Engineering design of high-power microwave applicators for stored product protection

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Abstract

The hypothesis, that excitation of an infested product at frequencies within the free water relaxation band above 18 GHz would enhance selective heating of the insect, has been tested at a frequency of 28 GHz with load energies ranging from 20 to 62 J per gram of infested product. Both dynamic (flowing) and static samples of soft white wheat *Triticum aestivum* (L.) infested with adults and larvae of the maize weevil, *Sitophilus zeamais* Motschulsky were exposed in a detuned resonant cavity applicator. A mortality of approximately 100% for adults and older larvae (and pupae) and >94% for the younger larvae (and eggs) was achieved in both cases. However, the efficiency of energy coupling in the dynamic case was nearly twice as great as for the static. Maximum product temperatures ranged from 35 to 52 ℃. Subsequent measurements of penetration depth of a singly traveling plane wave in a flowing grain-air mixture, including wheat and rice, indicated penetration depths of 30 to 38 cm The design principles learned in constructing the dynamic applicator will be used to develop a prototype unit capable of processing the infested product at rates of 27 metric tons/h

Introduction

The search for an operating frequency which would lead to the enhanced selective heating of insects in the Extremely High Frequency (EHF) and Super High Frequency (SHF) ranges is motivated by the need to develop alternatives to certain important agricultural chemical pesticides for the treatment of stored products which are to be banned by the Clean Air Act by the year 2001. Operation at discrete frequencies in the microwave and millimeter wave ranges, including Industrial Scientific and Medical (ISM) frequencies specified in the US Code of Federal Regulations (CFR 47, part 2), is attractive because of the availability of recently developed high-power oscillators with high continuous outputs and efficiencies at those frequencies. Unlike the relatively low-power microwave and lower frequency heaters operating at frequencies ⩽ 2.45 GHz, the EHF and SHF high-power sources offer the possibility of continuous processing of the treated-product at high throughput rates and taking advantage of the electromagnetic shielding inherent in the waveguide-like piping or ducting systems, that are common in transport systems at grain storage facilities.

Historical Perspective

Studies of the effectiveness and economics of controlling stored-grain insects with microwave energy at frequencies EHF and SHF ranges have continued These frequencies were previously believed to be less effective than frequencies in the 10 to 100 MHz range (Nelson and Stetson 1974; Nelson et al. 1996). However, based on the results of recent tests, Halverson et al. (1996a, 1996b & 1997) and Plarre et al. (1997) concluded that selective heating of the insect increases nonlinearly at frequencies above 10.6 GHz and that relaxation processes associated with free water in the insect and increased energy transfer to electrically small bodies at frequencies ⩾ 24 GHz would produce enhanced selective heating since the stored cereal grains contain water only in the bound form. Recently both dynamic (continuous process) and static (batch process) tests were conducted at 28 GHz at the Oak Ridge National Laboratory (ORNL) Fusion Engineering Division's 200 kW VGA-8000 (CPI, Palo Alto, California) CW gyrotron facility on samples of soft white wheat, *Triticum aestivum* (L.), infested with adults and larvae of the maize weevil, *Sitophilus zeamais* Motschulsky The results of this test, reported in Halverson et al. 1997, demonstrated the practicability of continuous processing of stored products at high mass-flow-rates.

The dynamic tests were conducted to verify that control of the air-to-product volume ratio in a detuned resonant cavity applicator would result in deeper penetration of energy into

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a diffused dynamic (flowing) product and to determine the relationship between energy, product temperature, and insect mortality in the flowing product. (This test is discussed from the entomological standpoint in a paper in this conference by R. Plarre et al., Microwaves at higher frequencies-can they be use for stored product pest control?). A prototype applicator to treat the infested dynamic product was designed and constructed for treatment at a frequency of 28 GHz. The disassembled cylindrical 1 m × 0.78 m dia. detuned resonant cavity applicator is shown in Fig 1. A means of controlling the volume ratio of the product while flowing through a 10.16 cm dia. quartz tube in the applicator was provided and hence the depth of penetration of the flowing bulk product could be controlled. Exposure time in the prototype applicator was determined by the length of time for a single grain to fall under the force of gravity through the 1 m long applicator Test samples were released from a test hopper and flowed through the applicator where they were exposed to the microwave energy for the fixed 600 ms time-of-transit period and then collected in a sample holder at the output. The results indicated 100 % kill of adults, pupae and old larvae, and > 94% of the young larvae and eggs over a minimum energy range per unit mass of product of about to 75 J/g at maximum product temperature of ≤ 36℃, about 44℃ and about 52℃ as shown in Figs 2(a) and 2(b). A comparison of the dynamic 28 GHz adult mortality at 7 d versus temperature data with that of static tests at 39 MHz at 8 d (Nelson and Stetson 1974) for adult rice weevils indicates that mortality at 28 GHz as a function of maximum grain temperature for the adult maize weevils appears to be identical within the statistical variance of the data. Since the load energy was not reduced to the level where 50% mortality occurred, the dynamic test alone could not demonstrate the expected increase in the selective heating of the insect compared to the 39 MHz case. However, enhanced selective heating was demonstrated in the static test subsequently described. No comparisons of mortality as a function of load energy could be made, because comparable published data at 39 MHz were not available.

In the case of the static tests at 28 GHz, a −3 dB thick layer (7 mm) of product containing capsules of infested soft white wheat was exposed for various time from 250 ms to 2 s to determine the relationship between mortality and exposure time at various input energies The results shown in Table 1 confirmed that energy was the dominant factor in determining mortality for exposure times as short as 500 ms. The temperatures given were taken by a single type K thermocouple located at the center of the 39.4 cm dia. dish which held the exposed static mass. Postexposure infrared scan recordings of the dish indicated that the spatial temperature distribution in the dish was lower than that at the thermocouple and therefore the measured temperature range given in Table 1 represents an upper bound to both the maximum and minimum values given. Hence, the knee of the logistic mortality curve for the 7 d adult mortality was actually lower than temperatures reported by others at 39 MHz and supports the thesis that coupling to the free water in the insect is a more efficient way of transferring energy than by coupling to bound water.

Table 1. Linear mortality curve fitting for the variables of load energy per unit product, maximum temperature, and exposure time/mass, for the static test at 28 GHz

Age	$M(U_{load})$%	$M(T_{max})$ %	$M(\Delta t)$ % (U'_m = constant)
	$22 \leqslant U_{load} \leqslant 44$ J/g	$35 \leqslant T_{max} \leqslant 46$ ℃	$0.42 \leqslant k\Delta t/m \leqslant 6.6$ ms/g
Young larvae	$0.28\ U_{load} + 84.4$	$0.57\ T_{max} + 70.23$	$2.23 k\Delta t/m + 84.4$
Older larvae	100	100	100
Adults	100	100	100

where:

$U'_m = U_m/m$ [J/g] is the specific energy input in terms of U_m per unit mass of product

$U_{load} = kU_m$

$= C\Delta T$ [J/g] is the amount of energy delivered to the sample per unit mass

$k = Cm\Delta T / U_m$ is the coupling coefficient

$U_m = P\Delta t$ [W-s] or [J]

m is the measured sample mass in grams [g]

Δt is the measured exposure time in seconds [s]

T_{max} is the measured maximum sample temperature in ℃

P is the measured input power in watts [W]

C is the specific heat of soft white wheat [J/g−℃]

In both dynamic and static tests at 28 GHz the adults and older larvae were killed more easily at lower input energies and lower product temperatures than the younger larvae. This implied that, in the case of adults and older larvae, the dominant energy transfer mechanism to the insect is by direct radiation rather than indirectly by conduction from the heated product. In the case of the younger larvae and eggs, radiation coupling may be diminished because of its much smaller energy cross section and the shielding effects of the wheat kernel in which they reside. Nevertheless exposure times of 600 ms were sufficiently long to kill the larvae but required greater energy input to do so with resulting in higher product temperatures. Older larvae are also somewhat shielded by the kernel but less than the younger because the older larvae have already excavated most of the inner matter in the kernel and thus are only shielded by a very thin layer.

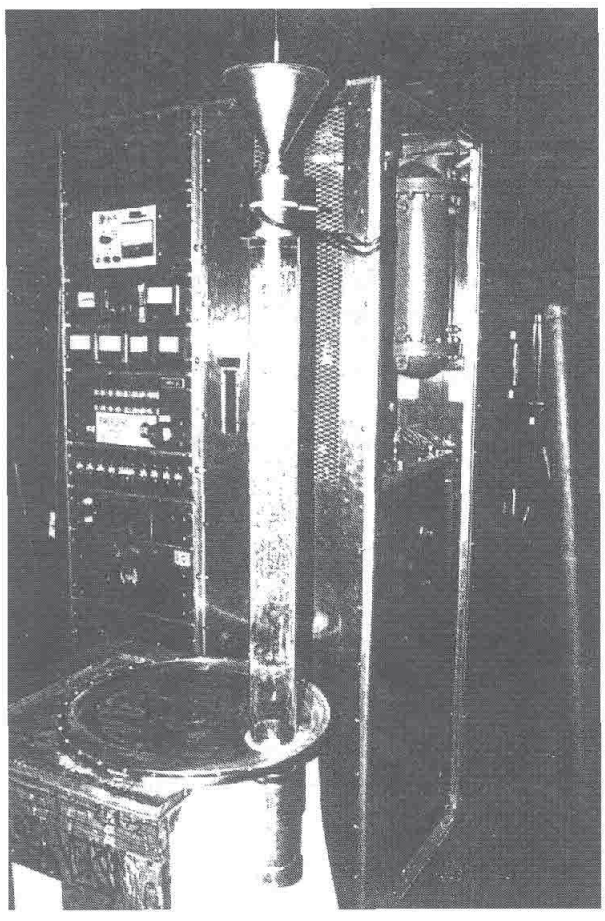

Fig. 1. Disassembled 1 m×0.78 m dia. microwave untuned cavity applicator showing hopper and release valve assembly, 1 m × 10.16 cm dia. quartz guide tube, cavity bottom cover plate and sample collector used for 28 GHz dynamic test.

One-way path attenuation tests were conducted recently on dynamic (flowing) samples of hard red wheat, soft white wheat, and long grain brown rice over a range of 18 to 50 GHz to validate previous calculations of increased penetration for the dynamic state (Halverson et al. 1998). This provided a direct measure of the depth of penetration of a singly traveling wave through the flowing product over a path length of 10.16 cm. This path length was chosen because it was identical to the diameter of the quartz tube used in the dynamic test. Three replicates of cultivars of hard red wheat, soft white wheat and brown rice were tested in the dynamic (flowing) state over each of three swept frequency ranges, 18 to 26.5 GHz, 26.5 to 40 GHz and 33 to 50 GHz and the one-way path attenuation between transmitting and receiving horns was measured directly. Prior to the direct measurement, penetration depth had been inferred from measurements of the dielectric properties of the bulk product by using the Landau, Lifschitz and Looyenga (Nelson and You 1990) equations for dielectric mixtures. The depth of penetration was then calculated from the attenuation constant for a specified air-product mixture. The direct measurements of soft white wheat were in agreement with the calculated values and demonstrated the random complex scattering properties of the flowing mass. Initial results indicate average penetration depths of about 30 cm were achieved at 28 GHz for volume ratios about 3%. It was also noted that both scattering and absorption occur within the flowing product. The former tends to act as a mode stirrer thus leading to greater field uniformity within the applicator. The microwave energy within the detuned cavity applicator may be thought of as a photon gas.

Ancillary static tests were performed at the University of Wisconsin at Madison on the Computer and Electrical Engineering Department's 14.25 GHz facility (Plarre et al. 1997) to verify the relationship between exposure time and mortality at a constant energy input. This test also involved exposure of samples of soft white wheat infested with maize weevils. The exposed samples were observed for mortality over a 35-days period. The results indicated that for the case of treatment of a static product exposure time has a lower limit in producing a high mortality with low variability. A comparison with data taken in the static test at 28 GHz shown in Table 1 indicates that the minimum exposure time appears to be facility and frequency specific. In particular the microwave power coupling efficiency (k) was much lower in the 14.25 GHz facility than in the 28 GHz facility. Therefore, to permit a normalized comparison of the results the exposure time per unit mass of product the variable $k\Delta t/m$ is introduced as defined in Table 1. The results indicate that for the constant energy case mortality appears to be a nonlinear function of exposure time once the lower exposure time limit has been reached. This limit was unique for each of the two test facilities and protocols studied here.

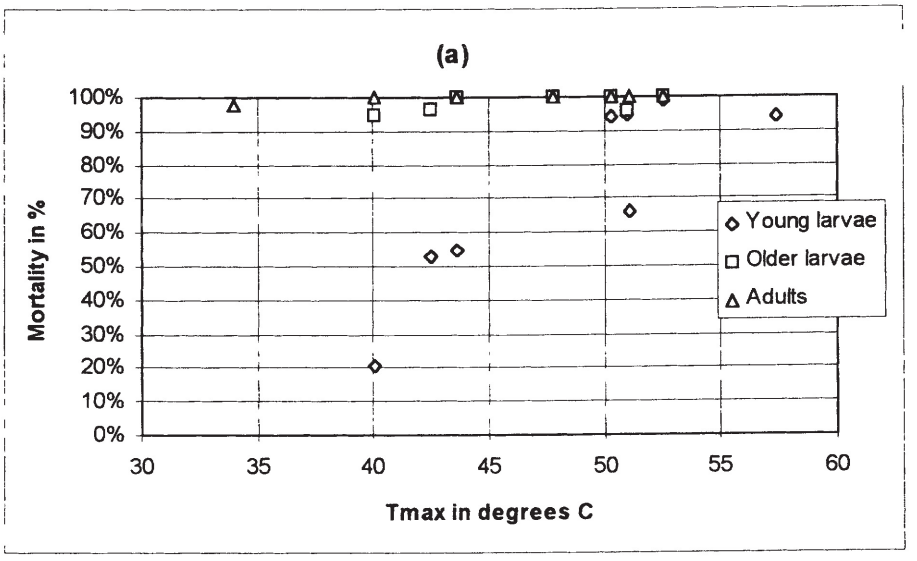

Fig 2a. Mortality of maize weevils in soft white wheat in the dynamic test at 28 GHz versus maximum product temperature T_{max}

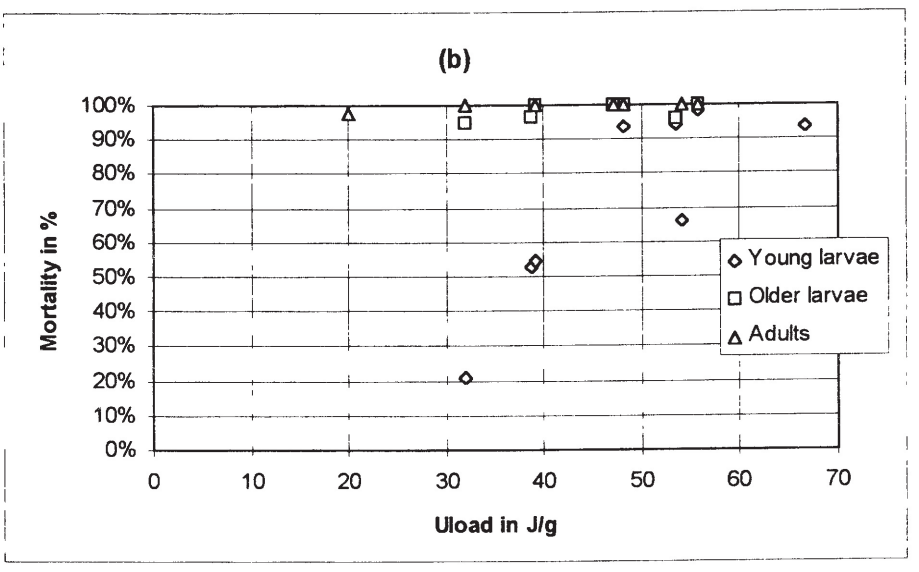

Fig 2b. Mortality of maize weevils in soft white wheat in the dynamic test at 28 GHz versus U_{load}

Design Equations

The depth of penetration calculations based on the complex dielectric properties of the medium was validated by the results of the depth of penetration measurements previously described. Therefore, the following theoretical equations may now be used to establish the design requirements for an applicator where the product is uniformly distributed by a diffusion means.

The depth of penetration of electromagnetic field into the bulk material in the applicator is normally characterized by the inverse of the attenuation constant or the penetration depth of the bulk material. The penetration depth is that distance over which the intensity of a singly traveling plane wave will be reduced by a factor of $1/e$ of its initial value A derived characteristic, the depth of penetration (Metaxas and Meredith 1993), defined by a -3 dB attenuation depth, or that depth over which the intensity of a singly traveling plane wave will be reduced by a factor of $(1/2)^{1/2}$, may also be used. The attenuation is related inversely to the density-dependent effective loss factor of the bulk material and the frequency. As frequency increases the penetration depth in a dense and lossy material decreases rapidly. Therefore, in a

mass flowing freely under the gravitational force, it is necessary to provide a means of controlling the bulk density to permit the energy to penetrate the product. The −3dB penetration depth, defined by equation (1) is dependent upon the complex dielectric properties of the individuals comprising the heterogeneous mixture of insects and product in the applicator. The attenuation of the wave intensity per unit length for a plane wave propagating through the mixture can be determined from the equation (2), derived from the propagation constant in complex dielectrics (Ramo and Whinnery 1953) and the dielectric mixture equation (3).

$$\delta_{3dB} = 0.3466/\alpha \quad (1)$$

Where:

$$\alpha = \omega \sqrt{\mu_0 \varepsilon_0 |\varepsilon_r|} \cos(1/2 \arctan(-\varepsilon''_r/\varepsilon'_r \pm 2\pi) + \pi/2 \text{Nerpers per meter} \quad (2)$$

$\mu_0 = 4\pi(10)^{-7}$ Wb/m

$\varepsilon_0 = 1/36\pi(10)^{-9}$ F/m

ε_r = Relative complex dielectric constant of mixture $= \varepsilon'_r - j\,\varepsilon''_r$

ε'' = Loss factor

ε'_r = Real part of relative dielectric constant

$\omega = 2\pi f$ HZ

From Nelson and You, 1990:

$$\varepsilon_r^{1/3} = v_2(\varepsilon_{r\,LLL})^{1/3} + v_1(\varepsilon_{r\,air})^{1/3} \quad (3)$$

$\varepsilon_{r\,LLL}$ is the relative complex dielectric constant of the individual infested kernel determined from independent measurements of ε_r for the infested product

$$\varepsilon_{r\,LLL} = \varepsilon'_{r\,LLL} + j\,\varepsilon''_{r\,LLL}$$

Where:

$\varepsilon_{r\,air} = 1$

v_1 = Ratio of the volume of air in the mixture to the total applicator volume $= 1 - v_2$

v_2 = Ratio of the volume of infested kernels in the mixture to the total applicator volume.

General solutions for the half-power (−3dB) depth of penetration of the fields into the granular medium may as a function of v_2 can be determined by letting v_2 be an independent variable and solving for v_1 and substituting values in equations (2), (3) and (1).

To determine v_2 in a particular case, where the system design requirements are established, the following design specifications must be known

- The mass flowrate f_m of the orifice gate valve of a specified inlet orifice of radius r_o.
- The average weight m_k and average volume V_k of a single kernel of treated grain determined by measurement or from published data.
- The axial length L and volume V of the cylindrical applicator.
- The average velocity V_k of a single kernel of grain falling under the force of gravity through the axial length of the applicator.

Given V_k and L the dwell time of a single kernel in the applicator will be:

$$t_d = L/V_k \quad (4)$$

Therefore, the total mass of the uniformly distributed product within the applicator at any time will be:

$$\Sigma m_k = f_m * t_d \quad (5)$$

The total number of kernels in the applicator will be:

$$N_k = \Sigma m_k / m_k \quad (6)$$

and the total volume occupied by the total mass of product in the applicator will be:

$$\Sigma V_k = N_k * V_k \quad (7)$$

Hence, the volume of product normalized with respect to V is:

$$v_2 = \Sigma V_k / V \quad (8)$$

and the normalized volume of air is:

$$v_1 = 1 - v_2 \quad (9)$$

Substituting the above values in (3) will yield particular solutions to (2) and (1). The particular solution is then compared to the general solution to determine if the penetration depth criterion, i.e. that the distance from any coupling aperture to the product within the applicator is equal or less than the −3 dB penetration depth defined by equation (1). If the penetration depth criterion is not met then the design specifications of the system must be changed by either decreasing the mass flowrate f_m or increasing the applicator volume V until the criterion is met. The input power requirements to produce the desired level of mortality may now be determined from the following equation in cases where the 100% lethal specific load energy ($U_{load100}$) and coupling efficiency (k) have been determined from test data

$$P_{in} = (U_{load100}/(k * t_d)) * \Sigma m_k$$

Other relevant design factors are given in Halverson and Bigelow 1998 (Patent Pending) which has been filed with the U S. Department of Commerce Patent and Trademark Office.

Discussion

The coupling between the gyrotron oscillator and the treated product in a dynamic state is greater than for the static mass as determined by the calculated coupling coefficient (Halverson et al. 1997). This implies greater system efficiency in dynamic treatment and consequently indicates the practicability and advantages of continuous processing of a diffused infested product By taking the advantage of the extremely high continuous power generation capability of the gyrotron, the process throughput rate can be increased substantially thereby eliminating the limitations of batch processing at lower powers. The design of the dynamic prototype facility is being modified presently to permit processing at an equivalent rate of 4 1/2 to 9 kg/s. Successful completion of a dynamic test on the modified

facility is a necessary precursor to the development of a demonstration unit capable of processing at a rate required by a typical storage facility by the year 2000.

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