Radio Frequency Thermal Treatment as Alternative Insect Pest Control in Storage

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ABSTRACT

Pest control in farm crop production, storage and during marketing has been practiced in the tropics and sub-tropic conventionally with the chemical treatments. The demand for food safety for human health concerns, the green production for environmental friendly purposes, which are the alternatives to chemical treatments for insect pest control and management, become the research, policy, and practical challenges. Radio frequency (RF) treatment can be one of the appropriate technical measures taking into account the need for cost effectiveness for Thailand to be competitive in world agriculture. It was found that in the post-harvest management process, especially in rice preserved for packaging and exporting, post-harvest losses were usually found from infestation of insects during storage, which include rice weevil (Sitophilus oryzae L.), Angoumois grain moth (Sitotroga cerealella (Olivier)), rice moth (Corcyra cephalonica (Stainton)) and lesser grain borer (Rhyzopertha dominica (F.)). The efficacy of RF on controlling these storage insects showed the reaction of the insects depended on the insect species and their growth stage. After using RF (27.12 MHz) at 70°C for 150 sec of exposure time, this treatment completely controlled C. cephalonica in milled rice and 180 sec for controlling R. dominica in paddy rice. However the 100% mortality of S. oryzae, occurred at the lower temperature of 50°C for 15 min. The RF-tolerance stages of C. cephalonica and R. dominica were egg adult and larval stages, respectively. The effectiveness of RF on controlling stored insect would depend, without adverse effects on commodity of exposed agricultural products.

Key words: Radio frequency, Insect control, Rice

INTRODUCTION

Pest control in crop production farm, storage and during marketing has been practiced in the tropics and sub-tropics conventionally with the chemical treatments. The demand for food safety for human health concern and the green production for environmental friendly purpose, the alternative to chemical treatments for insect pest control and management become the research, policy, and practical challenges. Whether through the biological or cultural or other solutions, the contemporary insect pest management options seem to be forced to confined to the non-toxic and non-destructive domains to serve the objectives of preventing agricultural quality and quantity losses, and responding to consumer's demand including food safety policy. Radio frequency treatment can be one of the appropriate technical measures taking in to account the need for cost effectiveness for Thailand to be competitive in world agriculture, and the fact that Thailand has a farming sector comprising many groups of role players.

Table 1. World sales of agrochemicals in the major regions of the world (Kogan and Bajwa, 1999).

Region	World sales of agrochemicals by region in a year					
	1990[1]		1992[2]		1996[3]	
	US $ (billion)	% share	US $ (billion)	% share	US $ (billion)	% share
North America	5.4	21.9	7.3	29.2	9.2	29.4
Western Europe	6.6	26.7	6.7	26.7	8.2	26.2
Eastern Europe	1.9	7.7	1.2	4.6	na	na
Asia	6.8	27.5	6.1	24.4	7.7	24.5
Africa	1.2	4.9	na	na	na	na
Latin America	2.8	11.3	2.4	9.5	3.3	10.4
Rest of the World	na	na	1.4	5.6	3.0	9.5
Total	24.7	100	25.0	100	31.3	100

na=not available

Source: [1]GIFAP. 1992. Asia Working Group. Publication of International Group of National Associations of Manufacturers of Agrochemical Products, Brussels.
[2]Chemistry & Industry, 15 November 1993.
[3]Agrow: World Crop Protection News. 28 February 1997.

In addition, it was found that in post-harvest management process, especially in rice preserved for packaging and exporting, post-harvest losses were usually found from infestation of insects during storage which include rice weevil (*Sitophilus oryzae* L.), Angoumois grain moth (*Sitotroga cerealella* (Olivier)), rice moth (*Corcyra cephalonica* (Stainton)) and lesser grain borer (*Rhyzopertha dominica* (F.)). The rice weevil is one of the most serious stored paddy rice pests. The females drill a tiny hole in the rice kernel, deposit an egg in the cavity, then plug the hole with a gelatinous secretion. The larval rice weevils complete their development inside a seed kernel and the adults cut exit hole to emerge. The invasion of the insect causes losses in weight and reduces rice quality by facilitating infection of microorganisms. Methyl bromide fumigation of paddy rice has been used to control rice weevil and other pests. Nevertheless, the use of methyl bromide had to be decrease and phased out by the end of 2004 due to its ozone depletion potential and being highly toxic to humans. Then, phosphine has been developed to be alternative fumigants to disinfest the stored grain. However, phosphine gas is flammable with high pressure and is to rapidly absorbed by humans and distributed throughout the body and is acutely toxic as well as needs long exposure time required for fumigation (7-30 days depending on the concentrations) (Lv et al., 2006). In addition, the use of fumigants has been restricted in developed countries under Montreal protocol since 2005 and in developing countries since 2010 (World Meteorological Organization, 1995; USEPA, 2001). In the future, disinfestations from stored pests will rely on alternative methods due to increasing legal restrictions. Thermal treatment from radio frequency is a viable alternative for stored grain protection due to the ability to create differential heat in a fairly short period. Heating provides several advantages in insect control including decreased insect feeding and its reproduction and mold infection. Furthermore, the radio frequency heat treatment is a feasible technique to avoid insecticide treatment and is environmental friendly.

Application with high frequency fields to heat a product is a physical method of energy input to eliminate insect pests that has been developed since 19^{th} century (Goldblith, 1966). Not only electromagnetic radiation (Figure 1) but also microwave and radio frequency, have the potential for fast heating in solid and semisolid materials having dielectric property especially those with low moisture. Dielectric heat is formed and transferred directly between electromagnetic waves and insect infested products. The process to control insects was investigated in grain by high frequency waves (Davis, 1934; Nelson and Whitney, 1960). The use of RF was further investigated during 1940s and 1960s including mostly disinfestations of insects (Fleming, 1944; Webber et al., 1946; Frings, 1952; Baker et al., 1956; Nelson and Whitney, 1960; Nelson and Kantack, 1966; Benz, 1975)

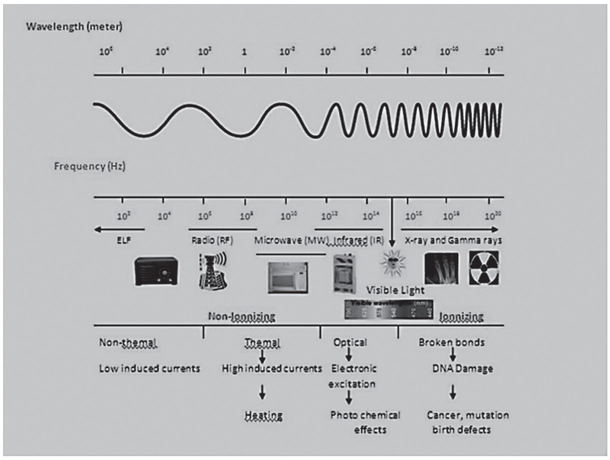

Figure 1. Electromagnetic radiation.

PRINCIPLES OF DIELECTRIC HEATING

Dielectric deals with poor electrical conduction between two parallel electrodes. Material, which contains no free ions and no unsymmetrical molecule (e.g. paper) is confirmed as no dielectric heating. This principle is carried a resemblance to exploit an energy loss to generate a thermal in the material filling the electrode-plates. Most of all of the matter containing polar molecules such as water, which compost with conducting components and is most readily heated and absorbs the energy. Dielectric heating is generated from electromagnetic energy at radio frequency (13.56, 27.12 and 40.68 MHz) or microwave (433, 915, 2,450 MHz). A high frequency is converted from oscillating electromagnetic field to RF power. As polar molecules in the material continually arrange in a line and reorient themselves to change electric field, then friction is formed and causes heat within conductive materials (Figure 2). Therefore, the water content of the matter is an important factor for these heating performances. In addition the heat is generated inside out and distributed throughout its mass within the peripheral of the container often hot rapidly. This is in contrast to conventional heating where heat enters the sample through its surface and transferred toward the center by thermal conduction and/or convection. The application of microwave and RF dielectric heating to agricultural products after post harvest management is a new technology and has attracted great interest following much research (Wang et al., 2003a). In this technology, the radiation energy is dissipated within the sample and afterward a great rate of heating can be obtained rapidly. In recent years, the radio frequency unit has been developed to large scale processing applications of materials by operating with belt conveyer systems on a big scale (Tang et al., 2000; Nijhuis et al., 1998).

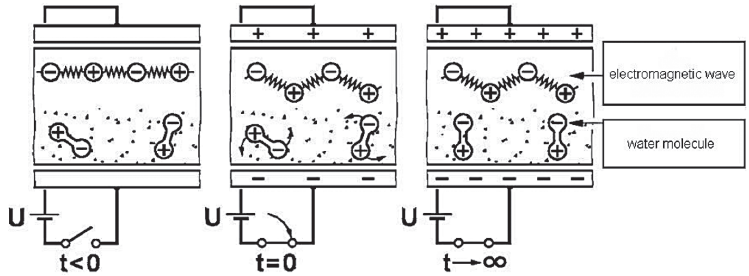

Figure 2. Molecules in the material continually arrange in a line and reorient themselves to change in electric field (Cwiklinski and von Hoersten, 2001).

Radio frequency heat treatment

Heating with radio frequency is operated by the wave generator, which is made from a vacuum circuit tube or semiconductor. High-energy radio waves are created through the electrode plates and then electric fields are assigned to heat target material. The band of 13.56, 27.12 and 40.68 MHz are also differing in energy or powers, which proceed through the material depending on the material properties and frequency. For heating the large material, lower frequency waves can pass into material deeper than high frequency, which is an ideal for heating small or slight material.

Mechanisms of radio frequency heat treatment

Dielectric material delivers low power when passed high voltage energy as alternating current at a frequency of 27.12 MHz, or 27,120,000 times per second. Electromagnetic fields at low frequency are produced with long wavelengths resulting in a possibility to control the direction. Dielectric is an insulating power which has no independent capacity (or free electrons) that moves within a conductor. However, the dielectric molecules can also arrange position by the electric field arising from electric dipole properties. This is caused by electric dipolar properties of the material that molecules can be divided into two categories.

Type of heat from electromagnetic absorption

Ionic polarization

Generally, the unpole molecule in the absence of electric field, electron moves around nucleus showing a positively charged and the center of positive charge overlap exactly with the center of the negative ions. Nevertheless, when the electric field acting on the molecule, electron in an atom is induced until the center of positive charge and negative ions move away from each other slightly. Then, it becomes a molecular electric dipole and the moment is immerged by the inductance.

Orientation polarization

Orientation polarization always occurs with a polar molecule, such as water molecules where the electrons are divided not equal or unsymmetrical on each atom of each molecule and shows electrical neutrality resulting from a 104° angle between the two OH- anions. However, polar molecules which randomly oriented usually confirm a stability of electric dipole moment value. When they pass through the electric field, the positive and negative charges in material move to change direction in an orderly arrangement by moving back and forth rotation, which occurs rapidly as the frequency of the waves. In the radio-frequency with ion mobility of 3-300 million times per second, resulting the speed of rotation and friction, causing the heat up rapidly within 2-3 seconds, or about 1 minute after receiving electromagnetic radiation, then the heat generated is distributed to other parts of the matter.

APPLICATION OF RADIO FREQUENCY

The radio frequency wave does not cause disintegration of the charge and the energy is transferred without breakdown of molecules, which causes mutations. When the wave disperses and contacts with materials, the power is partly absorbed by the elements having electrical conductivity, then heat is generated within the material. Since the energy is transferred to the object without the need for medium to convey the heat, subsequently reaction arises very rapidly within electromagnetic field especially the polar molecule illustrating the most intense. Therefore, the water content of the materials is an important factor for the radio frequency heating performance.

Usually, a pulse or signal of any specified radio frequency generator can be constructed in any infinite length and duration. The velocity with constant-phase surface of waves is propagated depending on the propagation constant (Macdonald, 1987). The complex permittivity of the medium, ε′ relative to a vacuum has a value of 8.85×10^{-12} Fm^{-1}. If the medium is non-conducting and the applied field is independent on frequency, the signal is propagated without distortion. However, in absorptive medium the harmonic wave is displaced in phase in the direction of propagation since the signal is dispersed. A significant change in dielectric properties when misplaced or overlapped in frequency range is called a dielectric dispersion. The quantity ε″ is a measure of the polarization. The number of polarizing mechanism is took place in each matter or element will reflect a characteristic relaxation frequency. The relaxation frequency may be understood as the relation between the electrical conductivity and the relative dielectric constant of the sample. At the relaxation of frequency, the material will show a maximal absorption. Thus, this principle has been applied to an indicated object with high moisture content such as in the case of the beetle or rice weevil infested with wheat kernel (Figure 3). The curves illustrate observed dielectric loss factor in materials in the frequency range 10^2 to 10^{11}Hz. Energy from radio frequency and microwave distribute in biological dielectric as material and cause partial loss of the dielectric when wheat are exposed in electromagnetic field. The molecular structure of materials in polar form tries to sort the field in the direction of the passing wave, then induces molecular friction within the frequency range of amplitude showing the most intense molecules vibrations which present high performance of energy transfer known as dielectric relaxation frequency. However, the difference between the forms of water (free water, bound water and constituent water) in the matter also affects the curve of loss factor of dielectric by the influence of electromagnetic fields.

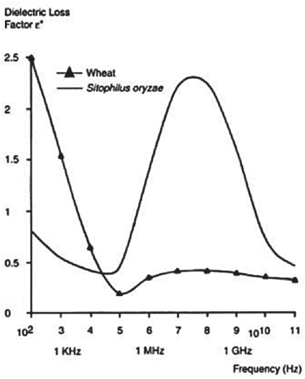

Figure 3. Change of dielectric properties of rice weevil (*Sitophilus oryzae*) in different spectrum of radio frequency and microwave generated as electromagnetic wave (Nelson and Charity, 1972).

The permittivity of dielectric is performed by the electric field consisting of two parts: 1. ε′ is a dielectric constant and presents the capacity of a material at a certain frequency and 2. ε″ is dielectric loss factor which shows electric energy dissipates into heat. The average power *P* dissipating in material volume V which is related to electronic field E and transformed into heat energy by dielectric property are expressed in terms of equation (1) or (2)

$$P = 2. ¶. f. \varepsilon_0. \varepsilon'' .E^2 .V \qquad (1)$$

$$P = 55.63 \text{ x } 10^{-12} f .\varepsilon''. E^2 \qquad (2)$$

The amount of heat released into object depends on the specific heat itself and the relative amount of the electromagnetic field that passed into the surface and is adsorbed (in some cased, thermal energy becomes 100%). However in theory, the heat is caused by all of absorbed power (no energy loss). A simplified model used to describe the power with the rate of rising temperature during heating can be expressed as equation (3).

$$Q= d\theta . M. c. 1.1627 \text{ x}10^{-3} \qquad (3)$$

Where Q is absorbed power per hour (kWh^{-1})

$d\theta$ Temperature increase during exposure (°C)

M Mass of material (kg)

c Specific thermal value of product (Cal g^{-1} $°C^{-1}$)

However, the relation between equation (2) and (3) can be performed when the absorbed power is completely transferred 100% in theoretical given by the equation

$$dt = Q P_{th}^{-1} \qquad (4)$$

Where dt is exposure duration in hour and P_{th} is all absorbed energy which is transferred to material in kW (if dt=1, then P_{th}= Q), then heat transfer into the matter can be calculated from the equation

$$P = 4.186 \text{ x } 10^6 . c. d\theta dt^{-1} \qquad (5)$$

Where $d\theta dt^{-1}$ means temperature in °C per time (s^{-1}) and P is absorbed power in Wm^{-3}

According to theory, the power from electromagnetic wave passed through material P_{th} fluctuates more from the monitored heat that is conveyed to the matter when the energy deliver is fragile.

Many studies have confirmed the merit of radio frequency to control insect pests during storage whereas the specific heat delivering to material has been adjusted in the form of thermal to control insects by lacking of excessive heat to be damage the mass or reduce the food quality. Nelson and Charity (1972) showed that the dielectric property of insects is higher than cereal grain by investigating the dielectric constant of insect at the frequency of 9.4 GHz and dielectric loss factor of wheat grain. The result was that the dielectric loss factor wheat was 0.9-1.8 depending on moisture content and the rice weevil (*S. oryzae*) was 13. The loss factors derived from estimation shows that insects take up more energy from the wave than wheat matter (Nelson, 2004). In addition, the low loss factor was also found in wheat indicating expressed the ability of microwave and radio frequency to be able to penetrate more intensely. The absorbed power and heat generated in insects differ from heat in material such as food products and are based on their moisture content. Generally, insects contain water or moisture between 50-65%, while the grain moisture is only 11-16%. The low frequency use accomplishes a divergence in heat dramatically accumulated in insect and material. Presently, only certain frequency bands are allowed by laws for industrial and scientific use in order to avoid interference with band used in telecommunications. Uses for high moisture solid foods have been less successful in extensive research conducted at 2450 MHz, but combined with convection heating method. The central wavelength is 12.2 and results in low penetrate depth then, the signal below 2450 MHz has been developed, such as 915 and 27.12MHz (Orsat and Raghavan, 2005). Especially at 27.12 MHz, the wavelength is in the order of 10m and some research has been conducted in sterilization of food products. The investigation found that using radio frequency at 27.12 MHz in processed model food, macaroni and cheese, produced better quality (Wang et al., 2003b).

RF APPLICATION FOR INSECT CONTROL

Insect infestation during storage

The development of electromagnetic waves application in controlling storage insect pest has been considered to have a relationship between physical and biological factors. Commonly, plant products have been used in two forms: producing ready to eat food and using as material like seeds or grain. The deterioration of food can happen during storage, caused by biological factors including various insects, mites and bacteria as well as physical factors including heat, coldness, relative humidity and light. The existing moisture and storage temperature are the most important for the final quality product as they can encourage destruction of living pest mechanisms to various degrees. Insect pests have been divided into two categories: those can survivable in all manufacturing process (i.e. rusty grain beetle, saw-toothed grain beetle and flour beetle) and insects infesting stored grains, which the majority of them are beetles, weevil, grain borer, Angoumois grain moth especially staple foods like wheat and rice in tropical and temperate regions (Coombs and Porter, 1986). The long-lived species like rice weevil; *S. oryzae*) and the lesser grain borer, *R. dominica* (Coleoptera: Bostrichidae) are primary pests of stored grain and cause quality loss in storage. The adults feed on grain and the larvae develops inside the kernel, while the female rice weevil chews a hole in the kernel, lays the egg inside, and seals the hole with a gelatinous secretion which protects the eggs (Rajendran, 2003). Practically, heat is an alternative method for insect pest control without chemical residues to environment, by slowing down the increase of insect population infested with stored-products.

Thermal treatment for insect control

The ideal conditions for stored product insects normally range between 25-32°C and 65-75%RH (Robinson, 2005). Above and below these temperatures, insect pest growth and fitness were affected including an extreme condition also been lethal to the insects. Heat treatment has been used against stored product pests and most of the storage insect response to elevated temperature. As in generalized report by Fields (1992) whose noted that insect populations declined at 35-42°C and move from worm heated area to cooler environment and the insect was eliminated when exposed to 45-50°C in 24 hr, 50-62°C in 1 hr, and above 62°C in 1 min. However, temperature effect may vary with individual tissue within the insects. Perez-Mendoza et al. (2004) used near-infrared spectroscopy to determine water content in adult rice weevil and the result confirmed that younger weevil (12 days old) tended to have higher water content (about 51%) than older weevil (95 days old, water content 47-49%) in both male and female.

In brief, radio frequency as an alternative heat treatment to disinfest food products and stored-products has been used for more than 50 years. This technique can be applied to the problem of stored grain insect pests (Figure 3). Insects show high dielectric loss factors. Heat can be transferred more rapidly under electromagnetic fields. When the energy is absorbed, the heat is generated rapidly in dielectric materials as insects. Nelson (1996) found that many kinds of insects, which destroy the agricultural products, could be controlled by radio frequency application with the short period of exposure time without demolishing the quality. In general, the successful temperatures to control the pests through radio frequency are 40-90°C depending on the properties of the product, insect characteristics and the wave's nature. The radio frequency heat treatment differently results in the individual insect species and each growth stage due to peculiarity of species, which perform phenotype as biological or physiological or body composition of each unusual insect. Many researches have involved the influence of heat in insect metabolism and they demonstrated concomitant increase in both metabolism and respiration up to a critical thermal limit as well as heat affect on nervous and endocrine system (Neven, 2000) and mortality ultimately. In addition, the radio frequency has affect on the insect with incomplete development of deformation such as the head and chest of the larva and pupa of flour moth infested with wheat grain when exposed to radio frequency of 39 MHz. The treated insect had reproductive rate lower than 50% due to the heat from wave frequency damage to ovarian tissue then, the rate of hatching eggs dropped out and become small in size (Nelson, 1996). For tolerance in each stage of insects, Johnson et al. (2004) has identified growth stages of the red flour beetle infested in nut which is resistance to radio frequency. The larvae old age stage is most tolerance to radio frequency at the temperature of 48-50°C, and followed by pupae, adult, egg and larvae respectively. In addition, it was found that the temperature of 52°C for 2 minute completely removed old age worm infesting almond, pins and pistachio.

Among the beetles, *Lasioderma serricorne* and *R. dominica* are highly tolerant to heat, while *Sitophilus* spp. and *Tribolium castaneum* are moderately tolerant (Robinson, 2005). The heat from radio frequency at 27 MHz is also used to eradicate codling moth (*Cydia pomonella* L.) infesting walnut. The experiment reported that the target temperature of 43 and 53°C for 2 and 3 minutes to control the codling moth at 3^{rd} and 4^{th} old age stage resulted in worm mortality 78.6 and 100% without impact on the quality i.e. peroxide content, total fatty acid and color of walnut kernels (Wang et al., 2001). Moreover, the temperature of 55°C completely eliminated worm of fifth-in star navel orange worm (*Amyelois transitella*) whereas the moisture content of walnut slightly decreased with no effect on the quality (Wang et al., 2003a). In addition, radio frequency 27.12 MHz at the lower temperature of 50°C with 3 minutes of exposure time has been developed and completely eradicated third stage of rice weevil worm filled with walnut (Wang et al., 2002). Therefore, radio frequency heat treatment is possible to apply in a mass walnut products in a short period of exposure time and replace current fumigated methyl bromide in processing plant. Nevertheless, not only in shell walnut but also in rice, the systemically fumigation is also used to eliminate the pests immediately before and after processing. The radio frequency also has been considered to replace chemical fumigation. Janhang et al. (2005) determined the effect of radio frequency 27.12 MHz at the temperature of 70, 75, 80, 85°C on disease i.e *Trichoconis padwickii, Fusarium* sp. and *Bipolaris oryzae* and *Curvularia lunata* with rice weevil infested in Kao Dawk Mali 105 (KDML105) rice. The result noted that the fungal contamination, viability of rice weevil and seed quality decreased with increasing temperature and the temperature of 75°C could completely control rice weevil and the could reduced fungal contamination by 41%. The same frequency can also be irradiated to eradicate codling moth, which is a major pest in rice. The radio frequency heat treatments at 60°C to various stages of codling moth infested in rice and review that it was most effective in survival stages i.e. egg and larvae by showing 98.9 and 98.35 percent mortality while the adult and worm were completely destroyed (Luechai et al., 2008). The laboratory scale study on the efficacy of radio frequency heat treatment to improve KDML rice quality confirmed the result obtained by cooking quality. Using radio frequency at temperature over 60°C resulted in color changing from translucent white rice to opaque yellow. The heat at 75°C caused rice to be become less sticky and more brittle as the higher temperature will affect the texture of rice. However, at a lower temperature (60°C) radio frequency heat treatment did not cause significant change to the physical property and moisture content of rice (Theanjumpol et al., 2007).

CONCLUSION

From literature review and research experiences, radio frequency to control insects appears to be a highly promising technique to satisfy the objectives of food safety and food quality in stored agricultural products whether horticultural, herbal agronomic or more particularly cereal crops. These products are used as animal feed, processed foods containing primarily grain, dry fruit, essential oils plant, spices and dried vegetables. The technique is also compatible with requirements for sanitation and food protection as ISO certification and HACCP. The integrated application between high frequency of electromagnetic fields and physical control can possibly be exploited as a means of protection (such as high concentration of carbon dioxide in sealed package). Therefore, the further study will aim to improve the precise method to deal with the conditions of food materials.

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