Postharvest Control of Insect Pests in Nuts and Fruits Based on Radio Frequency Energy

Juming Tang, Shaojin Wang
Department of Biological Systems Engineering
Washington State University
Pullman, WA 99164-6120, USA

James Hansen
USDA-ARS-YARL
5230 Konnowac Pass Road
Wapato, WA 98951, USA

Judy Johnson
USDA-ARS-HCRL
2021 South Peach Avenue
Fresno, CA 93727, USA

Elizabeth Mitcham
Department of Pomology
University of California
Davis, CA 95616-8683, USA

Steve Drake
USDA-ARS-TFQL
1104 North Western Avenue
Wenatchee, WA 98801, USA

Guy Hallman
USDA-ARS-KSARC
2413 E. Highway 83
Weslaco, TX 78596, USA

Keywords: heat, insect, quality, quarantine, radio frequency

Abstract

Postharvest phytosanitation is essential for international and domestic commerce of tree fruits and nuts in the USA. Current methods used in the industry rely, however, on chemical fumigants that are either harmful to the environment or to human health. The multi-billion dollar US tree fruit and nut industries are facing a major challenge in meeting more stringent regulatory restrictions and in addressing ever-increasing public concern over health and environment. Developing thermal treatment protocols was our major focus based on radio frequency (RF) energy or in combination with conventional thermal methods such as water or air heating. To achieve a delicate balance between minimized thermal impact on product quality and complete kill of insect pests, information on thermal death kinetics of insects and commodity quality degradation kinetics is needed. In this paper, the general research strategy, principle of RF heating, and some main findings for post-harvest insect pest control in nuts are discussed.

INTRODUCTION

Many types of fresh commodities serve as hosts for insects that are categorized as quarantine pests because of their threat to local agriculture. These insects can be found on the surface or in the interior of harvested produce. Because infested produce is often not easily detectable by external inspection, regulatory agencies in many countries have established phytosanitary quarantine protocols intended to prevent the introduction of exotic pests. Quarantine protocols may include pre-harvest techniques, such as sterile fly release, non-host status, and pest-free growing periods, as well as postharvest measures, such as commodity treatments.

Currently, the dried fruit and tree nut industries rely heavily on fumigation with methyl bromide (MeBr) and phosphine (hydrogen phosphide) for postharvest insect control. However, the Montreal Protocol (UNEP, 1992) has identified MeBr as an ozone depleter, which has resulted in a gradual annual reduction of most uses of MeBr and will result in its eventual elimination. Insect resistance to hydrogen phosphide has been documented in other commodities (Zettler et al., 1989), and the United States Environmental Protection Agency (USEPA) is considering increased restrictions on the use of hydrogen phosphide (USEPA, 1998). Although non-chemical treatments for postharvest dried fruits and nuts have been investigated in the past to some extent, little progress has been made and concerns over resistance and regulatory action have generated a renewed interest in developing alternative treatments.

Several alternative methods have been suggested, including ionizing radiation, cold storage, controlled atmospheres and combination treatments (Wang and Tang, 2001). All would require substantial capital investment and alteration of existing facilities. Cold storage and controlled atmospheres also require long treatment times for disinfestation, and there is concern over public acceptance of irradiated food. Heat treatments have been proposed to kill codling moth in different commodities using hot forced air or hot water dips (Yokoyama et al., 1991), but the lengthy exposure times needed may cause injury to the product (Lurie, 1998). Industrial radio frequency (RF) and microwave systems that are extensively used in the food processing, textile and wood processing industries may provide more rapid product heating (10-20°C/min) and have been suggested for control of postharvest insects (Tang et al., 2000; Wang et al., 2001). Knowledge of thermal death kinetics for targeted insects is essential in developing those thermal treatments.

The objective of this study was to develop postharvest treatments using RF energy to control common insect pests in in-shell walnuts and cherries based on the thermal death kinetics studies. A pilot-scale 27 MHz RF system was used to study process parameters leading to a complete kill of those insect pests. The effects of selected thermal treatments and storage conditions on common quality were also examined.

MATERIALS AND METHODS

Strategy for Developing New Heat Treatment Method

An important key to the development of successful thermal treatments is to identify a delicate balance between minimized thermal impact on product quality and complete killing of insects. It is possible to describe a 100% mortality curve and a safe quality curve as a function of temperatures for different agricultural products (Fig. 1). Because the activation energy for commodity quality changes in thermal treatments is generally smaller than that of insect mortality, the slope of this quality curve should be less than that of the insect mortality curve. The exact location and the slope of the quality curve depend on each commodity. The overlap between the lower region of the quality curve and upper region of the insect mortality curve defines the potential operation conditions for developing thermal quarantine treatments (Tang et al., 2000). A clear knowledge of the thermal death kinetics of insects is essential. Once the information for the thermal death kinetics of targeted insects becomes available, new treatment protocols can then be developed to deliver the desired lethal energy to the insects in a manner based on engineering principles that control the insects without damaging product quality.

Description of the Heating Block System

A heating block system was developed at Washington State University (WSU) and has been used to determine the thermal death kinetics of codling moth, Indianmeal moth and navel orangeworm (Johnson et al., 2002; Wang et al., 2002a;b). The system consists of top and bottom metal blocks, heating pads, an insect test chamber, controlled atmosphere circulating channels, and a data acquisition/control unit (Fig. 2). The heating blocks are made of aluminum alloys with low thermal capacitance and high thermal conductivity. The heating block system can treat up to 200 insects at a time at controlled heating rates between 0.1 and 20 °C/min. Calibrated type-T thermocouples inserted through sensor paths are used to monitor the temperatures of the top and bottom plates, and the air temperature in the chamber. The heating rate and the end-point temperature are controlled by the visual software WorkBench PC 2.0 (Strawberry Tree Inc., Sunnyvale, CA) via a solid state relay. The thermal capacitance of the blocks provides smooth temperature profiles over the heating period and precise control (±0.2°C) during the holding periods (Wang et al., 2002b).

Principle and Treatment System of RF Heating

The dielectric property data for the targeted insects, fruits and nuts provide general information for selecting optimal ranges of frequency and the design of the thickness of the treated bed for uniform RF heating. The complex relative permittivity, ε^*, of a material can be expressed in the following complex form:

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \qquad (1)$$

The real part ε' is referred to as the dielectric constant, and represents stored energy when the material is exposed to an electric field, while the dielectric loss factor ε'', which is the imaginary part, mainly influences energy absorption and attenuation. Dielectric materials, such as most agricultural products, can store electric energy and convert electric energy into heat. The increase in temperature of a material by absorbed electromagnetic energy can be expressed:

$$\rho C_p \frac{\Delta T}{\Delta t} = 5.563 \times 10^{-11} f E^2 \varepsilon'' \qquad (2)$$

where C_p is the specific heat of the material ($J.kg^{-1}.°C^{-1}$), ρ is the density of the material ($kg.m^{-3}$), E is the electric field intensity ($V.m^{-1}$), f is the frequency (Hz), Δt is the time duration (s) and ΔT is the temperature rise in the material (°C). From Eq. (2), the rise in temperature depends on the power, frequency, heating time and the material's dielectric loss factor.

RF energy was used as the main source of heating in our treatment protocols. To reduce temperature drop during the holding period and to improve the surface heating of in-shell walnuts, heated air was also used in combination with RF energy (Fig. 3). The RF power was supplied by a 6 kW, 27 MHz pilot-scale RF system (COMBI 6-S, Strayfield International Limited, Wokingham, UK). The gap between the electrode plates was adjusted so that the samples were treated with 0.8 kW RF energy. A tray drier (UOP8, Armfield Limited, UK) was used to provide forced hot air, and a fan and electric power settings maintained the airflow speed (1 m/s) and air temperature (55°C) in the RF cavity. The kernel temperature of a walnut in the center of the samples was measured using a fiber-optic sensor (Nortech Fiberonic Inc., Quebec, Canada) inserted through pre-drilled holes in the shell. These sensors provided 0.5°C accuracy in the test temperature range between 20 to 60°C.

RESULTS AND DISCUSSIONS

Thermal Death Kinetics of Insect Pests

Knowledge of the fundamental kinetics for the thermal death of insects will allow the prediction of lethal times over a range of temperatures. The thermal death time (TDT) curves were experimentally determined by identifying the minimum time needed to completely kill insects of a given sample size over a selected temperature range. TDT curves for fifth-instar codling moth, Indianmeal moth and navel orangeworm at the heating rate of 18°C/min were developed by Johnson et al. (2002) and Wang et al. (2002a;b) and are summarized in Fig. 4. The results suggest that navel orangeworm is the most heat resistant insect at the fifth-instar life stage.

Development of RF Based Treatment Protocols

Sixty walnuts each run were infested with the most heat resistant life stage of navel orangeworm. The final temperature (55°C) and 5 min holding time were selected and that provided room to achieve a complete control of the insects in walnuts based on about 3°C variation in temperature within the treatment area. Three protocols: RF+5min, RF+10min and RF with hot air+10min were used to determine both the insect mortality and product quality. Treatment results showed that insect mortality for control was 0% because all 180 larvae were found alive. All of the RF treatments resulted in 100% mortality in the tested samples.

Walnut and Cherry Quality

For commercial application, phytosanitation procedures must also retain product quality. Quality factors for walnuts include crackability, kernel color, moisture content and flavor. Walnuts contain high concentrations of polyunsaturated fatty acids, which are susceptible to the development of oxidative and hydrolytic rancidity, especially at high temperatures. The two main parameters indicating walnut oxidative rancidity are peroxide values (PV, meq/kg) and fatty acid (FA, % oleic). According to the industry standard (Diamond Walnut Company, Stockton, CA), good quality walnuts should have a PV < 1.0 meq/kg and a FA < 0.6%. Table 1 shows the mean values and standard deviations of the PV and FA values of the control and the longest RF treated walnut kernel samples. The final PV and FA values during accelerated storage of up to 20 d remained lower than the industry standard values for good walnut quality. None of the RF treated walnuts differed from the control in terms of the force required to crack the shell or the brittleness of the kernels. Sensory qualities and shell characteristics were not affected by the treatments.

Preliminary results on the quality of ‘Bing’ sweet cherries and mortality of codling moth larvae show that complete insect control was achieved below the region where fruit injury occurred at the temperatures from 48°C to 54°C (Fig. 5). The implementations of the treatments were very limited due to the small room for operations. These results suggest that the cherry temperature should be controlled precisely or we may find a way to increase the cherry thermal tolerance or to reduce the insect heat resistance before treatments.

Dielectric Property and Differential Heating

To understand interactions between selected commodities and electromagnetic energy at different temperatures, a test cell was developed to control and maintain the sample temperature during the measurements with an impedance analyzer (Model 4291B, Innovative Measurement Solutions Inc., Santa Clara, CA). The sample was confined in a stainless steel sample cell to allow the coaxial probe to fit into the cell and to contact well with the sample by a spring at the cell bottom. Wang et al. (2001) found that the dielectric loss factor was clearly different between codling moth larvae and walnut kernels, especially in the RF range at room condition (Fig. 6). The dielectric loss factor of the insects is much higher than that of walnuts. Codling moth larvae might absorb more energy than walnuts when subjected to the same electromagnetic field.

For the first time in the history of insect control research, we have proved experimentally that it is indeed possible to preferentially heat insects in nut products. We measured insect body and walnut kernel temperatures using fiber optic sensors during RF treatments. Fig. 7 shows the temperature-time history for codling moth larvae (slurry) and walnut kernels when subjected into 27 MHz RF system with a power of 1 kW. The heating rate for the insect slurry was about 1.4 to 1.5 times faster than for walnut kernels. This confirms the insects were preferentially heated in walnuts at 27 MHz. It is therefore, not necessary to raise walnut temperature to a lethal level to control insects. The significant preferential heating of insects in walnuts can be used to our advantage when developing insect control treatments to provide a large safety margin that can control insects without causing thermal damage to product quality, and to allow a short time process to reduce the use of RF energy.

CONCLUSIONS

- **Insect Mortality Data** A heating block system was used to determine the thermal death kinetics of codling moth, Indianmeal moth and navel orangeworm at a heating rate of 18°C/min. We found that the fifth-instar was the most heat resistant life stage and navel orangeworms were the most heat resistant insect as compared with codling moths and Indianmeal moths. A 0.5 order thermal death kinetic model was established to predict the lethal time to reach different levels of mortality.
- **Fruit Quality** At elevated temperatures, product quality should be evaluated to ensure a practical treatment protocol. It is reasonable to describe a safe quality curve as a function of temperatures for different agricultural products. The quality curves for walnut and cherry were obtained based on chemical and sensory analyses. The

treatment region between the lower part of the quality curve and the upper part of the insect mortality curve was used to guide the development of thermal quarantine treatments.

- **Dielectric Properties** Knowledge of the dielectric properties of insect pests and host commodities are needed for developing RF treatments. We have developed a new test cell that allows the frequency and temperature dependency measurement of dielectric properties of insect and host commodities. The dielectric property data suggest strong possibility of preferential heating of insect pests in nut commodities in the RF frequency range.
- **Differential Heating** By exploring possible differential heating of insect pests in host walnuts, we can potentially reduce the time and product temperature thereby reducing adverse effects on walnut quality, and allowing for a greater throughput of product through the equipment in the processing plants. Direct temperature measurement using fiber-optic sensors indicated that insect pests were heated 1.4 to 1.5 times faster than walnut kernels at 27 MHz frequency.
- **Preliminary Results on Process Protocol for Walnuts** Walnuts in the shell were infested with fifth instar codling moths and navel orangeworms before being treated with RF energy in a 27 MHz pilot-scale system to average kernel temperatures between 53 and 55°C. The heating time was about 3 min, compared to 60 min with heated air. After 3-5 min holding, insect mortality reached 100%. The two main walnut quality indexes, PV and FA values, were not affected by the RF treatments. RF treatments can, therefore, potentially provide an effective and rapid quarantine security protocol against insect pests in walnuts as an alternative to chemical fumigation.

Literature Cited

Johnson, J.A., Wang, S., Tang, J. 2002. Thermal death kinetics of fifth-instar *Plodia interpunctella* (Lepidoptera: Pyralidae). J. Econ. Entomol., in review.

Lurie, S. 1998. Postharvest heat treatments. Postharvest Bio. Technol., 14:257-269.

Tang J., Ikediala J.N., Wang S., Hansen J. and Cavalieri R. 2000. High-temperature-short-time thermal quarantine methods. Postharvest Bio. Technol., 21:129-145.

UNEP 1992. Fourth Meeting of the parties to the Montreal Protocol on substances that deplete the ozone layer. Copenhagen, 23-35 November 1992. UNEP, Nairobi, Kenya.

USDA, 1999. Agricultural statistics. USDA, Washington, DC.

USEPA, 1998. Reregistration Eligibility Decision. Aluminum and Magnesium Phosphide. Cases 0025 & 0645, Office of Pesticide Programs, Special Rev. and Reregist. Div.

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

Wang, S. and Tang J. 2001. Radio frequency and microwave alternative treatments for nut insect control: a review. Int. Agric. Eng. J., 10:105-120.

Wang S., Ikediala J.N., Tang J., and Hansen J. 2002a. Thermal death kinetics and heating rate effects for fifth-instar codling moths (Cydia pomonella (L.)). J. Stored Prod. Res., 38:441-453.

Wang S., Tang J., Johnson J.A. and Hansen J. 2002b. Thermal death kinetics of 5th-instar navel orangeworms (Lepidoptera: Pyralidae). J. Stored Prod. Res., 38:427-440.

Yokoyama, V.Y., Miller, G.T., Dowell, R.V. 1991. Response of codling moth (Lepidoptera: Tortricidae) to high temperature, a potential quarantine treatment for exported commodities. J. Econ. Entomol., 84:528-531.

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

Tables

Table 1. Chemical characteristics of in-shell walnuts treated by RF energy (3 replicates)

Storage time at 35°C (day)	Peroxide value* (meq/kg)		Fatty acid* (%)	
	Control	RF with hot air+10min	Control	RF with hot air+10min
0	0.01± 0.01	0.02± 0.01	0.10± 0.01	0.10± 0.02
10	0.28± 0.11	0.18± 0.12	0.15± 0.01	0.15± 0.01
20	0.64± 0.16	0.61± 0.03	0.21± 0.01	0.17± 0.03

*Accepted PV and FA values for good quality are less than 1.0 meq/kg and 0.6%

Figures

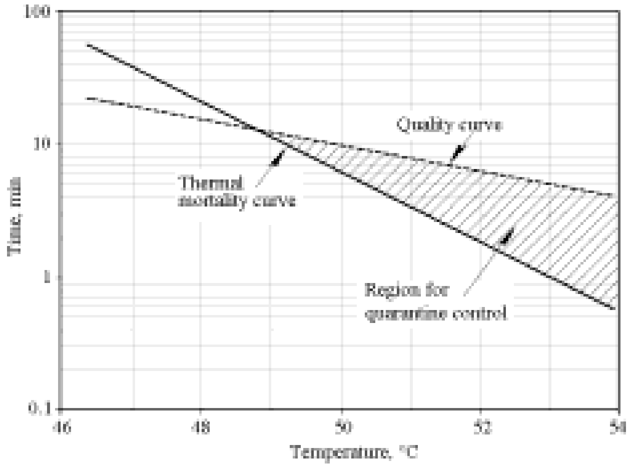

Fig. 1. Acceptable time-temperature treatment area obtained from different mortality and quality curves (Tang et al., 2000)

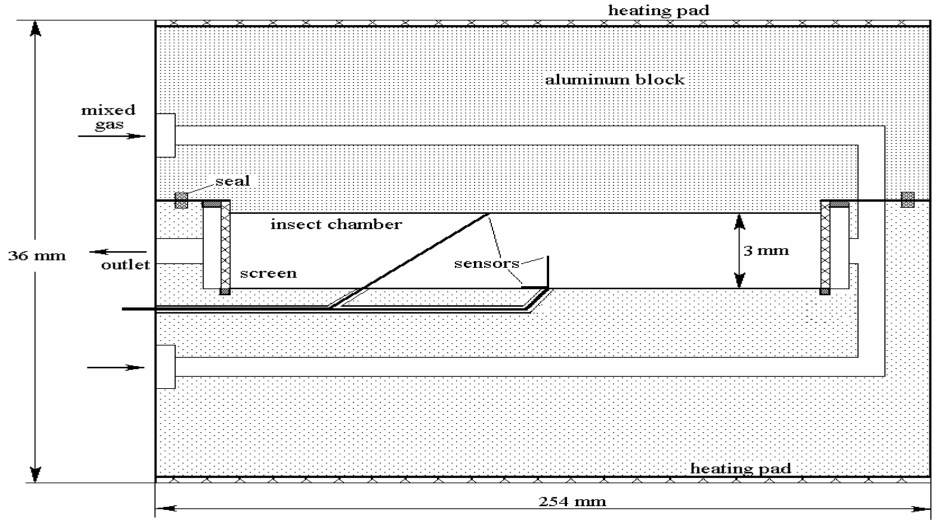

Fig. 2. Schematics of the WSU heating block system for insect mortality studies (Wang et al., 2002b).

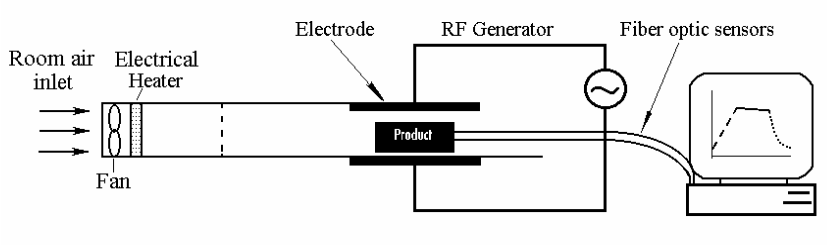

Fig. 3. Schematic view of the combined RF and hot air treatments of in-shell walnuts for insect control.

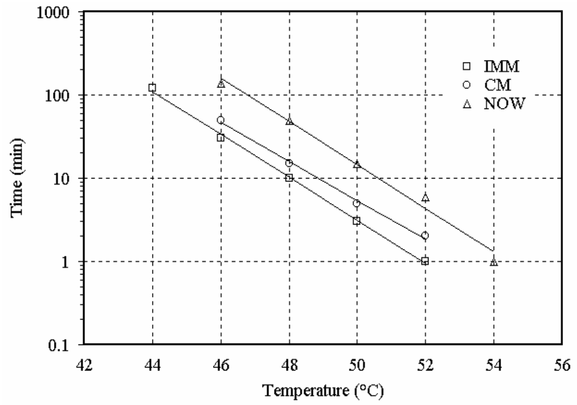

Fig. 4. Experimentally determined minimum time-temperature combinations for complete kill of 600 fifth-instar Indianmeal moth (IMM), codling moth (CM) and navel orange worm (NOW) after heating at 18°C/min.

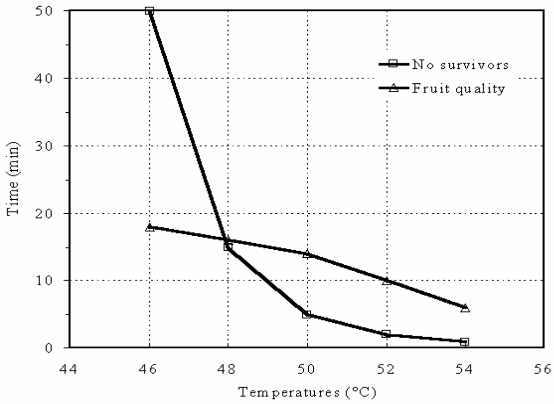

Fig. 5. Treatment efficacy of codling moth and cherry quality when exposed to water baths at specific temperatures and time.

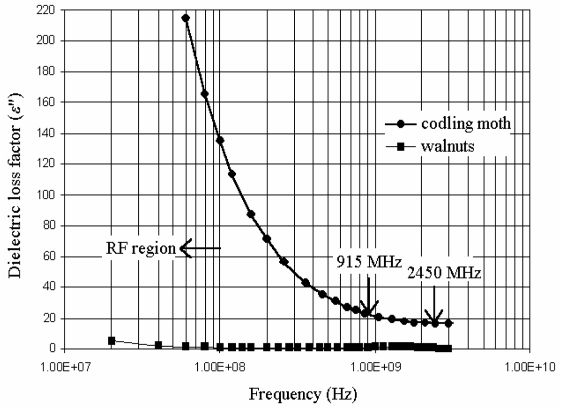

Fig. 6. Dielectric loss factor (ε″) of codling moth larvae and walnuts as a function of frequency (Wang et al., 2001).

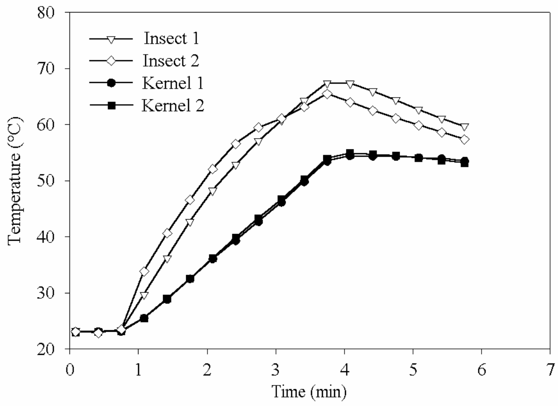

Fig. 7. Temperature profiles of walnut kernels and codling moth slurry when subjected to 27 MHz RF system (P=1kW)