Microwave technology for disinfestation of cereals and pulses: An overview

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Abstract Contamination of stored grain with insects, insect fragments, fungi, and mycotoxins is a major concern of the grain industry. The stored-grain insects affect the grains not only quantitatively but also qualitatively. Disinfestation of grains can be achieved by physical, chemical and thermal methods. Microwaves may be an alternate to chemical methods of killing insects in grain as their application do not leave any undesirable residues and thus might be very effective for controlling insect infestation compared to other available methods. Microwave disinfestation can provide a continuous process to allow large quantities of products to pass in a shorter period of time. Microwave disinfestation is considered safe and competitive alternative method to fumigation as it avoids environmental pollution. The aim of this review is to examine how the use of microwave treatment benefits grain producers, handlers, and processors seeking to use non-chemical methods for preventing and controlling insect infestation and fungal growth during storage.

Keywords Microwave · Disinfestation · Insect · Dielectric properties · Microwave system · Food grains

Introduction

A major problem in production, storage and marketing of the cereals and legumes is the infestation by the insects or pests (USADPLC 2007). Post harvest losses caused by insects, mites, rodents and microbes in stored grains have been estimated at 10 % throughout the world. These losses have been reported around 1 % and 10–30 % in developed

and developing nations respectively. Out of the total food grain losses, 5 % are caused by insects, 2 % by rodents and 5–30 % by molds and mycotoxins (Rajendran 2002). In India, losses due to insects and pest account as high as 17.5 % and have been estimated to be of worth Rs. 8,63,884 million (Dhaliwal et al. 2010). Grains harvested and stored in the summer season have more chance of infestation, which means that winter crops such as wheat, rye, barley or oats are more likely to have insect infestation than spring corn, soybeans or rice, which are harvested during the cooler, autumn months of the year (Chappell et al. 2000). Post harvest disinfestations include two basic features: (i) freedom from infestation within the seed or grain materials and (ii) effectiveness of the treatments to prevent cross-infestation from outside sources. Physical methods to control insects include different types of traps such as probe traps, pheromone traps, manipulation of physical environment (Sinha and Watters 1985), mechanical impact, physical removal, abrasive and inert dusts and ionizing radiations (Muir and Fields 2001). In biological methods, the natural enemies are released at particular location where they locate and attack the pests in grain mass. As there is no involvement of chemicals, these methods do not pose serious risk to the consumers or to the environment (Subramanyam and Hagstrum 2000). Consumer and environmental concern over the use of chemical fumigants has generated an interest in the non-chemical alternatives for disinfestations.

Radio frequency (RF) and microwave (MW) treatments have been studied as a non-chemical alternative for postharvest insect control in dried agricultural commodities viz. rice and wheat. Various researchers conducted post harvest disinfestation studies on agricultural products such as wheat (Shayesteh and Barthakur 1996), sorghum (More et al. 1992), rice (Xiong et al. 2004) and reported that microwave treatment is a potential means of replacing chemical fumigation in pest control. The use of microwaves in food

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processing was extended for killing insects (Wang et al. 2003b; Antic and Hill 2003), blanching of fruits and vegetables (Boyes et al. 1997), drying of fruits, vegetables and dairy products (Funebo and Ohlsson 1998; Mullin 1995), stabilization of rice bran (Tao et al. 1993), enzyme inactivation in cereal grains (Yadav et al. 2010), control of enzymatic browning in frozen *chapattis* (Yadav et al. 2008) and pre-treatment of oilseeds for efficient oil extraction (Irfan and Pawelzik 1999).

Microwaves are electromagnetic waves with wavelengths ranging from as long as 1 m to as short as 1 mm, or equivalently, with frequencies between 300 MHz (0.3 GHz) and 300 GHz (Pozar 1993). They are invisible energy waves that travel with the speed of light and are reflected by metals, transmitted through electrically neutral materials such as glass, most plastics, ceramics and paper, and absorbed by electrically charged materials. In the electromagnetic spectrum, microwaves lie between radio frequencies and infrared radiation. Microwaves include both ultra high frequency (UHF) and extremely high frequency (EHF). In all cases, they include the entire super high frequency (SHF) band (3 to 30 GHz, or 10 to 1 cm) at minimum. Radio frequency engineering often puts the lower boundary at 1 GHz (30 cm), and the upper around 100 GHz (3 mm). Microwaves can also be considered as electromagnetic force fields for better understanding of working of microwave oven. They interfere inside the microwave oven to produce high and low energy pockets. From the broad range of microwave frequencies available, only very few are used for industrial, scientific and medical applications (ISM). In this contribution, an effort has been made to provide an overview of the microwave application for disinfestation of cereals and pulses.

Principle of microwave disinfestation

Microwave heating is based on the transformation of alternating electromagnetic field energy into thermal energy by affecting polar molecules of a material. All the matter is made up of atoms and molecules and some of these molecules are electrically neutral and others are bipolar. The principle behind killing of insects using microwaves is the dielectric heating of insects which depend on its electrical properties. When an electric field is applied, the bipolar molecules behave like microscopic magnets and tend to align themselves with the field. As the electrical field changes millions times per second (e.g. 915 or 2450), these molecular magnets are unable to withstand the forces acting to slow them. The resistance to the rapid movement of the bipolar molecules creates friction and results in heat dissipation in the material exposed to the microwave radiation. Biological material placed in such radiation absorbs an

amount of energy which depends on the dielectric characteristics of the material.

There is a possibility of advantageous selective heating in mixtures of different substances (Hamid et al. 1968; Nelson 1972; Ikediala et al. 1999; Antic and Hill 2003; Wang et al. 2003a). When a mixture of dry food stuffs and insects are heated, the insects are heated upto lethal temperature because they contain more water as compared to the food stuff which is either left unaffected or gets slightly heated (Hurlock et al. 1979; Wang and Tang 2001).

The most important characteristic of microwave heating is volumetric heating, where, materials can absorb microwave energy directly and internally and convert it into heat. The conversion of microwave energy into heat is expressed by the following equation (Linn and Moller, 2003)

$$P = 2\pi E^2 f \varepsilon_0 \varepsilon'' / V \quad (1)$$

where P = power, W

E the electric field strength, V/m

f the frequency, Hz

ε_0 the permittivity of free space, F/m

ε'' the dielectric loss factor

V volume of the material, m³

Dielectric properties of materials

Dielectric properties are the electrical characteristics of a material which measure the interaction of food with electromagnetic fields (Ahmed et al. 2011). The dielectric properties of the materials depend on the frequency of the applied electric field, temperature of the material (Nelson 1973, 1991) and the amount of water in the material. The first reported measurement of insect dielectric properties was for bulk samples (insect and air space) of rice weevil and confused flour beetle at 40 MHz frequency (Nelson and Whitney 1960). Dielectric properties of insects are affected by the frequency and temperature. Various methods have been developed and used for measurement of dielectric properties of grains. The three most popular methods for measuring dielectric properties of foods are: open ended coaxial probe, transmission line and resonant cavity method (Ohlsson 1980). The moisture content has the maximum influence on the dielectric properties of grains at any frequency. The dielectric constant increases with increase in moisture content at any given frequency and decreases with increase in frequency. Other factors such as grain bulk density, temperature and chemical composition also influence the dielectric properties of grain (Nelson 1981).

Need for microwave disinfestation

The stored-grain insects not only affect the grains in quantitative terms but also affect the grain quality adversely. The grain quality decreases with time and increasing levels of infestation (Edwards et al. 1991). Insect infestation can also cause change in the chemical composition of the grain. It can lead to the increase in moisture, free fatty acid levels, non protein nitrogen content, and also decrease in pH and protein content (Sanchez-Marinez et al. 1997). Various methods of insect control have been practiced to prevent infestation of the grains. The most common method is the use of fumigants. Two of the commonly used fumigants were methyl bromide and phosphine. However, the use of methyl bromide is prohibited in India (Anonymous 2012). Phosphine has been used in a variety of habitats for long time (Rajendran and Muralidharan 2001). Conventional use of phosphine has not been successful in controlling insects because certain insects have developed resistance to phosphine (Bell and Wilson 1995). Moreover, concerns about development of resistance to phosphine have made the search for new alternatives. The chemical insecticides also affect the environment including air and water. Thermal disinfestation has been used extensively to disinfest food grains. One of the major problems associated with thermal disinfestation is that the activation energy of insects is greater than most of the food commodities and thus the functional properties of food grains is affected prior to killing insects. Hence, there is need to develop new, safe methods of controlling infestation in food. Microwave disinfestation seems to have a great potential as an alternative method of killing insects in stored-grain (Vadivambal et al. 2010). Microwave heating and drying has already captured a place in the agriculture and food industries. Grain insects are present on most farms in harvesting machinery, stock-feed, grain spills, and old seed. Unless insect control measures are applied, grain quality and value are likely to be reduced. The use of combination treatments can reduce the radiation dose required for disinfestation, which infers advantages for product quality. The combination of irradiation plus microwave radiation, high temperature, hypoxia, chemicals may achieve this goal of disinfestation and in turn will reduce the post harvest losses of grains (Tilton and Brower 1987).

Factors affecting microwave disinfestation

A large number of factors affect the microwave heat transfer behavior, which include thickness, geometry, and dielectric properties of the food. The heat capacity and dielectric properties change with moisture content and temperature and thus complicate the microwave drying

process. In addition, several other factors influence the uniformity of electromagnetic field. These factors can be divided into two groups: cavity effects and workload or product interaction. Cavity effects are due to design limitation, location of the microwave inlet point, shape of the cavity and hanging parts such as mixers which are used for stirring of the product to assure more uniform electromagnetic field distribution. Workload interactions include loss factor, penetration depth, thickness, shape and size of the product. By controlling the food geometry, uniformity in heating could be improved substantially. Design of the microwave oven, variation in the heat cycle, ingredient formulation, design of the package and a combination of the above affects the microwave heating (Ryyanen and Ohlsson 1996; Vilayannur et al. 1998).

Microwave generation method

Microwave generators can be operated in continuous or pulsed mode. In a continuous mode, energy is supplied continuously at constant power level, while in pulsed mode, energy is pulsed in on-off manner. High intensity microwaves are produced for a period of few microseconds or milliseconds, with the power supply recharging in between the pulses. Typical features of microwave disinfestation unit are that it kills insects, larvae, eggs and others, leaves no chemical residues and preserves quality. Industrial microwave heating or drying equipment have three major components (Fig. 1). The first component is the power supply unit where microwaves are generated at the required frequency. The second component forms the applicator, where the material is subjected to intense microwave fields, and to which any additional ancillary process equipment such as pumps for operation under moderate vacuum conditions, steam or hot air injection may be connected. Often the applicator forms the last part of a conventional processor. The other major component is control circuit that helps to optimize and regulate the overall performance of the microwave heater. Magnetron tubes are used primarily to generate microwave power. A ferrite iso-circulator protection

Fig. 1 Typical microwave heating system

between magnetron source and applicator can also be incorporated (Metaxas 1991).

Present scenario of microwave disinfestation

Insect mortality

Microwave energy was used long back by Webber et al. (1946) to control insects. Flour beetles in wheat flour and granary weevils in wheat were exposed to 2.45 GHz microwaves and no selective heating was obtained (Baker et al. 1956). He reported that temperature ($>82^{\circ}\text{C}$) is required in the host media to control the immature stages of both species. Nelson and Kantack (1966) studied the mortality of adult granary weevils in wheat and corn at equal moisture content and observed lower mortalities in wheat as compared to corn. Hamid et al. (1968) conducted experiments for the detection and control of *T. confusum*, *S. granarius* and *C. ferrugineus* in samples of wheat grains and its flour. He concluded that illumination of wheat in bulk quantities by microwave power is impractical for the control of wheat insects on a large scale, unless the infested wheat is circulated in a region of high electric field. It was further reported that the circulation of wheat and flour through a waveguide sustaining a high frequency electric field gives a economical and effective method for control of insects and larvae (Hamid and Boulanger 1969). They also studied the effect of high frequency radiation on the milling and baking qualities of wheat and observed no change in milling quality as well as in total protein content, but the bread making quality was affected significantly as temperature was increased. The effects were similar as in case of improper drying of grains. It was suggested to use lower-frequency power source so as to improve the drying efficiency and disinfestation of grains. Boulanger et al. (1969) compared the design, operation and cost of microwave and dielectric heating system for the control of moisture and insect infestation of grains. He concluded that microwave and dielectric heating systems are highly efficient and have significant advantage over conventional hot air dryers.

The comparative effectiveness of electric field for control of rice weevils in wheat has been studied by Nelson and Stetson (1974). Their results indicated that complete mortality of adult weevils in wheat at radio frequency (39 MHz) resulted in a grain temperature of 40°C , whereas, treatments at microwave frequency (2450 MHz) resulted in grain temperature of 80°C . The susceptibility of *T. confusum* in infested wheat by irradiating vials through microwave energy was studied by Watters (1976). Survival of pupae near the surface of wheat grains indicated non-uniform heat distribution. Complete mortality of eggs and pupae were obtained at 75°C . Bedi and Singh (1992) used microwave energy to control the three

stored-grain insect species: larvae of *Corcyra cephalonica* St. (Rice moth), adults of *Callosobruchus chinensis* L. (Gram dhora) and *Rhyzopertha dominica* (lesser grain borer). They reported that mortality of insects increased significantly with an increase in both the frequency and the exposure time. The effect of microwave radiation on eggs was higher followed by pupae, adults and larvae. Shayesteh and Barthakur (1996) reported that intermittent power supply is more effective in killing insects and thus the operational cost of microwave generator could also be minimized. Halverson et al. (1996) studied the mortality of *S. zeamais* and *T. castaneum* in wheat by microwave treatment at a frequency of 10600 MHz at a power level of 9–20 kW. Mortalities of $\geq 93\%$ and $\geq 94\%$ were obtained for *S. zeamais* and *T. castaneum*, respectively. Baysal et al. (1998) reported that heating for 90 s in a microwave oven is sufficient to kill most forms of the insect.

Halverson et al. (2003) conducted experiments to study the susceptibility of insect species and age (life stage) to microwave energy. Eggs and young larvae of the *R. dominica* were found most susceptible to microwave energy than the pupae. Banik et al. (2003) compared death rate of *E. coli* exposed to microwave radiation and conventional heat sterilization at the equal temperature and observed higher rate for microwave radiation. The effect of microwave radiation with cold storage on different age groups of Indian meal moth eggs was studied by Nasab et al. 2009 (Table 1). Vadivambal et al. (2008) studied the mortality of different life stages of *T. castaneum* in stored barley using microwaves and reported significant increase in mortality with increase in power level and exposure time. The germination capacity of the barley grains also decreased with increase in power level and exposure time. Vadivambal (2009) observed that mortality of *S. granarius* significantly varies with moisture content, exposure time and power and reported higher mortality in wheat for longer exposure time.

Table 1 Mortality of Indian meal moth eggs when stored at low temperature ($4\pm 1^{\circ}\text{C}$) after different microwave exposure duration

		Power(W)			
		Age(day)	100	300	500
24 h	1		75.6±4.04 ^c	80.1±4.90 ^b	85.4±3.82 ^a
	2		56.8±5.54 ^c	71.2±4.78 ^b	77.7±3.98 ^a
	3		80.1±5.57 ^b	83.6±3.73 ^{ab}	86.3±3.70 ^a
	4		80.2±5.58 ^c	83.6±3.73 ^{ab}	86.3±3.71 ^a
48 h	1		90.0±0 ^a	90.0±0 ^a	90.0±0 ^a
	2		65.3±2.98 ^b	78.1±5.47 ^{ab}	82.5±4.86 ^a
	3		76.8±4.19 ^b	77.1±4.20 ^b	90.0±0 ^a
	4		68.8±2.71 ^b	90.0±0 ^a	90.0±0 ^a

^{a-c} Values within the same column with different superscripts differ significantly ($p\leq 0.05$); $n=3$

Nasab et al. 2009

He also studied the mortality percentage of *T. castaneum* pupae at 28 s exposure time for different power levels and compared the susceptibility of life stages of *T. castaneum*. He concluded that eggs are the most susceptible followed by larvae (Table 2). Hassan et al. (2010) used laboratory microwave applicator operated at 2.45 GHz, to determine the mortality of maize weevil. He observed that 50 °C treatment for 3 and 5 min can control the maize weevil and longer exposure time may lead to higher mortality percentage in maize weevil adults. A pilot-scale industrial microwave system operated at 2.45 MHz was used by Vadivambal et al. (2010), to study the mortality of three stored grain insects: *Sitophilus zeamais*, *Tribolium castaneum*, and *Plodia interpunctella* at 14, 16, and 18 % moisture level in corn at various microwave power levels and exposure time. Singh et al. (2011) also evaluated the mortality of pulse beetle at adult stage as a function of exposure time and percent power level. They found lower germination percentage of seed with increase in power level. Further, they reported that during microwave exposure, the insects move towards the surface from inside the nutrient medium.

Microbe mortality

Microwaves have immense application in food processing and for inactivation of microorganisms and insects (Rosenberg and Bogl 1987). Fungal spores, bacteria and bacteriophage PL-1, specific to *Lactobacillus casei*, have also been reported to be sensitive to microwave radiation (Khalil and Villota 1985). The microwaves have been used to cause heat, thereby in the process destroy bacteria such as *Escherichia coli*, *Streptococcus faecalis*, *Staphylococcus aureus*, and *Salmonella* (Fujikawa et al. 1992; Heddleson et al. 1994; Atmaca et al. 1996). The bacterial cells are destroyed by heat generated through conduction in the substrate rather than direct impact of microwaves on the cells causing destruction. Experiments were conducted by Lozano et al. (1986) for eradication of seed-borne pathogens in cassava seed. Temperature was the most important factor affecting microbial control and an optimum microwave exposure time of 120 s (77 °C) was recommended for optimum level of germination and eradicating microorganism. An increase in moisture content and microwave heating resulted in elimination of most fungi after 30 s exposure time (Hari et al. 1992).

Table 2 Mortality of life stages of *T. castaneum* exposed to microwave radiation in wheat

Insect life stage	Power(W)	Moisture content					
		14 %		16 %		18 %	
		28 s	56 s	28 s	56 s	28 s	56 s
<i>Tribolium castaneum</i> eggs	0	20±0	30±10	33±11.5	20±10	20±0	20±10
	250	64±11.7	84±13.9	58±15.5	84±11.6	68±22.1	88±11.2
	300	81±18.9	93±11.1	85±15	100	88±11.2	96±10.2
	400	100	100	100	100	100	100
	500	100	^a	100	^a	100	^a
<i>Tribolium castaneum</i> larvae	0	0	0	0	0	0	0
	250	53±3.6	79±2.2	61±5.1	77±4.2	63±0.57	78±1
	300	72±4.4	93±1.3	74±5.6	95±0.7	78±4.04	96±1.7
	400	91±4.6	100	93±6.3	100	95±3.7	100
	500	100	^a	100	^a	100	^a
<i>Tribolium castaneum</i> pupae	0	7±5.8	3±5.8	10±0	7±5.8	7±5.8	3±5.8
	250	43±1.1	74±3.4	44±1.7	78±5.1	59±4.7	78±4.7
	300	55±9.4	86±2.3	67±1.7	94±2.8	72±2.5	91±0.5
	400	76±3.0	100	78±4.5	100	87±3.6	100
	500	100	^a	100	^a	100	^a
<i>Tribolium castaneum</i> adults	0	0	0	0	0	0	0
	250	45±11.6	77±2.9	56±2.9	81±4.9	55±11.2	73±9.1
	300	58±1.1	90±1.7	68±7.2	95±4.2	66±6.1	93±3.9
	400	85±5.0	100	86±2.5	100	90±2.3	100
	500	100	^a	100	^a	100	^a

^a Since 100 % mortality was achieved at 400 W, experiments were not performed at 500 W for 56 s; *n*=3

Microwave radiations in combination with other treatments

Microwave disinfestation has been used in combination with other physical or chemical treatments for effective disinfestation of cereal grains. An important key for the development of an acceptable alternative thermal treatment is minimal thermal impact on product quality and complete killing of insects. The efficiency of microwave and infrared radiation to control *S.oryzae* in soft winter wheat was studied by Kirkpatrick et al. (1972) and concluded that both microwave and infrared treatments can control insects but the temperature required to give 100 % mortality was higher for microwave energy. Therefore, it was suggested that the infrared heating is preferable over microwave heating. Gamma, infra-red and microwave radiation combinations have also been studied to control *R. dominica* in wheat by Kirkpatrick et al. (1973). Samples were given various treatments viz., gamma radiation, infrared, microwave, gamma radiation plus infra-red and gamma radiation plus microwave. The maximum reduction in the emergence was observed for gamma plus infra-red (99 %) followed by gamma plus microwave (96 %). Combination treatments were more economical and effective for control of insects in wheat. Fung and Cunningham (1980) also suggested that combination treatments result in more uniform heating of foods and destruction of bacteria. The control of stored-product insects in rye, corn, and wheat using combination of microwave and partial vacuum was studied by Tilton and Vardell (1982). They observed ineffective and small reductions in the emerging adults at lower rate of treatment whereas complete control of insects at high rate of treatment. Tilton and Brower (1987) treated the wheat grains with microwave radiations before and after gamma radiation to control insect population and suggested that the dose of gamma radiation could be reduced without reduction in the actual mortality of the insects, if a supplemental treatment is used.

Radio frequency and microwave treatment seem attractive as a quarantine treatment because they are quick, safe and do not damage the product quality (Wang and Tang 2001). Experiments have been conducted to determine whether the insects are preferentially heated in dry nuts and fruits using radio frequency (27 MHz) and microwave frequency (2450 MHz). Inserting temperature probes into a live insect causes loss of body fluid, which would affect the accuracy of the insect temperature measurement. Hence, model insects having dielectric properties similar to those of codling moth larvae have been developed using gel. Temperature measurements with model insects revealed 1.4–1.7 times greater heating of insects than walnuts at 27 MHz but no preferential heating of insects was detected at 915 MHz (Wang et al. 2003a). The effect

of soft electron treatment was studied by Imamura et al. (2004) on the life stages of *T. castaneum*, *P. interpunctella*, and *Callosobruchus chinensis* (L.). These studies indicated that adult stage is the most tolerant to radiation treatment compared with the early life stages because of limited cell division. Tireki et al. (2006) observed that during infrared assisted microwave drying, microwave energy was about nine times more effective than that of infrared. Valizadegan et al. (2009) reported that combination of microwave radiation and cold storage is highly compatible and synergistic for the management of *O. surinamensis*.

Advantages of microwave disinfestation

Fast and selective heating ability of microwave is main advantage over conventional heating method. As the dielectric properties of insects and grains are different, hence the selective heating of microwave is very beneficial (Shayesteh and Barthakur 1996). Microwave treatment can provide a continuous process to allow large quantity of products to pass in a shorter period of time. Another major advantage of using microwave energy is that no chemical residues are left in the food and hence there are no adverse effects on human beings (Hurlock et al. 1979). High frequency radiation not only kills insects due to dielectric heat induced within them but also affect the reproduction of the survivors (Hamid et al. 1968). Microwave treatment is considered a safe and competitive alternative method to fumigation, and can avoid problems of food safety and environmental pollution. An advantage with microwaves is the lack of interference with television and radio waves. Microwave radiation has specific advantages including: (a) the control of all developmental stages of storage pests, (b) short time for an effective control, (c) no hazardous side effects on stored products, (d) creation for susceptibility of treated insect to the type of stress such as controlled and cold atmosphere, (e) safety for the operators, (f) greater energy efficiency, (g) preservation and integrity of the product quality (savour and nutritional properties), (h) automation of the process, (i) compliance with the international environmental rules and with the requirements of the Montreal Protocol (Wang and Tang 2001). Microwave radiation has been investigated as an alternative to chemical fumigation (Karabulut and Baykal 2002). Heat generation by microwave energy occurs principally in the product, not in the oven walls or atmosphere. Therefore, heat losses from the oven to the surroundings are much lower, making more comfortable working temperatures. Fast start-up, shut-down and precise process control are possible in microwave heating (Mullin 1995).

Limitations of microwave disinfestation

Due to limited penetration the grain would have to be treated in shallow layers. One of the major problems associated with microwave heating is the non-uniform temperature distribution. Researchers have tried to develop a model for the microwave heating to predict temperature distribution in the microwave heated food (Yang and Gunasekaran 2004; Campanone and Zaritzky 2005). Microwave drying is known to result in a poor quality product if not properly applied (Adu and Otten 1996). It has also been observed that microwave treatment longer than 90 s (64 °C) caused marked changes in wheat grain endosperm structure. The percentage of damage increases with prolonged time of microwave treatment (Blaszczak et al. 2002). Another issue with the microwave heating is the large number of factors that affect the microwave heat transfer behavior such as thickness, geometry, and the dielectric properties of the food. Other factors which influence the uniformity of electromagnetic field are cavity effects and workload or product interaction.

Future prospects

Many researchers have suggested ways to reduce the intensity of uneven heating. Fung and Cunningham (1980) suggested that microwave heating in combination with conventional heating would result in more uniform heating of foods and destruction of bacteria. A device and method for uniform heating of foods in microwaves was designed by Zhang et al. (2004) to reduce the problems of cold spot, uneven heating and splattering of food. Gunasekaran and Yang (2007) concluded that pulsed microwave heating resulted in more uniform temperature distribution in the samples than the continuous microwave heating. It has been seen that only major stored-grain insect pests have been studied, so there is a scope that other stored-grain insect mortalities could be studied. The generation of ‘hot spots’ during industrial microwave heating is of great concern for process optimization (Zhu et al. 1995). A hot spot can be defined as a local area of very high temperature that results from the temperature dependence of material properties. The treatment of infested grain by microwave treatment appears a reliable alternative to conventional post-harvest in the near future, either with stationary or mobile applicators on the farm or quarantine purposes during the loading process before grain storage and seed sowing (Dolinska et al. 2004)

Conclusion

The most important key element in the development of an acceptable alternative insect control method using microwave

energy is to identify a balance between minimized thermal impact on the product quality and complete killing of the insect population. The study of the impact of microwave disinfestation is very vital in order to improve the technology for modification and/or optimization/formulation of treatment conditions to minimize the losses. A thorough knowledge of the dielectric properties and tolerance of the material being treated and thermal resistance of the insect species is required so as to achieve a balance between complete eradication of the insects and to maintain the product quality.

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