Disinfestation of *Rhyzopertha dominica* (F.) Using Microwave Heat Treatment to the Malaysian Paddy

Manjur Ahmed, Fareq Malek, R. Badlishah Ahmad, Mostafijur Rahman, Khairudi bin Mohd Juni

Abstract**—**Dielectric spectroscopy was used to analyze *Rhyzopertha dominica* (F.) or lesser grain borer for microwave heat treatment to Malaysian paddy MR219 . The temperature dependency of the dielectric properties of *Rhyzopertha dominica* (F.) and Malaysian paddy MR 219 were analyzed for the frequency range of 200 MHz – 20 GHz and for the temperature range of 24 ^{0}C – 65 ^{0}C. Four excited temperature points, i.e., 34 ^{0}C, 40 ^{0}C, 48 ^{0}C and 55 ^{0}C showed that these temperature points can absorb more microwave energy, thereby increasing the interior temperature of *Rhyzopertha dominica* (F.) significantly. Predictive model was developed to make relationship between the dielectric properties and related factors (i.e., temperature and frequency). At high temperature, the complex organic constituents of *Rhyzopertha dominica* (F.) were determined to be dielectrically inert. General equations that utilized frequency and temperature were developed to describe the dielectric properties of *Rhyzopertha dominica* (F.). Effects of ramp period and holding time to achieve higher mortality were analyzed. Observation results were analyzed to reach 100% mortality of *Rhyzopertha dominica* (F.).

Keywords**—**Dielectric properties, microwave energy, paddy, mortality, responses, Rhyzopertha dominica (F.); Rhd.

I. Introduction

RICE - (*Oryza sativa* L.) - is the most important staple food crop in the world and it is a major commodity for international and domestic trade. But, rice seeds are affected adversely by many insect pests and fungi, destroying the viability and germination capability of the seeds and rendering them useless for the production of rice [9]. The absence of pre- or post-harvest paddy may cause barrier for international and domestic trades. *Rhyzopertha dominica* (F.), the lesser grain borer, attacks a wide range of stored cereals and breeds extensively in a warm climate [10], such as that of Malaysia. The lesser grain borer is a serious pest that destroys stored grain and cereal products. The adults and larvae bore into grain seeds and eat the kernel, leaving a hollow husk [11].

Manjur Ahmed is a student in the School of Computer and Communication Engineering, Universiti Malaysia Perlis (UniMAP) , 02000 Kuala Perlis, Perlis, Malaysia (e-mail: manjur_39@yahoo.com).

Fareq Malek is with the School of Electrical System Engineering, Universiti Malaysia Perlis (UniMAP), 02000 Kuala Perlis, Perlis, Malaysia (e-mail: mfareq@unimap.edu.my).

R. Badlishah Ahmad is with the School of Computer and Communication Engineering, Universiti Malaysia Perlis (UniMAP) , 02000 Kuala Perlis, Perlis, Malaysia (e-mail: badli@unimap.edu.my).

Khairudi bin Mohd Juni is a student in the Electrical System Engineering, Universiti Malaysia Perlis (UniMAP) , 02000 Kuala Perlis, Perlis, Malaysia (e-mail: ishtaqtu@gmail.com).

Various methods are used in an effort to control these insect pests in rice paddies and in the harvested rice [1]. Chemical fumigation has played an important role on a global basis in controlling insect pests and bacteria in agricultural commodities [14]. In Malaysia, a mixture of pirimiphos-methyl (12.0 mg of the active ingredient), permethrin (1 mg), and piperonyl butoxide (5.0 mg) is used as one liter per ton of paddy to achieve complete prevention of infestation (100% insect control) throughout the grain storage period [12]. Another method used in Malaysia is sealed storage with carbon dioxide (CO_2) gas [12]. There is interest worldwide in reducing the quantities of pesticides and chemical fumigants used in agricultural commodities, so there is clearly a need to develop non-chemical treatment methodologies.

Electromagnetic heat treatment is a new thermal method for post-harvest treatment of agricultural commodities. This method leaves no chemical residue on the commodities, ensures acceptable quality of the commodities, and causes minimal impact on the environment [15,16]. Hence, determining the dielectric properties of *Rhyzopertha dominica* (F.) (lesser grain borer) will elucidate the internal heating mechanism and provide the basis for further development, improvement, and scale-up of appropriate protocols for the use of microwave treatment for pest control. Frequency-temperature mapping with respect to dielectric properties will show the susceptibility of insects to heat and provide important information for selecting the optimal ranges for the frequency-temperature relationship. Many studies have explored the feasibility of using electromagnetic energy to eliminate insect pests from various agricultural commodities. However, none of these studies has focused on the control of insect pests in rice production paddies or in stored rice.

Therefore, the objectives of this study are to analyze the dielectric properties of *Rhyzopertha dominica* (F.) at different frequencies (200 MHz-20 GHz) and temperatures (24 ^{0}C-65 ^{0}C) with respect to Malaysian paddy MR219. Then, model the temperature–frequency relationship with the dielectric properties of *Rhyzopertha dominica* (F.). After that, analyze the mortality achievement in terms of holding time.

II. Measurement Of Dielectric Properties

To guide the development of microwave treatment of agricultural commodities, knowledge of the dielectric properties (Eq. 1) of insects and commodities is essential for understanding their interactions with electromagnetic energy [18]. In fact, data on the dielectric properties of the targeted pests in the paddies and in the stored product are required for selecting the optimal ranges of frequency. The complex relative permittivity, ε*, of a material can be expressed in the following complex form:

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

The real part of Eq. (1), ε′, is the dielectric constant, which represents the energy that is stored when a material is exposed to an electric field; the imaginary part of eq. (1) is the dielectric loss factor, ε'', which mainly influences energy absorption and attenuation [9].

$$P_{abs} = \sigma E^2 = 5.563 \times 10^{-11} f \varepsilon'' E^2 \quad (2)$$

where P_{abs} represents the absorbed power or power loss density (in W/m^3) per unit volume in the dielectric. E represents the rms electric field intensity in V/m.

A.Preparation of Sample

Paddy MR219 and Rhyzopertha dominica (F.) both were collected from Kilang Baras Dibuk Sdn, Perlis, Malaysia. Adult Rhyzopertha dominica (F.) insects were collected from the paddy and placed into a small, 50-cm^3 jar. Jar contained about one point (20 cm^3) of paddy and about 200 young adult insects. At the time of the experiment, the Rhd were fully separated from the paddy sample in order to acquire an accurate determination of the dielectric property of the Rhd. The adult Rhd used for the dielectric measurement were two to four weeks old. To reduce the air gap, we ground the paddy to make whole paddy flour and also meshed all insects. Moisture content was measured by drying the samples at a temperature of 110 ^{0}C for 16 hours. The moisture contents of the two paddy MR219 samples were found to be 9.6% and 27% (dry basis). Measuring The Dielectric Properties Dielectric properties of paddy MR219 and Rhyzopertha dominica (F.) were measured by high temperature probe. Agilent E8362B PNA network analyzer with installed Agilent 85070E Material Measurement software used in this experiment. Polyscience immersion water temperature controller (USA) used for controlling the water bath. Sample temperature controlled by immersing the sample beaker and observed the sample temperature using HANNAH k-type thermocouple.

A sample paddy of 300 gm was taken to measure the temperature-time relationship of paddy MR219. The paddy was infested by adding 200 *Rhyzopertha dominica* (F.) and kept for 48 hours.

B.Measurement

The dielectric properties of the samples of paddy MR219 and Rhd were measured by a high-temperature probe. An Agilent E8362B PNA network analyzer with installed Agilent 85070E Material Measurement software was used in the experiment. A Polyscience immersion water temperature controller (USA) was used for controlling the temperature of the water bath. A portable microprocessor-based, K-Type thermocouple (Hanna, model 9043) was used with an ultra-fast penetration, K-type thermocouple probe (Hanna, model 766C1). The microprocessor-based, K-Type thermocouple had a accuracy of ±0.2%, and the probe had a response time of four seconds. This probe was capable of measuring temperatures in the food and semi-solid materials up to a maximum temperature of 300 ^{0}C.Measurements were conducted for the frequency range of 200 MHz to 20 GHz and the temperature range of 24 ^{0}C to 65 ^{0}C. The measuring points within these frequency and temperature ranges were 51 and 18, respectively. Every measurement was conducted a minimum of three times, and the results were used to calculate the standard deviation.

III. Dielectric Variations of Paddy and *Rhyzopertha Dominica* (F.):

Dielectric properties are very important in process design and applications that use the microwave heating protocol. A clear concept about the dielectric properties of a material can lead to an advanced perception of internal heating mechanisms. Dielectric constant measures the ability of a material to couple with microwave and dielectric loss factor measures the ability of a material to heat by absorbing microwave [14]. Typical dielectric spectrum of whole paddy flour sample having moisture content 27% (d.b.) and Rhd mesh at ambient temperature 24 ^{0}C are presented in Fig. 1.

Rhyzopertha dominica (F.) or Rhd demonstrated higher dielectric constant (ε') and dielectric loss factor (ε'') values within 200 MHz to 20 GHz as compared to the paddy MR219. For paddy MR219, the ε' and ε'' values are essentially independent of frequency whereas the ε' values of Rhd decreased sharply until a certain frequency was reached. In addition, the ε'' values of Rhd decreased as frequency was increased to 7.5 GHz, after which they remained essentially constant up to a frequency of 20 GHz. The higher values of ε' and ε'' for the Rhd indicate that there is a strong interaction between the Rhd with the electromagnetic radiation, with the dissipated electrical energy being converted into heat energy [14,17]. The variations of the dielectric properties of *Rhyzopertha dominica* (F.) and Malaysian paddy MR219 are provided in Table I. The Lesser Grain Borer (Rhd) mesh is exhibited higher values of dielectric constant (ε') and dielectric loss factor (ε'') within 200 MHz to 20 GHz as compared to the paddy flour. Also the ε'' values of Rhd mesh decrease with frequencies and then remain constant at the range of 7.5 to 20 GHz. Higher values of ε' and ε'' in Rhd indicate that there is a strong interaction between the component of Rhd mesh with the electromagnetic radiation for dissipation of the electrical energy into heat energy [6].

Table I shows that there are differences of ε' and ε'' between Rhd and paddy. Wang found that the dielectric loss factor of codling moth larvae was much larger than walnut kernels, especially in the RF range at room temperature [7]. Therefore, codling moth larvae absorb more energy than walnuts [8].

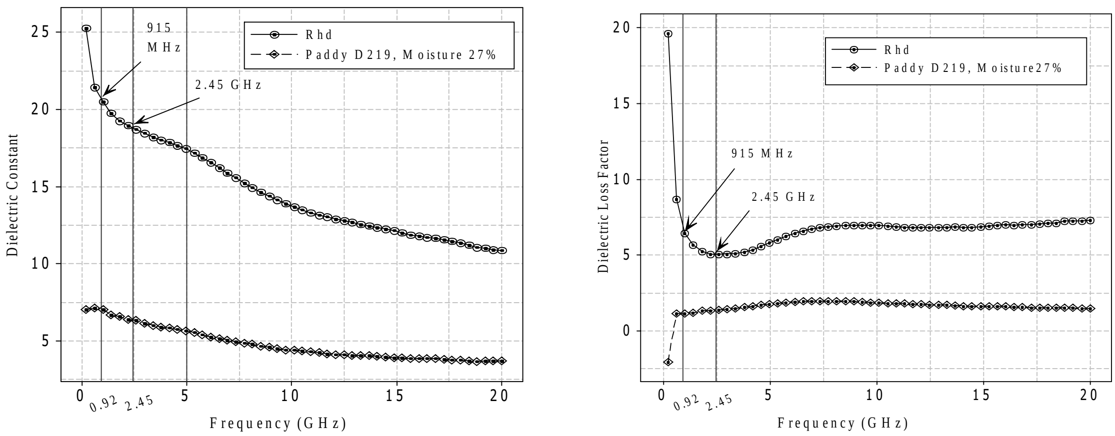

Fig. 1 Dielectric properties of *Rhyzopertha dominica* (F.) and Malaysian Paddy MR219 (moisture 27% d.b.) at 24 ^{0}C; a) dielectric constant vs frequency b) dielectric loss factor vs frequency

TABLE I
DIELECTRIC CONSTANT AND LOSS VALUES OF SOME SPECIFIC FREQUENCIES USING CROSSHAIR TO THE FIGURES. STANDARD DEVIATIONS ARE ± 0.2 TO ± 0.04 BETWEEN 0.5 – 5 GHZ

Frequency, GHz		**Lesser Grain Borer (Rhd)**	**Paddy MR219 (Moisture 9.64%)**
0.5	ε'	22.25	2.26
	ε''	10.55	1.65
0.915	ε'	20.78	1.9
	ε''	6.97	0.853
1.8	ε'	19.36	1.7
	ε''	5.28	0.516
2.45	$\boldsymbol{\varepsilon'}$	**18.85**	**1.65**
	$\boldsymbol{\varepsilon''}$	**5.07**	**0.35**
3	ε'	18.54	1.65
	ε''	5.2	0.26
4	ε'	17.94	1.65
	ε''	5.32	0.095
4.5	ε'	17.7	1.59
	ε''	5.57	0.094
5	ε'	17.48	1.60
	ε''	5.87	0.010

IV. TEMPERATURE DEPENDENCY WITH DIELECTRIC PROPERTIES OF LESSER GRAIN BORER

It is well known fact that dielectric properties of biomaterials change with temperature [7]. Since the paddy and insects will be subjected to microwave system for heating, there dielectric properties need to be measured as a function of temperature. The dielectric loss factors (ε'') of Rhd gradually decreases and sometimes increase with increase in temperature. The dielectric losses of some specific frequencies are almost minimum at 52^{0}C temperature (Fig. 2). After this 52^{0}C temperature, ε'' starts to increase in a little bit. Andreuccetti examined the possibility of using 2.45 GHz microwave frequency to completely kill woodworms by heating the larvae to 52–53 °C which took less than 3 minutes [7]. From Fig. 2, it has been shown that there is a closely interaction between the 2.45 GHz curve and 3, 3.5, 4, 4.5, 5 GHz curve. Therefore industrial microwave frequency 2.45 GHz has significant meaning to get 100% mortality of Rhd.

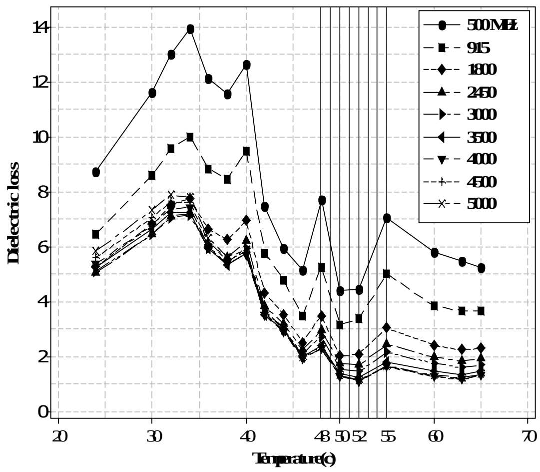

Fig. 2 Dielectric loss factor of Lesser Grain Borer (mesh) as a function of temperature (23-65 ^{0}C) at specific frequencies (500-5000 MHz).

The predictive model in actual terms (uncoded) is given below which can be directly used to compute the values of dielectric constant ($\boldsymbol{\varepsilon}'$) of Rhd at any given frequency (F) and temperature (T),

$$\boldsymbol{\varepsilon}' = 52.272 - 1.407 * F - 1.159 * T + 0.017 * F^2 + 0.006 * T^2 + 0.017 * F * T \quad (3)$$

where, $F =$ Frequency, $200MHz < F < 20\ GHz$ and $T =$ Temperature ^{0}C, $23 < T < 66$.

TABLE II
DIELECTRIC CONSTANT AND LOSS VALUES OF LESSER GRAIN BORER WITH RESPECT TO TWO DIFFERENT TEMPERATURE

	915 MHz		2.45 GHz	
Temperature	ε'	ε''	ε'	ε''
24 ^{0}C	20.523	6.4672	18.7382	5.0638
30 ^{0}C	23.2574	8.6166	21.2041	6.4372
40 ^{0}C	18.0264	9.4999	15.8068	6.2068
48 ^{0}C	5.9241	5.2631	5.2496	2.9687
50 ^{0}C	3.5923	3.1646	3.2457	1.7304
52 ^{0}C	2.647	3.3627	2.5185	1.6842
55 ^{0}C	3.0917	5.0095	2.9964	2.4375

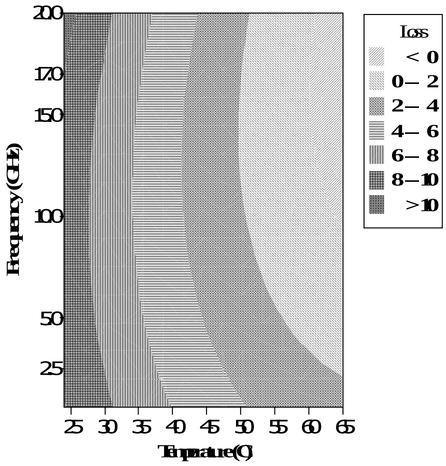

Fig. 3 Contour Plot of Dielectric Loss Factor vs Frequency (GHz) and Temperature of Lesser Grain Borer

```
Estimated Regression Coefficients for Loss

Term              Coef   SE Coef      T       P
Constant         3.291   0.101    32.448   0.000
Temperature     -4.705   0.104   -45.327   0.000
Frequency       -0.646   0.098   - 6.578   0.000
Temperature2     1.257   0.175     7.201   0.000
Frequency2       1.131   0.183     6.175   0.000
Temp*Freq       -0.955   0.175   - 5.468   0.000
  R-Sq = 76.89% and confidence level = 95
```

The predictive model in actual terms (uncoded) is given below which can be directly used to compute the values of dielectric loss factor ($\boldsymbol{\varepsilon}''$) of Rhd at any given frequency (F) and temperature (T),

$$\boldsymbol{\varepsilon}'' = 19.1867 - 0.100 * F - 0.446 * T + 0.012 * F^2 + 0.003 * T^2 + 0.005 * F * T \qquad (4)$$

where, F = Frequency, $200MHz < F < 20\ GHz$ and T = Temperature ^{0}C, $23 < T < 66$.

V. COMULATIVE EFFECT OF RAMP PERIOD AND HOLDING PERIOD

Different heating rates resulted in different ramp periods to reach the same holding temperature [13]. For first order kinetics, the following relationship may use to approximately determine the cumulative effect for any given temperature–time history [13], in terms of equivalent total lethal time (LT) M*accum* (min) at a reference temperature, T_{ref} (^{0}C):

$$\text{M}accum = \int_0^t 10^{(T(t)-T_{ref})/z} dt \qquad (5)$$

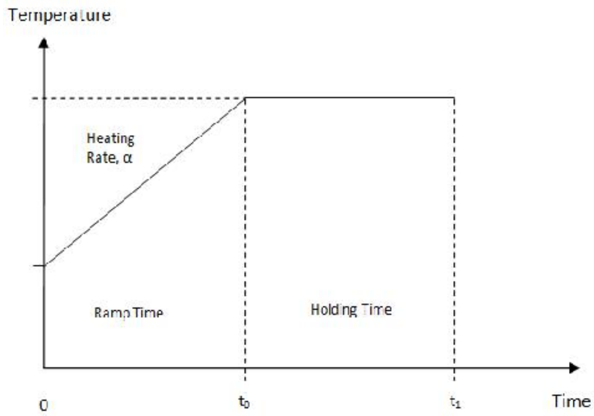

Fig. 4 Typical temperature-time history for mortality achievement.

Fig. 5 describes the typical $T(t)$ temperature-time history where T_0 is the starting temperature (^{0}C); T_h is the holding temperature (^{0}C); t_0 and t_1 are the times at the end of the ramp and the holding period, respectively. During the ramp period, the temperature is a linear function of time, therefore, $\boldsymbol{T(t) = T_0 + \alpha t}$, where $\boldsymbol{\alpha}$ is the heating rate (^{0}Cmin^{-1}).

Heating rate is believed to have a significant effect on insect metabolism and physiological adjustment to the heat treatment [14]. Consequently, a longer holding time is required at a final temperature in order to achieve the same mortality at a slower heating rate. Higher heating rate should provide greater mortality (required smaller lethal time) because of a lack of non-lethal temperature conditioning of the insects [15]. It was observed that in Malaysian paddy MR219, when subjected to MW heat with infesting Rhd, effects of holding time are required to reach the lethal temperature to achive the high mortality of Rhd. Table III shows that holding time is important to reach the lethal temperature of Rhd even though the heating rate is very high.

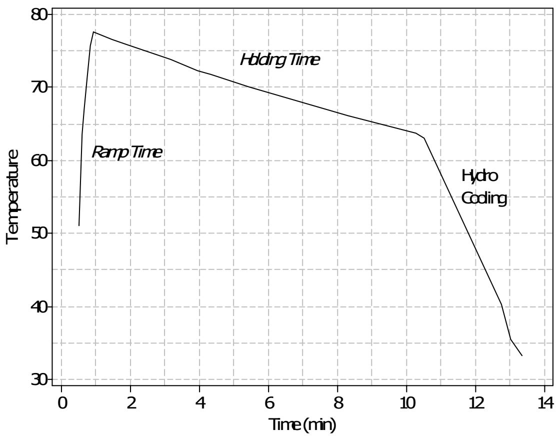

Fig. 5 Temperature-time profile of paddy MR219 when subjected to microwave heat treatment at frequency 2.45 GHz and MW power 1KW

TABLE III
HOLDING TIME EFFECT OF THE MORTALITY OF LESSER GRAIN BORER WHEN SUBJECTED TO MW HEAT TREATMENT TO PADDY MR219. MW POWER 1K

Temperature and time	Holding time	Mortality
At 78 ^{0}C and 60 second. Paddy (300 gm) with 244 Rhd.	3 min	98.4 %
	7 min	99.2 %
	10 min	100 %

VI. MORTALITY OBSERVATION OF LESSER GRAIN BORER WHEN INFESTED TO PADDY MR219

Thermal mortality of Rhd is achieved when temperature reaches to its lethal temperature. High temperature and less time is important feature for microwave heat treatment to the agricultural commodities when subjected to microwave environment. Mortality of Rhd was achieved at 40, 45, 55 and 60 seconds and 100% mortality was observed at 60 second when infested paddy MR219 was subjected to 2.45 frequency and 1KW power microwave environment.

Tang [16] observed for normal heating method that, the minimum temperature-time relationship to completely kill 600 fifth-instar codling moths at temperature above 3 min and heating rate of 18 ^{0}Cmin^{-1}.

TABLE IV
MORTALITY (%) EFFECT OF THE LESSER GRAIN BORER WHEN SUBJECTED TO MW HEAT TREATMENT TO PADDY MR219. MW POWER 1KW. AND FREQUENCY 2.45 GHZ

Heating rate	Time (second)	Mortality (%)
1.68 ^{0}C sec^{-1}	40	96.7 %
1.4 ^{0}C sec^{-1}	45	98.5%
1.4 ^{0}C sec^{-1}	55	98.8%
1.4 ^{0}C sec^{-1}	60	100%

The most important characteristic of microwave heating is volumetric heating, which is different from conventional heating. Conventional heating of agricultural or biological commodities occurs by conduction where heat must diffuse from the surface of the material. Volumetric heating means that materials can absorb microwave energy directly and internally where it is converted into heat within a small time [17], [18]. Therefore, microwave energy can increase the interior temperature of commodities quickly and reduce treatment times significantly, which will eliminate insect pests and enhance the viability of grains.

VII. CONCLUSION

Dielectric properties of insects are important to consider the electromagnetic heat treatment in paddy to control the insects without losses the quality. It was analyzed the dielectric properties of Lesser Grain Borer, *Rhyzopertha dominica* (F.) and established some generalized equation with respect to frequency, temperature and dielectric property. Cumulative effects of ramp period and holding period were analyzed. Mortality of *Rhyzopertha dominica* (F.) was observed when infested to Malaysian paddy MR219 and subjected to 2.45 GHz frequency with 1KW MW power environment.

REFERENCES

[1] Vadivambal Rajagopal, “Disinfestation Of Stored Grain Insects Using Microwave Energy,” *PhD Thesis,* Department of Biosystems Engineering, University of Manitoba, 2009.

[2] Pattaya Janhang, Nattasak Krittigamas, Wolfgang Lücke, Suchada Vearasilp. “Using Radio Frequency Heat Treatment to Control the Insect *Rhyzopertha dominica* (F.) During Storage in Rice Seed (*Oryza sativa* L.),*” Conference on International Agricultural Research for Development*, Tropentag 2005.

[3] D. M. Pozar, *Microwave Engineering*. John Wiley, New York, 1998.

[4] Wenquan Che, Zhanxian Wang, Yumei Chang and Peter Russer, “Permittivity Measurement of Biological Materials with Improved Microwave Cavity Perturbation Technique,” *Proceedings of the 38th European Microwave Conference*, Amsterdam, The Netherlands, October, 2008.

[5] Stuart O. Nelson, Philip G. Bartley, Jr., and Kurt C. Lawrence, “Measuring RF and Microwave Permittivities of Adult Rice Weevils,”

IEEE Transactions On Instrumentation And Measurement, Vol. 46, No. 4, August, 1997.

[6] Jasim Ahmed, Hosahalli S. Ramaswamy, Vijaya G.S. Raghavan, "Dielectric properties of Indian Basmati rice flour slurry", Journal of Food Engineering 80: 1125–1133, 2007.

[7] S. Wang, J. N. Ikediala, J. Tang, J. D. Hansen, E. Mitcham, R. Mao and B. Swanson, "Radio frequency treatments to control codling moth in in-shell walnuts," *Postharvest Biology Technology*, 22: 29–38, 2001.

[8] Shaojin Wang And Juming Tang, "Radio Frequency Post-Harvest Quarantine And Phytosanitary Treatments To Control Insect Pest In Fruits And Nuts," *Postharvest Treatment and Technology*, Vol. 4, pp. 17–53, 2004.

[9] Andreuccetti, D., M. Bini, A. Ignesti, A. Gambetta and R. Olmi. "Microwave destruction of woodworms," *Journal of Microwave Power and Electromagnetic Energy*, 29: 153–160, 1994.

[10] G.E.P. Box, W.G. Hunter and J.S. Hunter, *Statistics for Experimenters: An Introduction to Design, Data Analysis and Model building.* John Wiley and Sons, New York, U.S.A, 1978.

[11] A.I. Khuri and J.A. Cornell , *Response Surfaces: Designs and Analyses*. Marcel Dekker, Inc., 1987.

[12] D.C. Montgomery , *Design and Analysis of Experiments*. Fifth Edition. John Wiley & Sons, 2001.

[13] J. Tang, J.N. Ikediala, S. Wang, J.D. Hansen, R.P. Cavalieri, "High-temperature-short-time thermal quarantine methods," *Postharvest Biology and Technology*, 21, 129–145, 2000.

[14] L.G. Neven, "Effects of heating rate on the mortality of fifth-instar codling moth (Lepidoptera: Tortricidae)," *Journal of Economic Entomology*, 91: 297–301, 1998.

[15] wang and tang. "Radio frequency post-harvest quarantine and phytosanitary treatments to control insect pest in fruits and nuts," Production Practices and Quality Assessment of Food Crops, *Postharvest Treatment and Technology*, Vol. 4, pp. 17–53, 2004.

[16] S. Wang, J.N. Ikediala, J. Tang, J.D. Hansen, "Thermal death kinetics and heatingrate effects for fifth-instar *Cydia pomonella* (L.) (Lepidoptera: Tortricidae)," *Journal of Stored Products Research*, 38, 441–453, 2002.

[17] J. Mullin, Microwave processing. In:*New Methods of Food Preservation*, ed. G.W. Gould, 112-134. Bishopbriggs, Glasgow: Blackie Academic and Professional, 1995.

[18] H. Linn and M. Moller, Microwave heating. *Thermprocess Symposium*, Dusseldorf, Germany. June 16-21, 2003.