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Abstract

Principles applicable to controlling stored-product insects with radiofrequency (RF) energy and general findings of research on this topic are reviewed. Data are presented on the frequency dependence of the dielectric constant and dielectric loss factor of insects and grain, and use of such information is discussed in relation to RF treatment for insect control. Some aspects of practical application are also considered.

Introduction

It has been known since the 1920's that insects can be killed by exposure to high-frequency electric fields. Many researchers have explored the possibility of controlling various insect species with RF electric energy since then, and their findings have been reviewed^{1,2,3,4,5,6,7}

Insects infesting grain, cereal products, wood, seed, and other stored products can be controlled through dielectric heating by microwave or lower frequency RF energy. Some studies have also been conducted with insects in soils, fruits, and other food products. Raising the temperatures of infested material by any means is a possible insect-control method if the infested product can tolerate temperature levels necessary to kill the insects. Dielectric heating offers an advantage over more conventional types of heating if the insects can be heated selectively, i.e., if the insects absorb energy at a higher rate than the host material and can be rapidly raised to a lethal temperature without excessively heating the host product.

Recent advances in the application of microwave power and interest in nonchemical methods of controlling insects have stirred new interests in potential use of RF energy for insect control. The purpose here is to summarize the general findings and to review briefly some of the fundamental principles relating to insect control using RF electric energy.

In many of these studies, the question has usually arisen as to the nature of the lethal mechanism(s) responsible for the injury or death of the insects exposed to RF electric fields. Most investigators believe that deleterious effects can be accounted for on the basis of RF dielectric heating. Often, "specific effects" attributed to the electric field have been explained by differential or localized heating of insect body tissues. However, some observations may or may not be satisfactorily explained on this basis^{6,8}, and further research is needed to resolve the question.

Fundamental Principles

Since known principles useful for insect control depend upon thermal effects, the concepts involved in RF dielectric heating of substances will be considered briefly.

The power dissipated per unit volume in a dielectric under the influence of an alternating electric field may be expressed as $P = E^2\sigma = E^2\omega\epsilon_0\epsilon'' =$

$$2\pi f E^2 \epsilon_0 \epsilon'' = 55.63 f E^2 \epsilon'' \times 10^{-12} \text{ W/m}^3 \quad (1)$$

where E represents the electric field intensity in the dielectric (V/m), f is the frequency of the alternating field (hertz), ω is the angular frequency ($2\pi f$), ϵ_0 is the permittivity of free space (8.854×10^{-12} farad/m), and σ and ϵ'' are, respectively, the a-c conductivity and the relative dielectric loss factor or loss index of the material at the particular frequency considered. The loss factor, ϵ'' , is the imaginary part of the complex relative permittivity, $\epsilon_p = \epsilon_p' - j\epsilon_p''$, the real part, ϵ_p' , being the dielectric constant.

The time rate of temperature increase ($^{\circ}\text{C/s}$) in the dielectric, as a result of energy absorption from the RF field, may be expressed as

$$dT/dt = 0.239 \times 10^{-6} P/\rho c \quad (2)$$

where P is power density in W/m^3 , and c and ρ represent, respectively, the specific heat and specific gravity of the dielectric. This expression neglects heat losses from the dielectric during exposure and is not valid if energy is used for the volatilization of water or other material in the dielectric.

While Eqs. 1 and 2 are applicable to homogeneous dielectrics under specified conditions, they are difficult to apply to heterogeneous dielectrics or mixtures of materials. In these cases, the relationships should be valid for individual constituents of the mixture, but reliable values for the field intensity, E , the loss factor, ϵ'' , and even the specific heat and specific gravity may be somewhat difficult to obtain.

For the simple case of a sphere of one material (medium 1) embedded in an infinite medium of another material (medium 2), the relationship between field intensities in the two media may be expressed as

$$E_1 = E_2 \left[1 - \frac{\epsilon_{r1} - \epsilon_{r2}}{2\epsilon_{r2} + \epsilon_{r1}} \right] = E_2 \left[\frac{3\epsilon_{r2}}{2\epsilon_{r2} + \epsilon_{r1}} \right] \quad (3)$$

Thus, the relative magnitude of the dielectric constants of materials in the mixture and their geometric shapes and relationships will influence the electric field intensity distribution in a mixture of materials.

At microwave frequencies, the attenuation of the energy as it penetrates large objects is another factor to be considered. The degree of attenuation depends mainly upon the dielectric loss factor of the materials.

While an accurate analytical approach to the action of microwaves (and lower frequency RF energy as well) on a complex mixture such as insects and their host materials may appear futile, an understanding of the basic principles can provide useful insight in explaining observed phenomena.

General Findings

With regard to insect-control studies, many early findings can be substantiated by considering the basic principles. The heating rate of materials exposed to RF electric fields increases with increasing field intensity and with increasing frequency (Eqs. 1 and 2). Since the loss factor of hygroscopic materials generally increases with moisture content, their heating rates also are higher when moisture contents are greater.

Studies have shown that many insects infesting grain, cereal products, and wood products can be controlled by short exposures to RF fields that do not damage the host material. Generally, resulting temperatures in the host material necessary for control of insects range between about 40° and 70° C, depending upon the host, the insect species, and the nature of the RF treatment. So far as is known, however, RF methods have not been practical because they are more costly than chemical or other control methods.

Entomological Factors

Differences in susceptibility to control for different insect species have been noted when treated in common host media under comparable conditions. Some differences are no doubt attributable to interspecific characteristics of a biological or physiological nature, but some may be explained by variations in size and geometric relationships.

Differences have also been found in the susceptibility of different developmental stages within the same species. In general, the adults are more susceptible to control by RF fields than are the immature forms, i.e., egg, larval, and pupal stages. Some of the stored-grain insect species have been found more susceptible to control outside the grain kernels than when concealed within the kernels.

Various injuries to the legs and other appendages have been observed for insects subjected to sublethal RF exposures. These injuries have usually been attributed to high E-field concentrations and consequent localized heating during RF exposure. Interspecific differences have been found in the degree of delayed mortality observed during the weeks following RF treatment.

Reproductive sterilization of the type produced by ionizing radiations has not been observed in RF-treated insects. Reproductive capacity, however, is reduced in surviving adults by treatments which achieve a relatively high mortality of the population.

Physical Factors

The influences of various physical factors, such as frequency, electric field intensity, pulse modulation, heating rate, and characteristics of host materials, have also been studied. General conclusions are difficult to draw concerning some of these factors. High field intensities are more effective than low field intensities in some instances. High heating rates are to be preferred, generally, to minimize thermal loss from the insect to the host medium. Although pulse modulation permits the use of higher field intensities at some frequencies, definite advantages of modulation have not been confirmed.

Contrasting differences in effectiveness of RF insect-control methods have been noted when widely differing frequencies have been used. In particular, comparisons of stored-grain insect-control treatments

at frequencies of 11 to 90 MHz with treatments at 2450 MHz have shown the lower frequency range to be much more efficient in controlling the insects^{7,9}. Resulting temperatures in the host media were considerably higher at 2450 MHz than at the lower frequencies for exposures required to control the different insect species and developmental stages of those species.

The importance of frequency has been further illustrated by studies of the frequency dependence of the dielectric properties of insects and host medium. Values for the dielectric constant and dielectric loss factor of adult rice weevils, *Sitophilus oryzae* (L.), and wheat, *Triticum aestivum* L., have been measured over a wide range of frequencies⁹. Frequency dependence of the dielectric constant, ϵ'_n , and the loss factor, ϵ''_n , for these two kinds of materials is illustrated in Figs. 1 and 2. An analysis of the differential dielectric heating to be expected at different frequencies, based on Eqs. 1 and 3 and values of ϵ'_n and ϵ''_n , revealed that the dielectric loss factor is the dominant factor to be considered. Therefore, it is obvious from the data of Fig. 2 that better selective heating of the insects should be expected in the frequency range between about 5 and 100 MHz than can be expected at frequencies above 1 GHz.

Since the curves for ϵ'_n and ϵ''_n of rice weevils and wheat, as illustrated in Figs. 1 and 2, are characteristic of some dielectric dispersion and absorption phenomenon (Fig. 3), it is probable that the relaxation frequencies (frequencies of maximum loss) will shift to higher frequencies as the temperatures of the materials increase. Shifts in relaxation frequencies of two orders of magnitude may be possible in the temperature range through which the insects must be elevated to achieve complete mortality. If this occurs during RF treatment at a fixed frequency of 40 MHz, for example, it means that the insect-to-grain loss-factor ratio will decrease during the exposure, and the relatively large selective heating advantage possible at the beginning of the exposure may be reduced during latter stages of the exposure. Therefore, it may be possible to materially improve the efficiency of RF treatment for insect-control purposes by increasing the frequency during exposure to more nearly follow the maximum insect-to-grain loss-factor ratio as the treatment progresses.

Practical Aspects

If the anticipated shift in relaxation frequencies occurs, as explained in the foregoing example, the optimum frequency for finishing the treatment may well approach the microwave range. The most practical design for a high-power RF-treating system would likely include two or more fixed-frequency power oscillators. The infested product would be conveyed continuously through the system with the exposure starting at the lower frequency and finishing at the higher frequency.

Cost estimates for RF insect control in grain, based on fixed-frequency equipment operating at one frequency, indicate that RF methods might be 3 to 5 times more expensive than chemical controls currently in use. Various other factors influencing practical application have also been considered⁷. A major improvement in the efficiency of RF treatment could materially change the economic picture. Therefore, a survey of the frequency and temperature dependence of the dielectric properties of insects and host materials for any particular application may provide important information on which to assess the practicability of an RF application.

Continually increasing concern about environmental

aspects of chemical control methods is another factor that should be considered. Speed of treatment and lack of potentially harmful chemical residues are two unique advantages which RF methods have to offer. With improvement of efficiency and with developing technology, RF insect-control methods may become practical for certain applications

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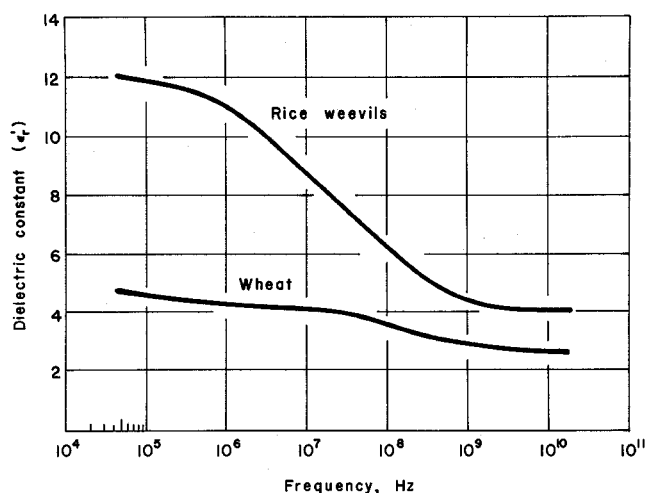


Fig. 1. Dielectric dispersion of bulk samples of adult rice weevils and of hard red winter wheat (10.6% moisture) at 24° C.

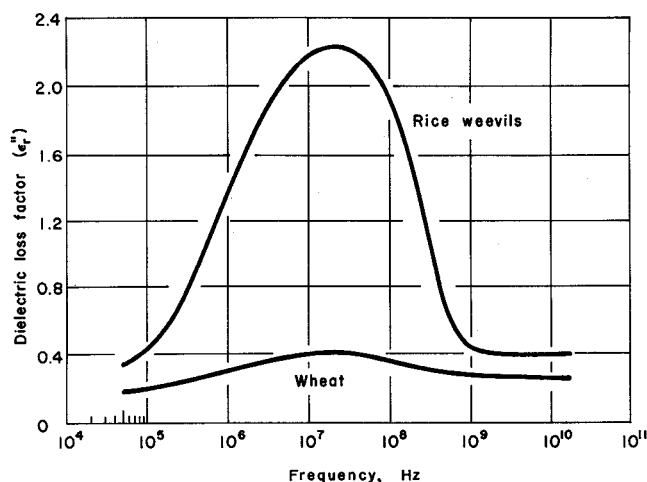


Fig. 2. Dielectric absorption of bulk samples of adult rice weevils and of hard red winter wheat (10.6% moisture) at 24° C.

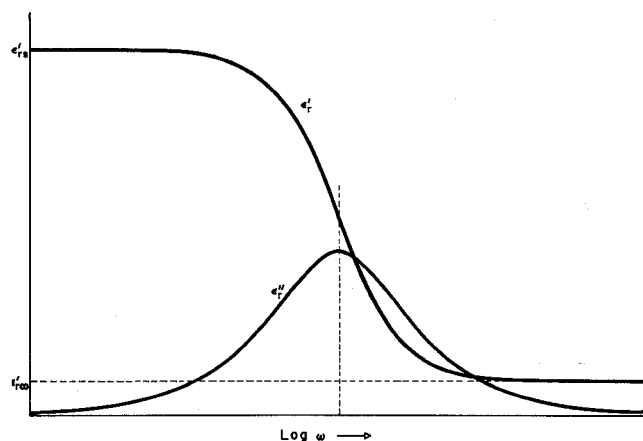


Fig. 3. Dispersion and absorption curves representing the Debye relaxation process for polar molecules.