Materials and methods

2.1. Model development

2.1.1. Assumptions

The assumptions used in the model development were as follows: (1) a RF treatment consisted of $n + 1$ number of RF units with n number of stirrings in between; (2) there was no stirring in each RF unit; (3) the rise in mean and standard deviation in walnut temperatures increased linearly with RF heating time; (4) walnut temperature after RF heating followed a normal distribution; (5) the upper limit temperatures were not considered for insect control; (6) heat transfer during walnut stirring between two RF units was negligible, and the stirring of walnuts only randomly changed their positions in the container without reducing their temperature.

2.1.2. Models to predict the mean temperature and standard deviation without stirring

Let X_0 represent the initial walnut temperature distribution with a mean of μ_0 and a standard deviation of σ_0. Let X_t represent a normal distribution in walnut temperatures after RF heating for t minutes, with $\Delta\mu$ and $\Delta\sigma$ representing the rise in mean and standard deviation, respectively. Since the rise in mean and standard deviation of walnut temperatures is attributed entirely to RF heating, the temperature distribution after RF heating without stirring, X, is a summation of X_0 and X_t. The rise in mean and standard deviation bears the following relationships (Neter et al., 1996):

$$\Delta\mu = \mu - \mu_0 \tag{1}$$

$$\Delta\sigma = \sqrt{\sigma^2 - \sigma_0^2} \tag{2}$$

where μ and σ represent the mean and the standard deviation of distribution X.

Based on the first set of experiments that we will discuss later, the predicted rise in mean and standard deviation of temperature was linearly related to the heating time. That is:

$$\Delta\mu = a_1 t \tag{3}$$

$$\Delta\sigma = b_1 t \tag{4}$$

where a_1 and b_1 are constants. The mean and the standard deviation of temperature by heating t minutes are:

$$\mu = \mu_0 + a_1 t \tag{5}$$

$$\sigma = \sqrt{\sigma_0^2 + (b_1 t)^2} \tag{6}$$

Combining Eqs. (3) and (4) gives:

$$\Delta\sigma = \lambda\Delta\mu \tag{7}$$

where λ is defined as the uniformity index (b_1/a_1), which is a parameter that reflects the heating uniformity in a RF unit, and is dependent on the design of the unit and interactions between the unit and a specific product in a fixed configuration. By definition, when the rise in mean increases one degree by RF heating, the rise in standard deviation will increase by λ degrees. If the value of λ is small, the RF system is well-designed because the rise in mean leads to a slower rise in standard deviation. Otherwise, the RF system causes large temperature variations. The value of λ for a new system can be determined by experiments.

Assuming that it takes t_T minutes for the mean temperature to increase from the initial mean μ_0 to a desired mean μ_T, from Eq. (5) we have:

$$t_T = \frac{\mu_T - \mu_0}{a_1} \tag{8}$$

In the mean time, the standard deviation will increase from σ_0 to σ_T, when there is no stirring. Combining Eqs. (6) and (8) yields:

$$\sigma_T = \sqrt{\sigma_0^2 + [\lambda(\mu_T - \mu_0)]^2} \tag{9}$$

2.1.3. Model to select the number of stirrings for a required temperature distribution

The most cost-effective way of stirring is administered between only two subsequent RF units heating for an equal duration. We further assume a thorough stirring between the two RF units. In total, the walnuts are heated $n+1$ times in $n+1$ RF units and stirred n times. After heating for t_r minutes in each RF unit, the rise in temperature follows a normal distribution of ΔX_r, with the rise in mean of $\Delta\mu_r$ and the rise in standard deviation of $\Delta\sigma_r$. According to statistical property theory (Meyer, 1970), the variance of the sum of independent random variables is the sum of variances of these variables. The final temperature distribution X is thus the sum of the initial temperature distribution X_0 and $n+1$ of ΔX_r distributions (Meyer, 1970), that is:

$$X = X_0 + \sum_{i=1}^{n+1} (\Delta X_r)_i \tag{10}$$

From Eqs. (3) and (4), the value of $\Delta\mu_r$ and $\Delta\sigma_r$ are $\Delta\mu_r = a_1 t_r$ and $\Delta\sigma_r = b_1 t_r$. Furthermore, the mean μ and the standard deviation σ of the final temperature distribution X is:

$$\mu = \mu_0 + (n+1)\Delta\mu_r = \mu_0 + (n+1)a_1 t_r \tag{11}$$

$$\sigma = \sqrt{\sigma_0^2 + (n+1)\Delta\sigma_r^2} = \sqrt{\sigma_0^2 + (n+1)(b_1 t_r)^2} \tag{12}$$

Since the satisfaction of the mean temperature of X would achieve the desired value μ_T, the heating time for each RF unit is:

$$t_r = \frac{(\mu_T - \mu_0)}{(n+1)a_1} \qquad (13)$$

Combining Eqs. (7), (12) and (13) yields the standard deviation for the final product temperature distribution:

$$\sigma = \sqrt{\sigma_0^2 + \frac{(\mu_T - \mu_0)^2 \lambda^2}{n+1}} \qquad (14)$$

According to Eq. (14), when the number of stirrings increases, the standard deviation will decrease.

To determine the minimum number of stirrings needed, we assume that the mean temperature is μ_T, the low limit temperature is selected to be L, and the desired probability for walnut temperature less than L is P. We can determine the normal score z_P associated with probability P by setting $P =$ probability of ($z \le z_P$) in the standard normal distribution. After n stirrings with the standard deviation σ in Eq. (14), the z_P value needed to meet the desired P of the left tail in the normal distribution is:

$$z_P = \frac{L - \mu_T}{\sigma} = \frac{L - \mu_T}{\sqrt{{\sigma_0}^2 + (((\mu_T - \mu_0)^2 \lambda^2)/(n+1))}} \qquad (15)$$

The minimum number of stirrings then is:

$$n = \frac{(\mu_T - \mu_0)^2 \lambda^2}{((L - \mu_T)/z_P)^2 - \sigma_0^2} - 1 \qquad (16)$$

In the above formula, P, μ_T and L are selected for a specific treatment. Normal score z_P is determined by P from a normal distribution table. Table 1 presents the typical normal scores as a function of the desired probability from a statistical handbook (Neter et al., 1996). The values of the uniformity index λ, initial mean μ_0, and initial standard deviation σ_0 can be obtained by experiments and are related to RF system design, sample weight, and container size. Once we have all these parameters, the minimum number of stirrings can be calculated using Eq. (16).

Table 1
Typical normal scores as a function of the desired probability (Neter et al., 1996)

Desired left tail probability, P	Normal score, z_P
0.05	−1.645
0.025	−1.957
0.01	−2.326
0.008	−2.409
0.005	−2.574
0.001	−3.090
0.000032	−4.000

2.2. Model validation

To validate the above mathematical models, a 12 kW, 27 MHz pilot-scale RF system (Strayfield Fastran with E-200, Strayfield International Limited, Wokingham, UK) was used to heat in-shell walnuts to determine temperature distribution versus heating time. A plastic container (40 cm × 27 cm × 12 cm) was placed between two parallel plate electrodes (104 cm × 80 cm), in which 4.5 kg of in-shell walnuts were heated. The gap between the electrodes was adjusted to have a suitable heating rate of about 10 °C/min with a RF power of 4 kW. A detailed description of the RF heating system can be found in Wang et al. (2002c). After a predetermined heating time, the container was immediately taken out of the RF system for temperature measurement. For stirring tests, the RF-treated walnuts were placed in a large container (55 cm × 40 cm × 14 cm) and stirred manually for 20 s. After the stirring was complete, the walnuts were placed back in the treatment container. The surface walnut temperature in the container was measured by an infrared camera (Thermal CAM$^{\text{TM}}$ SC-3000, N. Billerica, MA) having an accuracy of ±2 °C. Each measurement took about 3 s and the sample was then placed back into the RF cavity for further heating under the same conditions. Two different sets of experiments were conducted: (1) to determine the rise in mean and standard deviation of in-shell walnut temperature without stirring after heating for 0, 0.5, 1, 1.5, 2, 2.5 and 3 min, and (2) to determine the walnut temperature distribution after 3 min RF heating with two intermittent stirrings. In each of the thermal images, 45,056 individual temperature data were collected over the container and used for statistical analyses.

3. Results and analyses

3.1. Model validation

3.1.1. Validation of Eqs. (3), (4) and (9)

Fig. 1 shows a typical walnut surface temperature distribution obtained by thermal imaging after a RF treatment for 3 min without stirring. There were some hot spots (∼69 °C) and cold spots (∼37 °C) within the area of thermal measurement. The measured cold spot temperatures using the infrared imaging system might be lower than the real minimum product temperature. Mitcham et al. (2004) randomly measured eight kernel temperatures using fibre-optic temperature sensors among 500 walnuts in a sample during each RF treatment that brought the sample average temperature to 55 °C, and observed a maximum temperature difference of less than 15 °C. It was evident from Fig. 1 that the cold spots were observed only between individual walnuts. Voids among in-shell walnuts trap infrared radiation, a phenomena commonly referred to as the "black hole effect" (Incropera and DeWitt, 1996). This under-estimated the true void temperatures, a reality accepted by researchers using infrared temperature measurement methods.

As a typical example, the corresponding experimental frequency distribution versus temperature shown in Fig. 1 was presented together with a normal distribution (Fig. 2). The measured temperature distribution matched the normal distribution reasonably well, except that the experimental distribution after heating skewed slightly to the right (right side with heavy tail). This represents a conservative pest control scenario where the true probability of the left tail of the measured temperature distribution was not larger than that in the normal distribution with the same mean and standard deviation. Whenever the left tail distribution in the normal distribution satisfies the desired level of temperature control, the predicted true left tail distribution will also satisfy this level.

Table 2 lists the measured mean and standard deviation and the predicted standard deviation of walnut temperatures as a function of heating time in RF systems. The initial mean temperature (μ_0) and standard

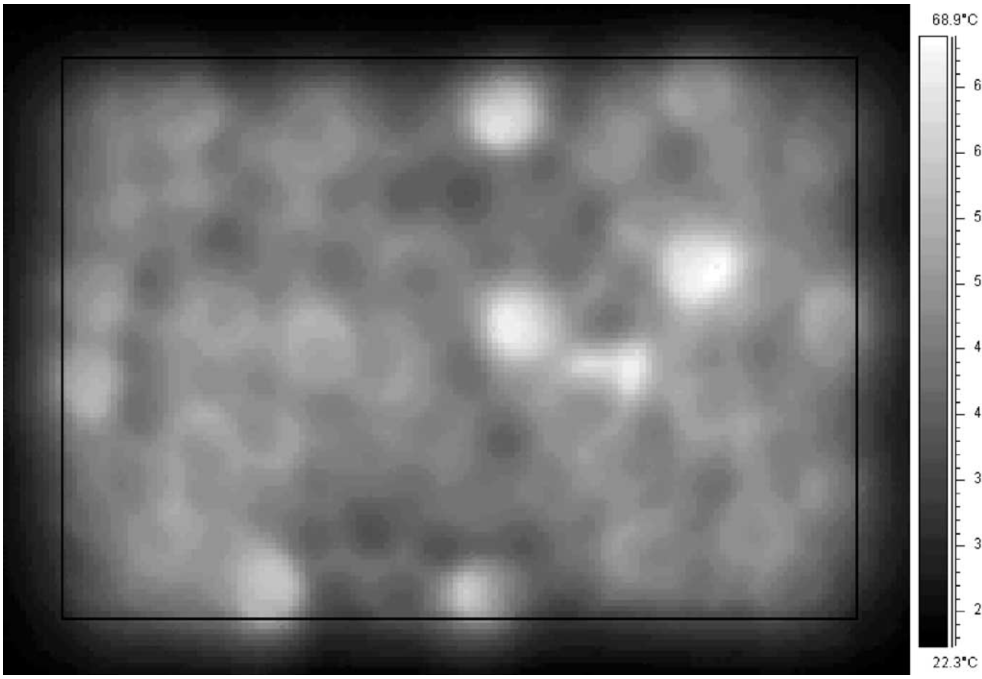

Fig. 1. Temperature distributions of in-shell walnuts obtained by thermal imaging within the boundary field used for statistical analyses after 3 min of RF heating without stirring.

Table 2
Mean and standard deviation of walnut temperatures as a function of heating time in RF systems without stirrings

Temperature (°C)	Heating time (min)						
	0	0.5	1	1.5	2	2.5	3
Measured mean, μ	18.5	24.3	29.4	34.6	39.0	42.8	47.6
Measured standard deviation, σ	0.4	1.1	1.8	2.7	3.5	4.0	4.8
Predicted standard deviation, σ_T	0.4	1.0	1.9	2.7	3.4	4.0	4.8

deviation (σ_0) were 18.5 and 0.4 °C, respectively. When running the regression of $\Delta\mu = \hat{a}_0 + \hat{a}_1 t$, we had the estimated intercept of $\hat{a}_0 = 0.896$ with a P value of 0.12. Since the P value was larger than the critical value of 0.05, we could not reject the null hypothesis of $a_0 = 0$. Similarly, from the regression of $\Delta\sigma = \hat{b}_0 + \hat{b}_1 t$, the estimate of the intercept was $\hat{b}_0 = 0.170$, with a P value of 0.149. We could not reject the null hypothesis of $b_0 = 0$. That is, Eqs. (3) and (4) are valid based on the experimental data.

Now that both intercepts were determined to be zero, we ran the regression with zero constant to determine the slopes. For $\Delta\mu = \hat{a}_1 t$, the estimated slope was $\hat{a}_1 = 9.978$. The corresponding R^2 was 0.994, very close to 1, suggesting that the normal probability plot was linear and the regression was acceptable. For $\Delta\sigma = \hat{b}_1 t$, the estimate slope was $\hat{b}_1 = 1.649$. The corresponding R^2 was 0.990, also close to 1, once again, suggesting that the normal probability plot was linear. Since the intercept was determined to be zero for both Eqs. (3) and (4), we ran the regression with a zero intercept to determine the slope between the rise in standard deviation and the rise in mean temperature, which helped us determine the uniformity index for the above mentioned test condition. As shown in Fig. 3, the estimate slope was $\hat{\lambda} = 0.165$ with $R^2 = 0.999$. From our experiments, the rise in mean was 9.978 °C per minute and the rise in standard deviation was 1.649 °C per minute.

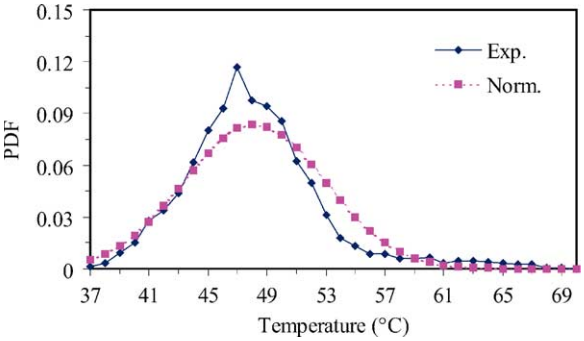

Fig. 2. Distribution comparisons of probability density frequency (PDF) of walnut temperatures between normal (Norm.) and experimental (Exp.) distributions after 3 min of RF heating without stirring.

As also shown in Table 2, the predicted standard deviation by Eq. (9) was in a good agreement with the measured value at each heating time. The relative error was less than 4%.

3.1.2. *Validation of Eqs. (11) and (14)*

In our RF heating experiments with stirring, the t_r for each heating interval was 1 min (3 min/(2 + 1)). The measured experimental data after stirring indicated that the left tail of the temperature distribution was below that of the normal distribution and the right tail of the experimental distribution was shifted close to the mean temperature when compared to tests without stirring (Fig. 4). The experimental results in Table 3 indicated that the left side probabilities from the experimental distribution were always less than that in the normal distribution with the same mean and standard deviation. As described earlier from the RF heating tests, the rise in mean for each RF heating period (1 min) was $9.978t_r$ °C. The predicted mean and standard deviation of X for a total heating period of 3 min with two intermittent stirrings were 48.43 and 2.88 °C, according to Eqs. (11) and (14), respectively. Our experiment results in Fig. 4 showed that both the left and right tails of the walnut temperature distribution after two intermittent stirrings were significantly reduced as compared to that without stirrings. This resulted in a smaller standard deviation of 3.0 °C after the stirrings as compared with

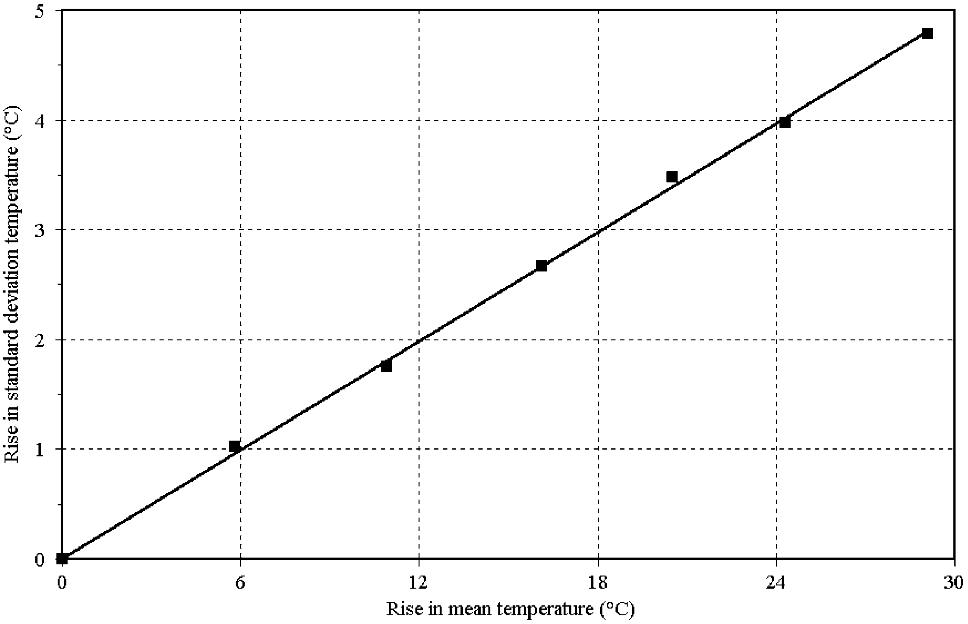

Fig. 3. Relationship between the rise in standard deviation and the rise in mean of walnut temperatures (the slope defined as a uniformity index λ was 0.165 with $R^2 = 0.999$).

4.8 °C without stirring. The observed mean value of 45.6 °C was slightly smaller than the predicted value, but the difference was insignificant. This reduction in the mean temperature was probably caused by heat losses during stirring. In practical treatments, efforts can be made to minimise the amount of heat loss during stirring by applying hot air. Furthermore, the standard deviation from the experiment was 3.0 °C, which was very close to the theoretical value of 2.88 °C. Therefore, the mean temperature and standard deviation predicted by Eqs. (11) and (14) were validated against the experimental values, and can be used to select the appropriate number of stirrings needed in industrial applications.

3.2. Model application

3.2.1. Influence of operational parameters on heating uniformity

The validated Eq. (9) was further used to predict the standard deviation so that the practical targeted walnut temperature of 55 °C could be reached for insect control in the treatment protocol (Wang et al., 2002c). The heating time needed to raise the mean temperature to the given value of $\mu_T = 55\,°\mathrm{C}$ was 3.66 min from Eq. (8) and the standard deviation σ_T increased to 6.05 °C based on Eq. (9) for RF heating without stirring.

For industrial implementations, the non-uniform heating of walnuts with different positions and

Table 3
Comparing left tail probabilities of the two and three standard deviations (S.D.) between experimental distributions and normal distributions

	Heating time (min)							Normal distribution
	No stirring						2 stirrings	
	0.5	1	1.5	2	2.5	3	3	
Left 2 S.D. (%)	1.28	1.55	1.08	1.62	1.17	0.59	0.63	2.28
Left 3 S.D. (%)	0	0	0	0.07	0.02	0	0.01	0.14

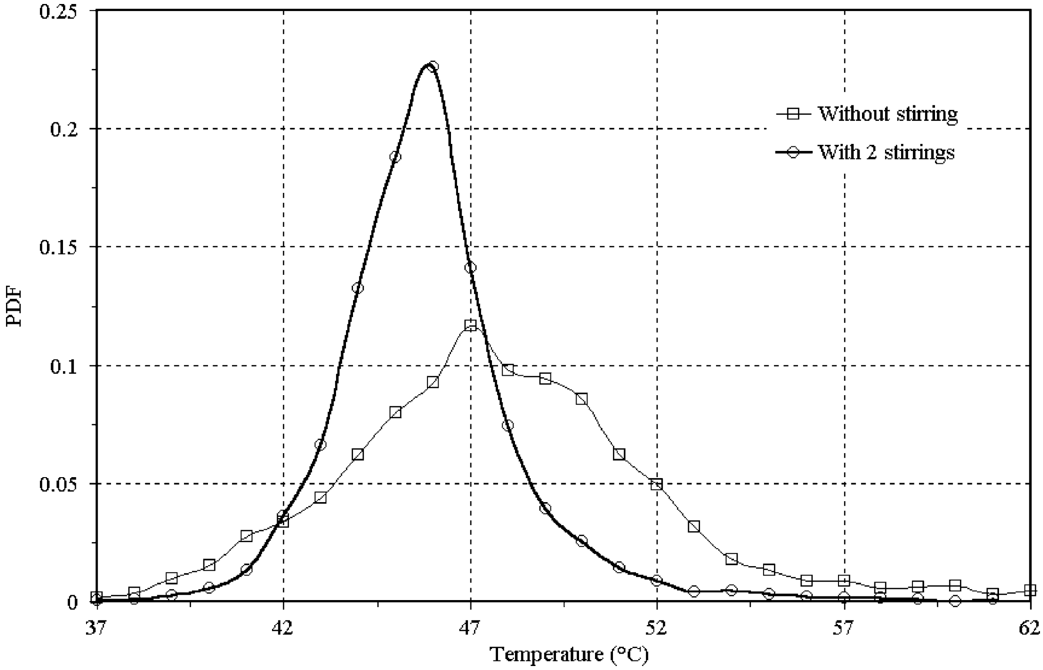

Fig. 4. Distribution comparisons of probability density frequency (PDF) of walnut temperatures between using 2 intermittent stirrings and no stirring after 3 min of RF heating.

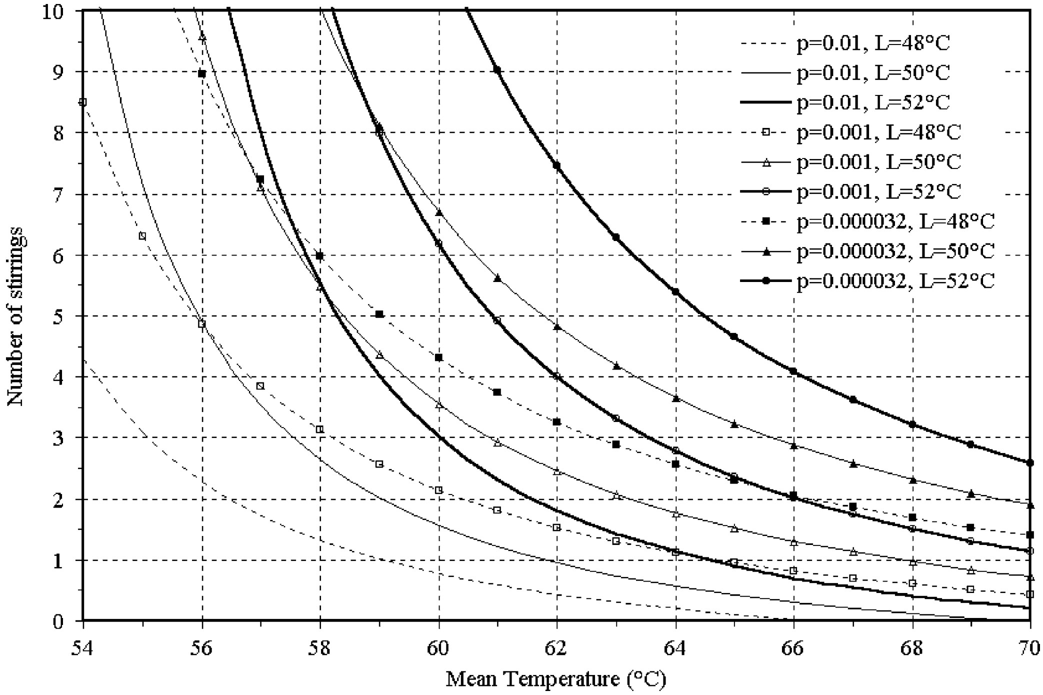

Fig. 5. Minimum number of stirrings predicted by the mathematical model as a function of the mean temperature with different probability levels (*P*) for walnut temperatures below the low limit temperature (*L*).

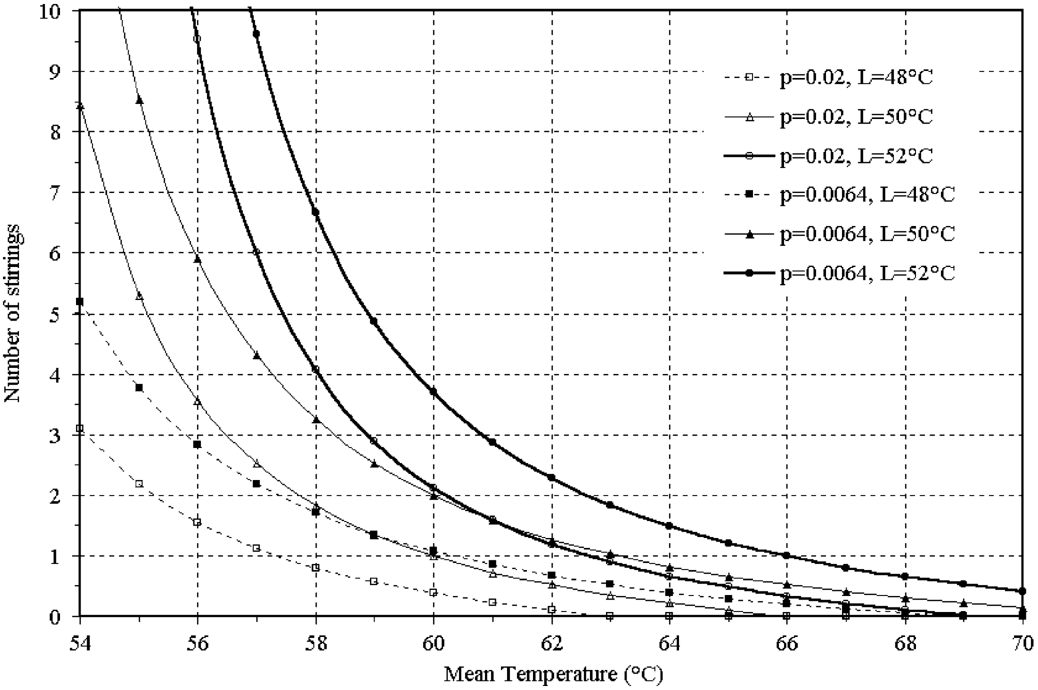

Fig. 6. Minimum number of stirrings predicted by the mathematical model under desired security levels (P_s) of 0.000032 and 0.0001, three lowest temperatures (L) and the mean temperature for the natural infestation level (P_n) of 0.5%.

orientations always exists in large-scale RF systems even after sorting. To kill hidden insect pests and meet the quality standard, it is imperative to maintain effective temperature control throughout the process. Given a selected value of the left-tail probability level (P), the lowest temperature (L) and the mean temperature, the minimum number of stirrings can be predicted by Eq. (16). To demonstrate how to use the model Eq. (16) for the selection of an n value, we considered the cases of three different low limit temperatures (48, 50 and 52 °C). These temperatures correspond to a holding time of less than 20 min for insect control in possible industrial applications (Wang et al., 2002b). Fig. 5 illustrates the predicted number of stirrings as a function of the mean walnut temperatures between 54 and 70 °C for several possible combinations of P and L. In general, the number of stirrings increased with decreasing P and increasing L. For example, if the desired treatment requires that less than 1% ($P = 0.01$) of the walnuts be under 48 °C, we may design a treatment to obtain a mean temperature of 66 °C without using any stirring. With two RF units and one intermittent stirring, the mean temperature can be reduced to 60 °C. A three-step RF heating with two intermittent stirrings would further reduce the required mean product temperature to 57 °C. It is clear from this example that increasing the number of stirrings reduces the use of RF energy and may reduce adverse thermal impact on product quality. But as shown in Fig. 5, the advantage of stirring diminishes as the number of the stirrings increases. A balance needs to be determined between capital investment of RF units, energy use and product quality.

The choice of P value significantly influences the required number of stirrings. For example, if we increase the P value to 0.0032% ($P = 0.000032$), four stirrings are needed for the temperature combinations of $L = 48$ °C with a mean temperature of 61 °C, while five stirrings are needed for a mean temperature of 57 °C (Fig. 5). The selection of the L value also significantly influences the number of stirrings needed to reach a certain mean temperature as shown in Fig. 5.

3.2.2. Selecting P value for treatment development

In developing a treatment to provide a desired security level (P_s) against a target insect pest, we need to have knowledge of the natural infestation level (P_n). The left-tail probability level P in Eq. (16) can be estimated by the following relationship:

$$P = \frac{P_s}{P_n} \tag{17}$$

For example, if the natural infestation level of the codling moth in walnuts is 0.5% ($P_n = 0.005$) (Vail et al., 1993), the probability level P is calculated from Eq. (17) to be 0.0064 for a probit 9 quarantine treatment ($P_s = 0.000032$). That is, the treatment should leave less than 0.64% walnuts below a lethal temperature level (e.g. 48 °C). For a phytosanitory treatment, the value of P_s, can be much larger. We may set P_s at 0.0001 (equivalent to 0.01% survival or 99.99% mortality). Then from Eq. (17), P will be 0.02 for the same natural infestation level of 0.5% (i.e. $P_s = 0.005$).

Fig. 6 demonstrates the influence of the above two levels of security (i.e. $P = 0.02$ and 0.0064) on the required number of stirrings. For the above mentioned phytosanitory treatment and a selected L value of 48 °C, the treatment can be designed to achieve a mean product temperature of 63 °C without using any stirring. With two RF units and one intermittent stirring, however the mean temperature can be reduced to 58 °C. If we reduce the P value to 0.64% ($P = 0.0064$) for quarantine purposes, three stirrings are needed for the temperature combinations of $L = 48$ or 50 °C and the mean temperatures of 56 or 59 °C, respectively (Fig. 6).

For laboratory work with an artificial infestation level $P_n = 1$, that is $P = P_s$, the chart presented in Fig. 5 can be used to estimate the number of stirrings needed.

3.2.3. Influences of the uniformity index (λ) on the number of stirrings (n)

The uniformity index λ, is a parameter unique to a specific RF unit and the treated commodity in a fixed configuration in industrial applications. Before the mathematical model is used, experiments must be conducted to determine the relationship between the rise in standard deviation and the rise in mean walnut temperature and then to determine the corresponding value of λ. The RF system should be maintained in an optimised condition as designed during the installation and the operation to maintain a low value of λ. The number of stirrings is very sensitive to λ because n is proportional to λ^2, according to Eq. (16). That is, reducing λ by 50% would result in a four-time decrease in n. Therefore, it is critical to reduce the value of λ in designing a RF based treatment. Means to reduce λ values include designing a RF cavity with the best possible RF field distribution, using hot air during stirring, and tumbling walnuts during RF heating.

4. Discussion

Although, the mathematical models expressed by Eqs. (14) and (16) have been developed for RF heating of in-shell walnuts, these models are applicable to general RF and microwave heating as long as two fundamental assumptions are met: (1) a linear relationship between the rise in standard deviation and the rise in mean temperature and, (2) a normal distribution of the product temperatures. From a dielectric heating engineering point of view, the first assumption can be readily met for materials with a dielectric loss factor that does not increase sharply with temperature. Dry nuts and fruits generally satisfy this condition in both RF (10–100 MHz) and microwave (300–2450 MHz) ranges (Wang et al., 2003b). The second assumption can be mostly met by designing RF and microwave applicators.

The above discussion regarding the use of product temperature information to predict insect pest control does not take into consideration the possible differential heating of insects in walnuts reported by Wang et al. (2003a). The selections of the related design and operation parameters based on Eq. (16) are conservative, therefore, and should provide an extra margin of security.

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References

Andreuccetti, D., Bini, M., Ignesti, A., Gambetta, A., Olmi, R., 1994. Microwave destruction of woodworms. J. Microwave Power Electromagn. Energ. 29, 153–160.

Birla, S.L., Wang, S., Tang, J., Hallman, G., 2004. Improving heating uniformity of fresh fruits in radio frequency treatments for pest control. Postharvest Biol. Technol. 33, 205–217.

Buranasompob, A., Tang, J., Mao, R., Swanson, B.G., 2004. Rancidity of walnuts and almonds affected by short time heat treatments for insect control. J. Food Process. Pres. 27, 445–464.

Frings, H., 1952. Factors determining the effects of radio-frequency electromagnetic fields and materials they infest. J. Econ. Entomol. 45, 396–408.

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.

Headlee, T.J., Burdette, R.C., 1929. Some facts relative to the effect of high frequency radio waves on insect activity. J. NY Entomol. Soc. 37, 59–64.

Hirose, T., Abe, I., Sugie, R., Miyanowaki, F., Kono, M., 1970a. Studies on dielectric heating of tobacco (III): on killing of tobacco injurious insects and an effect on filling capacity of tobacco shreds by microwave heating (1). Jap. Monop. Corp. Cent. Res. Inst. Pap. 112, 63–73.

Hirose, T., Abe, I., Sugie, R., Miyanowaki, F., Kono, M., 1970b. Studies on dielectric heating of tobacco (IV): on killing of tobacco injurious insects and an effect on filling capacity of tobacco shreds by microwave heating (2). Jap. Monop. Corp. Cent. Res. Inst. Pap. 112, 75–85.

Incropera, F.P., DeWitt, D.P., 1996. Fundamentals of Heat Transfer. Wiley, New York.

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

Mate, J.I., Krochta, J.M., 1997. Whey protein and acetylated monoglyceride edible coatings: effect on the rancidity process of walnuts. J. Agric. Food Chem. 45, 2509–2513.

Meyer, P.L., 1970. Introductory probability and statistical applications, 2nd ed. Addison-Wesley, London.

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.

Nelson, S.O., Payne, J.A., 1982. RF dielectric heating for pecan weevil control. Trans. ASAE 31, 456–458.

Neter, J., Kutner, M., Wasserman, W., Nachtsheim, C., 1996. Applied Linear Statistical Models, 4th ed. McGraw-Hill/Irwin, New York.

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.

Vail, P.F., Tebbets, J.S., Mackey, B.E., Curtis, C.E., 1993. Quarantine treatments: a biological approach to decision-making for selected hosts of codling moth (Lepidoptera: Tortricidae). J. Econ. Entomol. 86, 70–75.

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., 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., Ikediala, J.N., Tang, J., Hansen, J.D., 2002a. Thermal death kinetics and heating rate effects for fifth-instar *Cydia pomonella* (L.) (Lepidoptera: Tortricicae). J. Stored Prod. Res. 38, 441–453.

Wang, S., Tang, J., Johnson, J.A., Hansen, J.D., 2002b. 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.P., Bower, J., Biasi, B., 2002c. 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., Cavalieri, R.P., Davis, D., 2003a. Differential heating of insects in dried nuts and fruits associated with radio frequency and microwave treatments. Trans. ASAE 46, 1175–1182.

Wang, S., Tang, J., Johnson, J.A., Mitcham, E., Hansen, J.D., Hallman, G., Drake, S.R., Wang, Y., 2003b. Dielectric properties of fruits and insect pests as related to radio frequency and microwave treatments. Biosystems Eng. 85, 201–212.